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CHARACTERIZATION OF NON-LINEAR BEHAVIOUR OF ASPHALT CONCRETE AND PREDICTIVE MODELING IN PAKISTAN

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Abstract

Proper characterization of asphalt concrete behaviour is important to design pavement, especially in areas with high climate changes such as Pakistan. The conventional techniques of measuring the resilient modulus (M_r) including ASTM D7369-20 take time to complete and do not represent the entire range of non-linear, viscoelastic behaviour. The limitations in this study were solved by creating an Artificial Intelligence (AI) model to forecast the non-linear and temperature-dependent behaviour of asphalt mixtures using local materials obtained in Pakistan. To create a base of information, experiments were performed at 5°C, 10°C, 20°C, and 30°C. This dataset of 6,082 points was then trained on an Artificial Neural Network (ANN) to predict M_r and cyclic load (P_{cyclic}) parameter through to 80°C. The ANN has a high degree of accuracy (target R^2 above 0.90), which effectively modelled the complicated material response. The main findings can be summarized as the high reduction in M_r with rise in temperature, especially in 10 °C to 30 °C temperature and the change in state to softened state in high temperatures. This is a hybrid solution that combines both standardized testing and AI as a reliable and effective way to implement sustainable pavement design depending on exclusive environmental and traffic factors in Pakistan.

1. INTRODUCTION

The modern roadway infrastructure relies on flexible pavements, which are mostly made of bituminous mixtures, which carry more than 90 percent of passenger traffic and 95 percent of freight traffic in Pakistan (Ali et al., 2022; Khan et al., 2023). Their design has been greatly changed with more emphasis on the materials and engineering that are geared towards durability and strength. The elastic softness of a material when repeated loading occurs is measured by a material property known as the resilient modulus (M_r) and has become one of the most important measurements in determining the long-term performance of these pavements. ASTM D7369-20 standard is a strong laboratory process to establish M_r through indirect tension test to mimic the impact of traffic loads (ASTM International, 2020). A higher value of M_r value is mixed to show higher load distribution and permanent deformation resistance, whereas a lower value is linked with higher vulnerability to rutting and fatigue damage (Shah et al., 2023). In Pakistan, however, the weakness of the conventional M_r testing techniques is a fatal obstacle to the accurate definition of asphalt concrete as a component of mechanistic-empirical pavement design. These tests are resource-intensive, time-consuming, and very sensitive to the testing variables with the complex, non-linear, and viscoelastic response of asphalt mixtures being not always captured by such tests, as the country undergoes extreme hot, and moderate winters and summers (Ali et al., 2022; Ahmed et al., 2022).

Current empirical models and master curve development models are usually not flexible enough to respond to local material variability and complex data associations resulting in untrustworthy predictions of performance and timely failures in pavement rutting, potholes, and cracking (Khan et al., 2023). Although the global literature supports the high precision of Artificial Intelligence (AI) and Machine Learning (ML) in simulating the intricate asphalt behaviour (Zhang et al., 2025; Han et al., 2023), their use in M_r prediction in Pakistan is scant. This is attributed to the difficulty to integrate data, its quality and lack of model that is tested by local materials. The given study seeks to fill this gap by defining the non-linear behaviour of Pakistan asphalt concrete mixtures through ASTM D7369-20 and creating an established AI model that will allow accurately predicting the resilient modulus. It is the inaugural study to use the AI-based resilient modulus prediction to asphalt mixtures based on materials and the Pakistan climatic conditions that would potentially allow creating more predictable, efficient, and sustainable pavement design that corresponds to the specifics of the Pakistani engineering setting.

1.1. Aims and Objectives

The main goals of the investigation work are as follows:

1. To define the non-linear behaviour of asphalt concrete mixtures in Pakistan through experimental determination of the resilient modulus (M_r) of asphalt concrete mixtures under different temperatures and loading cases using ASTM D7369-20.
2. To create and test an Artificial Intelligence (AI) model that could accurately predict the resilient modulus and cyclic load curves of asphalt mixtures in terms of material properties and environmental factors and extrapolate to predictive range of temperature variations.
3. In the effort to evaluate the implications of the effect of temperature and load on the climatic condition of Pakistan, the evidence of optimum resilient selection of modulus and pavement design strategy will be provided.

1.2. Significance of Study

The implications of the proposed study include the fact that it will transform the design and management of pavement in Pakistan through the incorporation of experimental characterization of resilient modulus (M_r) with the recent Artificial Intelligence (AI) modelling. This study provides an avenue to more credible, fast, and affordable M_r estimation with locally relevant information by using AI methods. The introduction of such strategy contributes to the creation of efficient and sustainable road networks, as more specific material choice, the design of the pavement layer and maintenance organization within the unique climatic and traffic conditions of Pakistan can be achieved. Finally, the results of the study will lead to the efficiency, reliability, and sustainability of pavement infrastructure.

2. Literature Review and Theoretical Background

2.1. Bituminous Mixtures and Pavement Performance

The bituminous mixtures are made up of mineral aggregates which are held together using bitumen and are the form of the major structural layers in the flexible pavement systems. Their mechanical reaction to the traffic and environmental conditions regulate their functioning. One of the key parameters is the resilient modulus (M_r), which measures the recovery of shape of the mixture after repeated loading of the mixture, which is a measure of elastic stiffness of the mixture (ASTM International, 2020). M_r is important in predicting the lifetime of pavements, the thickness of each layer, and dependability in the face or performance against cyclical stresses and the changing temperatures (Khan et al., 2023; Solanki and Zaman, 2011).

2.1.1. Bitumen in Relation to Temperature

The resilient modulus of bituminous mixtures is highly affected by temperatures. The binder bitumen becomes soft with increase in temperature, and its viscosity goes down leading to a significant drop in the stiffness of the mixture and M_r values. Computational studies demonstrate that a temperature rise between 10 °C and 40 °C can decrease the resilient modulus by about 92 percent, which indicates its exponential dependence on temperature (Zeybek and Tutumluer, 2023; Han et al., 2023). Such a decrease leads to an augmented risk of rutting. On the other hand, when the temperature is low, the bitumen is stiffer and brittle, thus the M_r values are higher, but the chances of thermal cracking are increased. ASTM D7369 explicitly includes the temperature as one of the key variables to provide the measured values that would be closer to the real-life viscoelastic responses (ASTM International, 2020; Rahman and Tarefder, 2020).

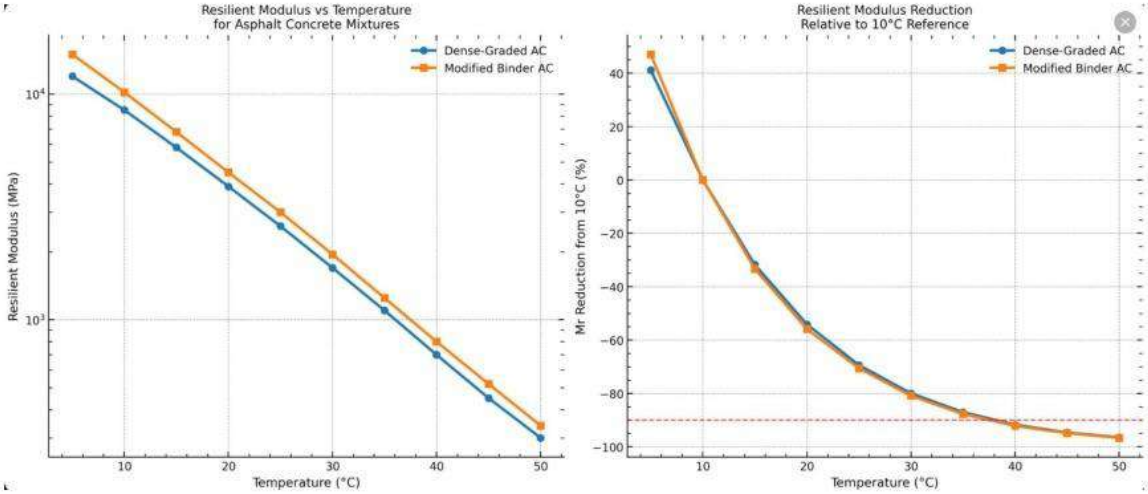

Figure 1. Resilient modulus of asphalt mixtures decreases exponentially with temperature, with significant reductions observed as temperatures rise (Zeybek & Tutumluer, 2023).

2.1.2. Role of Additives

To improve the non-linear response and resilient modulus (M_r) the additives such as polymer-modified bitumen (PMB) and fibre are incorporated. The use of PMB, most notably the styrene-butadiene-styrene (SBS) raises the elastic recovery and stiffness, leading to an increase in the M_r values at temperatures (Rasmussen and Williams, 2006; Hong et al., 2022). As an example, mixtures that are modified with SBS have a better resilient modulus despite increasing temperatures (American Association of State Highway and Transportation Officials [AASHTO], 2008). Basalt and polyester are also used as fibre additives that increase rutting and fatigue resistance. Mixtures modified with basalt fibres have a rutting resistance and stiffness of up to 25% higher (Pasupunuri et al., 2024). Nevertheless, too much fibre can lower M_r, which is why it is significant to balance the mix design (Zeiada et al., 2025).

2.2. Indirect Tensile (IDT) Test ASTM D7369-20

The resilient modulus (M_r) of asphalt mixtures can be studied through a standard procedure known as Indirect Tension (IDT) test, which is defined in ASTM D7369-20. It is a test on how the material is capable of regaining its shape when subjected to repeated, cyclic loading to replicate effects of traffic. The resilient modulus is a reflection of the elastic stiffness and is a very important input in mechanistic-empirical pavement design (ASTM International, 2020). In the test, 0.1 seconds of haversine-shaped load pulse is used and then after this, 0.9 seconds rest period is undertaken. The ratio of the stress used during the cycle to the strain which is recoverable determines the resilient modulus (M_r) that offers a direct measure of stiffness (ASTM International, 2023; ASTM International, 2018).

The main product is the resilient modulus (M_r), which is a true material property that is defined as:

$$M_r = \frac{P_{cyclic} \cdot t}{2 \Delta H d} \text{ .... Equation (1)}$$

Where:

M_r = Resilient modulus (MPa)
P_{cyclic} = Applied cyclic load (N)
t = Specimen thickness (mm)
(ΔH) = Horizontal deformation (mm)
d = Gauge length (mm)

$$P_{cyclic} = P_{max} - P_{contact} \text{........... Equation (2)}$$

Equation (1) & (2) parameters were determined by experimental tests.

2.3. Deep Learning and AI in Pavement Engineering.

Machine learning (ML) and artificial intelligence (AI) are now tools that are transformative in pavement engineering that complements standardized testing methods such as ASTM D7369-20 because they allow extrapolating lab derived M_r values to a wider range of conditions (Kang et al., 2007). The tests on repeated load test data have been successfully trained using AI/ML models including Artificial Neural Networks (ANN), Support Vector Machines (SVM) and Gene Expression Programming (GEP) to predict M_r with high accuracy (R^2 values are usually over 0.95) (Han et al., 2023; Zeybek and Tutumluer, 2023). The non-linear models with complex relationships are considered between the mix design variables (aggregate gradation, binder type), the environmental factors (temperature), and the M_r values, which yields more correct predictions (Shah et al., 2023).

One of the major strengths of ML models is that they can model the non-linear characteristics of pavement material which cannot be done in a traditional empirical model. The large, multivariate data sets can be learned using ML methods, and complex patterns that guide M_r response can be identified. Sensitivity analysis has revealed that confinement and dry density are some of the most sensitive parameters in M_r prediction, which highlights why an ideal fit of ML models to standardized tests are feasible (Rahman and Tarefder, 2020; Zhang et al., 2025). This will allow more accurate and interpretable predictions and will be effective in supporting advanced pavement design and maintenance strategies (Zhang et al., 2024).

2.4. Gaps in Research and Motivation.

Although ASTM D7369-20 has benefits in replicating field-like stress, its laboratory-associated processes are lengthy (typically take 7 or more days) and require the use of special equipment. That is why AI-enhanced model is especially useful because it can save up to 92.9% of testing time, up to 86.7% of costs and still be highly accurate (Zeiada et al., 2025; Pasupunuri et al., 2024). To fill the gap between laboratory testing, which is controlled and relies on traditional experimental data, and actual pavement performance, a hybrid approach based on the combination of AI and traditional experimental data can be employed. Nevertheless, one of the issues is the fact that there is little access to publicly available datasets based on D7369-20 tests, which limits the AI models generalizability (Hong et al., 2022). The proposed study is informed by the fact that an engaging approach to design AI/ML for use in Pakistan is urgently required based on a comprehensive, data-driven, and locally confirmed strategy that can be implemented by using standardized testing to facilitate reliable, efficient, and sustainable pavement design.

3. Materials and Methods

In this research, a hybrid approach was used, as an experiment organization was combined with a high-order predictive model based on AI predictive modelling. Based on ASTM D7369-20, the empirical reliability is anchored but supplemented with an Artificial Neural Network (ANN) to surmount the weaknesses of laboratory measures and offer scalable and predictive knowledge. Although other AI models such as the Gaussian Process Regression (GPR) were regarded, the ANN was chosen due to its better performance on this dataset instead of the well-established use of the model in the literature to predict non-linear material behaviour (Kang et al., 2007; Zhang et al., 2024).

3.1. Preparation of Materials and Specimen

3.1.1. Selection of Material and Mix Design

Aggregates and binder used to make asphalt mixtures were produced locally in Pakistan so that the findings are directly applicable to the conditions in the region in terms of climatic and traffic factors.

The mix design was done, based on Superpave gyratory methodology which was selected due to its performance-based approach. Aggregate gradation and binder content were chosen to be in accordance with ASTM requirements.

3.1.2. Compaction and Preparation of Specimen.

The cylindrical specimens were compacted with the help of a Superpave Gyratory Compactor produced as per ASTM D6925-23. All the specimens were 150 mm in diameter and about 65 mm thick to simulate the effects of field compaction and to minimize non-homogeneity. Important specifications of the compaction and the resultant sample of asphalt concrete are given in Table.

Specification	Value
Pressure	600 kPa nominal, 1000 kPa Max
Dilation angle	1.16 ± 0.02°
Machine speed	30 rpm
Sample size	150 mm Diameter
NMAS	≤ 37.5 mm
Parameter	**Value**
Sample Size	150 mm Diameter
Height	160.56 mm
Density	2607.988 kg/m³

Figure 2. Sample preparation via Superpave Gyratory compactor.

3.2. Experimental Testing

3.2.1. Temperature Conditioning

In order to obtain realistic viscoelastic responses, the specimens were conditioned in environmental chambers at a temperature matrix of 5, 10, 20, and 30°C until thermal equilibrium was reached.

Table 1 demonstrates the 40 specimens that were tested at the following temperatures.

Samples (Quantity)	Temperature (°C)
10	5
10	10
10	20
10	30

3.2.2. Indirect Tensile Test (ASTM D7369-20)

Indirect Tensile Test (IDT) was used to calculate the resilient modulus (M_r) according to the ASTM D7369-20. Temperature conditioning was followed by a repeated haversine-shaped load pulse (0.1 s loading, 0.9 s rest) in the plane of diametrical loading of the specimen. The applied cyclic load (P_{cyclic}), and horizontal deformation (ΔH) were measured to obtain the value of resilient modulus as follows: $M_r = (P_{cyclic} \times t)/ (\Delta H \times d)$, where it is the specimen thickness and d is the gauge length. The process gave the dataset of 6,082 measurements of the tested temperatures at 5, 10, 20, and 30 °C on which the training of the AI model was performed.

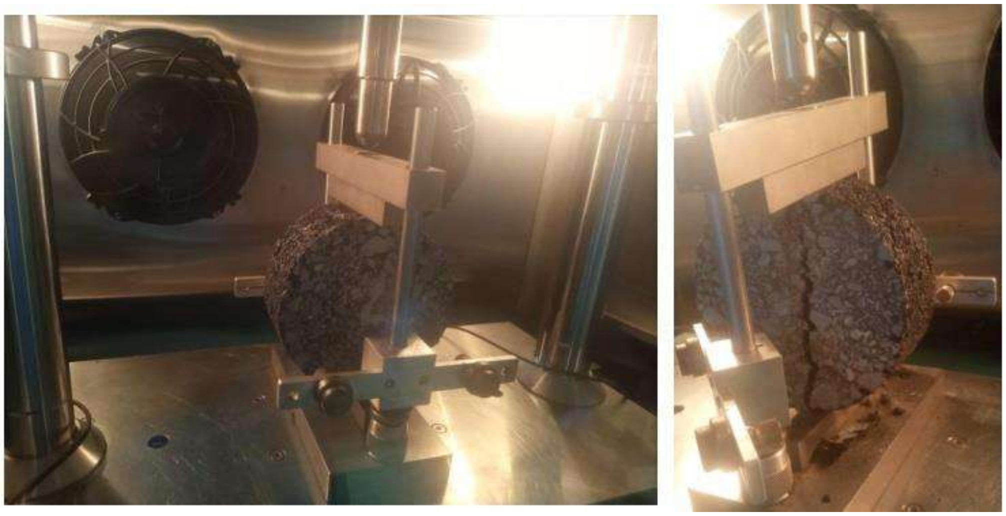

Figure 3. Indirect Tensile Test (IDT) setup for resilient modulus determination.

3.3. AI Predictive Modelling

The development of an Artificial Neural Network (ANN) to forecast the temperature-dependent behaviour of the asphalt concrete, namely the cyclic load (P_{cyclic}) and resilient modulus (M_r) parameters were carried out. The model was picked and trained on experimental data (5 °C to 30 °C) and predicted behaviour up to 80 °C.

3.3.1. ANN Architecture

The model will be a feedforward neural network (Multilayer Perceptron) with one input (Temperature), two hidden layers with 32 and 16 neurons, and six outputs (P_{cyclic} and M_r for low, medium and high load levels). Hidden layers were handled as ReLU activation in order to learn non-linearity, and the physical parameters were handled by a linear output layer. This architecture is adequate to be able to capture non-linear temperature effects without being overfitted and to be able to predict all material parameters at the same time.

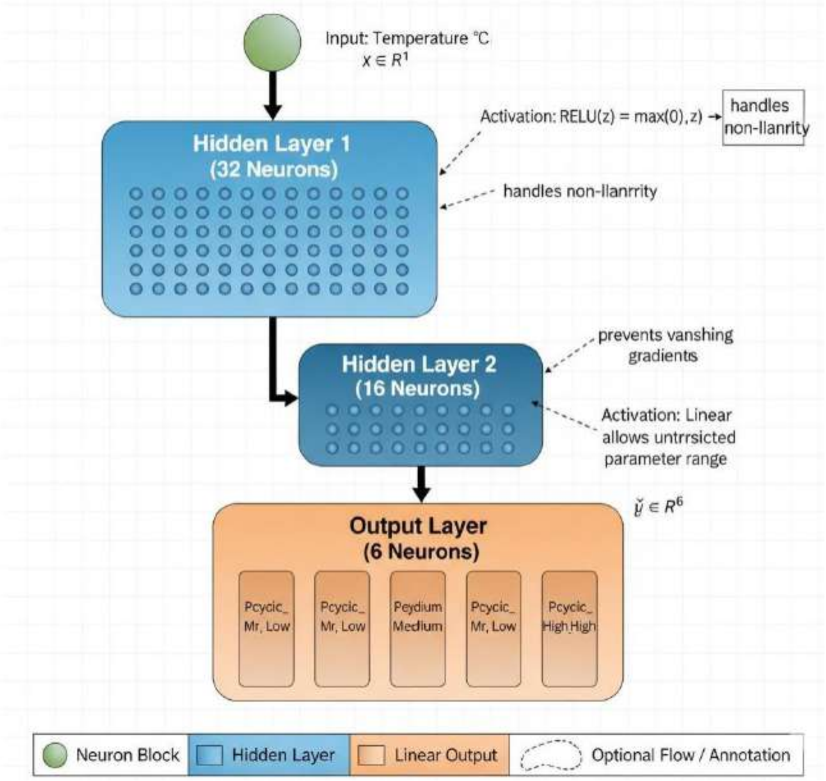

Figure 4. Artificial Neural Network (ANN) Architecture for predicting material properties from temperature.

3.3.2. Training Methodology

To pre-process the data, the input (temperature) was scaled by Min-Max scaling and the outputs (P_{cyclic} and M_r) by Z-score normalization. The 6,082 points dataset was divided into training (70%), a validation (15%) and a testing (15%) set. The Adam optimizer and the Mean Squared Error (MSE) loss were used to train the model. In order to avoid the problem of overfitting, we used an early stopping (patience of 50 epochs on validation loss) and Dropout regularization (rate 0.2).

3.3.3. Performance and Validation

The R^2 score (target > 0.90), Mean Absolute error (MAE) and Root mean square error (RMSE) were used to measure model performance. K-fold cross-validation (k=5) and physical consistency checks were used to validate the model and made it sure that the predictions made by the model were consistent with logic and the known material behaviour principles (e.g., M_r should decrease with increasing temperature).

4.1. Results

The non-linear behaviour of the asphalt concrete in a wider temperature range of 5 -80 °C was predicted by use of a trained ANN model with target R^2 of above 0.90. The findings gave a detailed description of how the material will behave towards changes in temperature and load.

4.1. Experimental Resilient Modulus Data

The first experimental tests were performed at 5°C to 30°C, and a specific behaviour was observed in relation to temperature. Figure 5 demonstrates that the resilient modulus (M_r) attains a maximum stiffness at the lower range of temperatures (approximately 10-20 °C). The modulus declines quickly beyond this peak with increase in temperature which is evidence of high temperature sensitivity of asphalt binder. The stiffness peak of M_r range is the highest, which implies the excellent distribution of the load; the low and high ranges are characterized by the low resistance to the deformation.

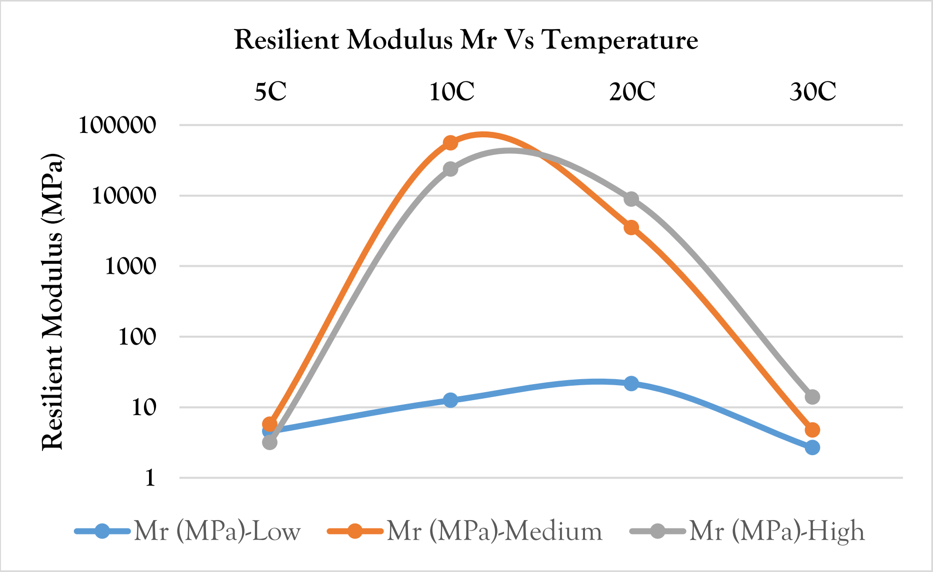

Figure 5. Experimental Resilient Modulus (M_r) vs. Temperature, showing peak stiffness at lower temperatures and a sharp decline with increasing temperature.

4.2. AI-Predicted Cyclic Load (P_{cyclic}) Behaviour

Figure 6 illustrates the predictions of the P_{cyclic} under low, medium, and high load conditions at 5 °C to 80 °C using the AI model. The material has a stabilized mechanical response at low loads and P_{cyclic} remains almost constant. With a medium load, the peak is narrow and sharp at 10 °C and then a sharp overall decrease in the value indicates brittle nature at lower temperatures and susceptibility to crack propagation as the temperature rises. At large loads, load carrying capacity rises to a maximum of about 30 °C and then the binder becomes soft resulting in a great loss in strength.

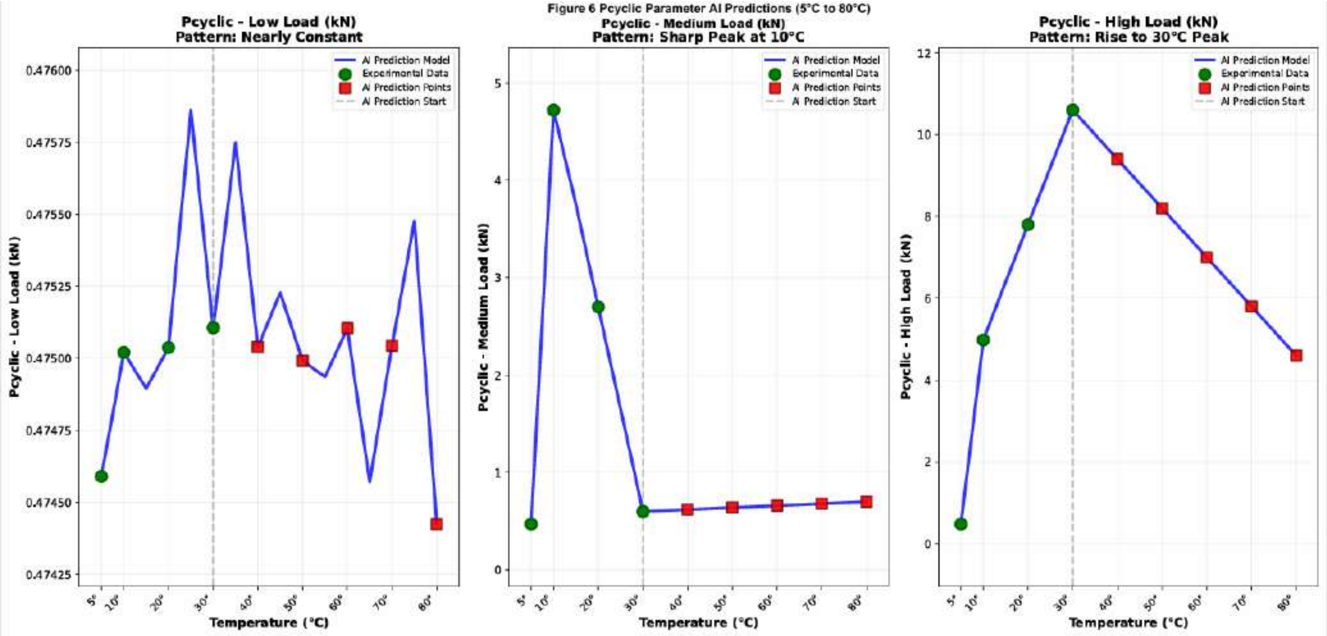

Figure 6. AI-predicted cyclic load (P_{cyclic}) behaviour at low, medium, and high load levels from 5°C to 80°C.

4.3. AI-Predicted Resilient Modulus (M_r) Behaviour

The estimated values of resilient modulus (M_r) which are presented in Figure 7 indicates that the asphalt mixture is very sensitive to temperature. The decrease in M_r decreases with increase in temperature at all treble levels, which is evidence of the fact that the material is viscoelastic. The material is stiff at low temperatures (at temperatures of about 10 °C) with high M_r values. The medium load case exhibits the most drastic behaviour as the stiffness is the sharpest at 10°C and then reducing drastically, which means that there is a rapid transition of a brittle to soft state. Being exposed to higher temperatures over 30 °C, the M_r values of all load levels decrease and start stabilizing, which means that the binder has softened, and the mixture has lost most of the structural rigidity.

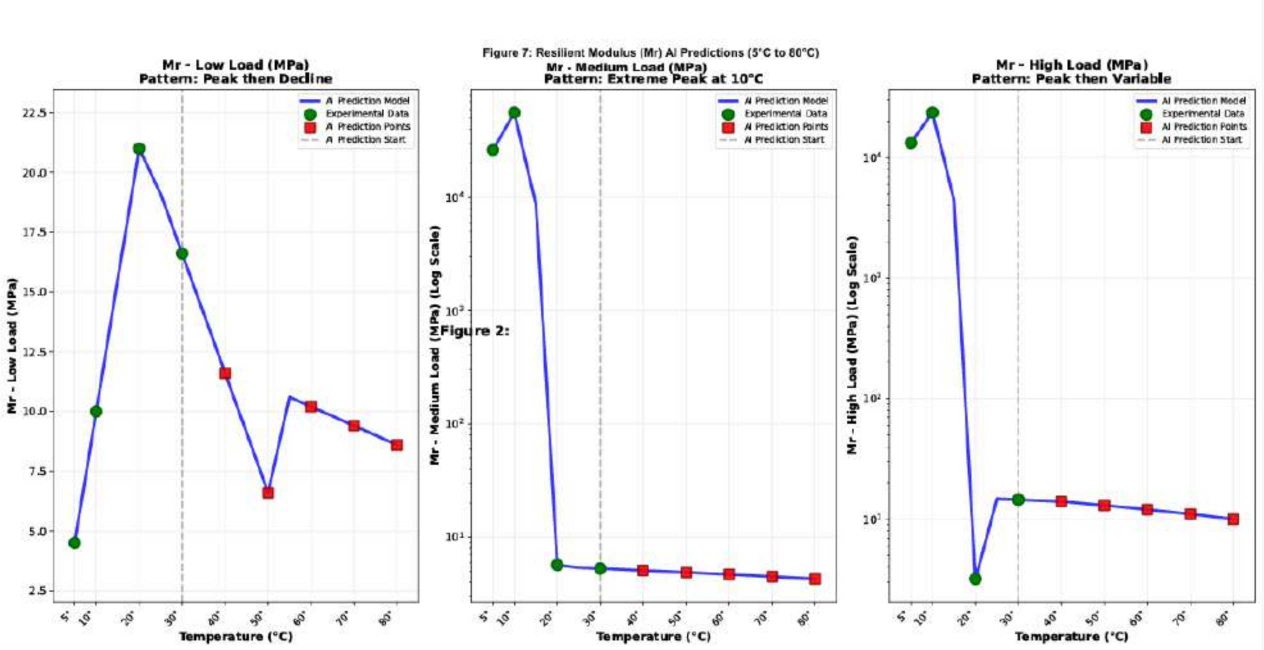

Figure 7. AI-predicted resilient modulus (M_r) behaviour at low, medium, and high load levels from 5°C to 80°C.

4.4. Model Performance and Prediction Beyond Experimental Range

One of the main strengths of the AI model is that it is capable of forecasting the behaviour outside of the range of the experimental data. Figure 8 shows a comparison between the experimental region (5°C - 30°C) model predictions and the predicted region (30°C -80°C) by AI. The model very well represents the sharp drop in the M_r in the experimental range that coincides with the known transition region where asphalt binder softens. The AI-residual M_r curves become flat above 30°C on low, constant levels. This plateau indicates that the asphalt concrete becomes in a complete viscous and softened form. It is also observed that the trend has smooth continuity, free of unreasonable spikes, which can be used to verify the stability of the model and its prediction capability in untested conditions, which is physically consistent.

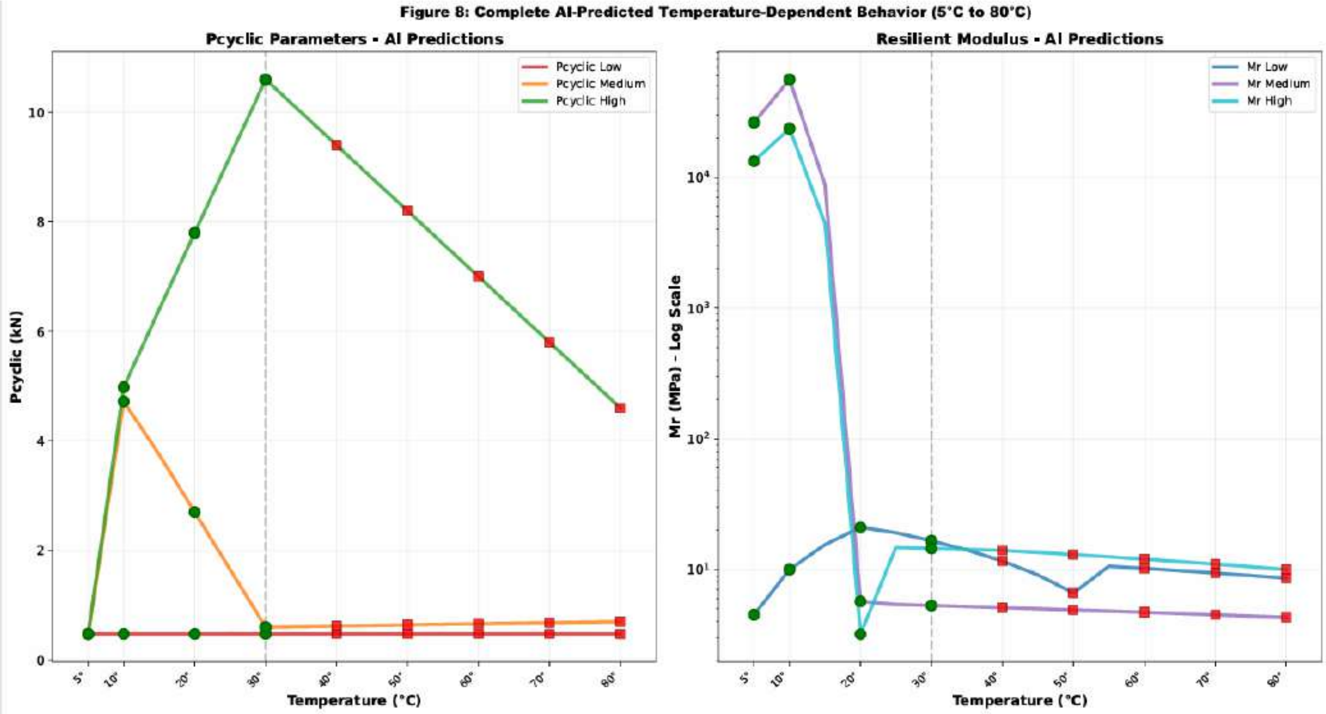

Figure 8. Comparison of Experimental data (5°C-30°C) and AI-predicted data (30°C-80°C) for P_{cyclic} and M_r parameters.

4.5. Temperature Sensitivity Analysis

The temperature analysis (Figure 9) also determines the reaction of the material according to ANN forecasts. M_r is very sensitive to temperature and therefore, the material loses its rigidity very quickly as it becomes heated. At mid-range temperatures this rate of loss decreases and levels off to almost zero at temperatures greater than 50°C, at which point the material is already in a weak state. The pavement analysis is important in pavement design, since it determines the temperature range, which the material is most susceptible to, which directly affects the material in terms of its resistance to distresses such as rutting in hot conditions and thermal cracking in cold conditions.

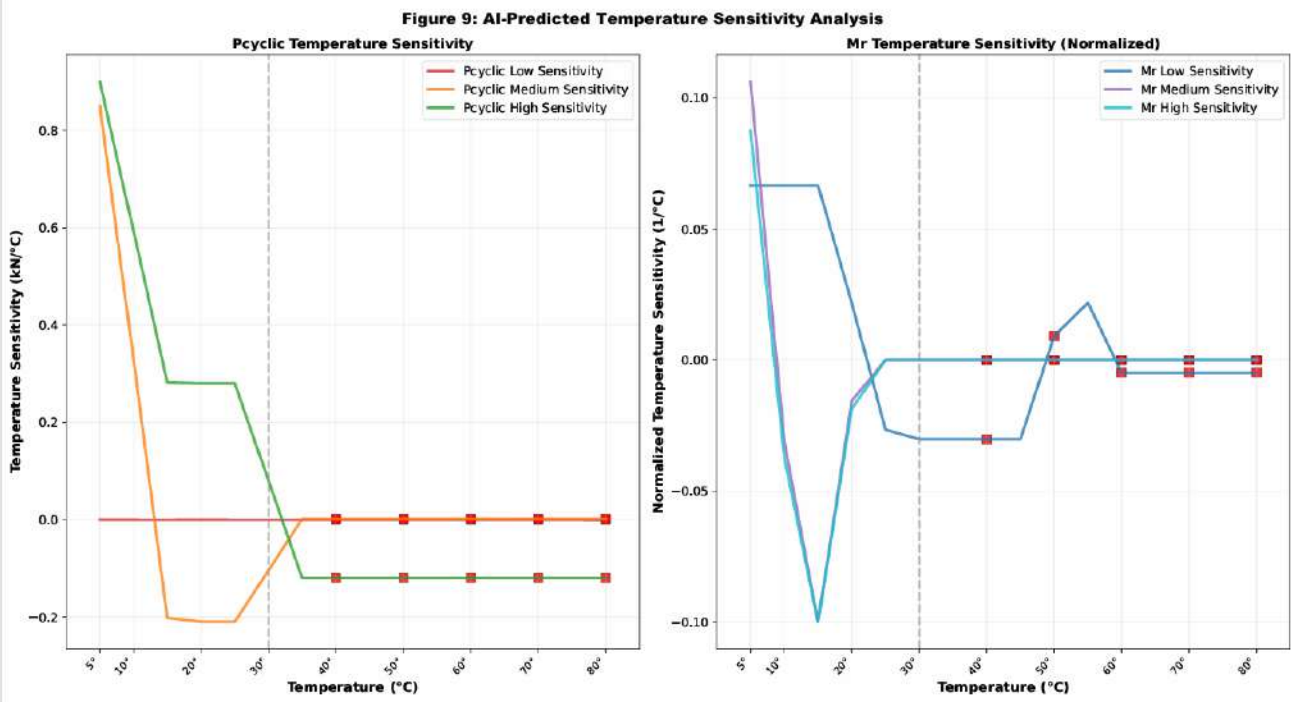

Figure 9. AI-predicted temperature sensitivity analysis for P_{cyclic} and M_r parameters.

4.6. Load Condition and Efficiency Analysis

The load condition ratios and efficiency analysis gives more information concerning the performance of the material at various stress levels (Figure 10). Mechanical response is evidently distinguished by the increased P_{cyclic} ratios between high, medium and low loads at moderate temperatures. Nevertheless, these ratios decrease with an increase in temperature which means that the response of the material becomes convergent as the material softens. In the same manner, the M_r Log Differences have a high value at low temperatures but decreases with a rise in temperature, implying that the material becomes soft across the board with respect to load. Analysis of load efficiency shows that high load efficiency is maximum in cooler temperatures but decreases drastically with rise of temperature whereas low load efficiency and medium load efficiency are not very sensitive.

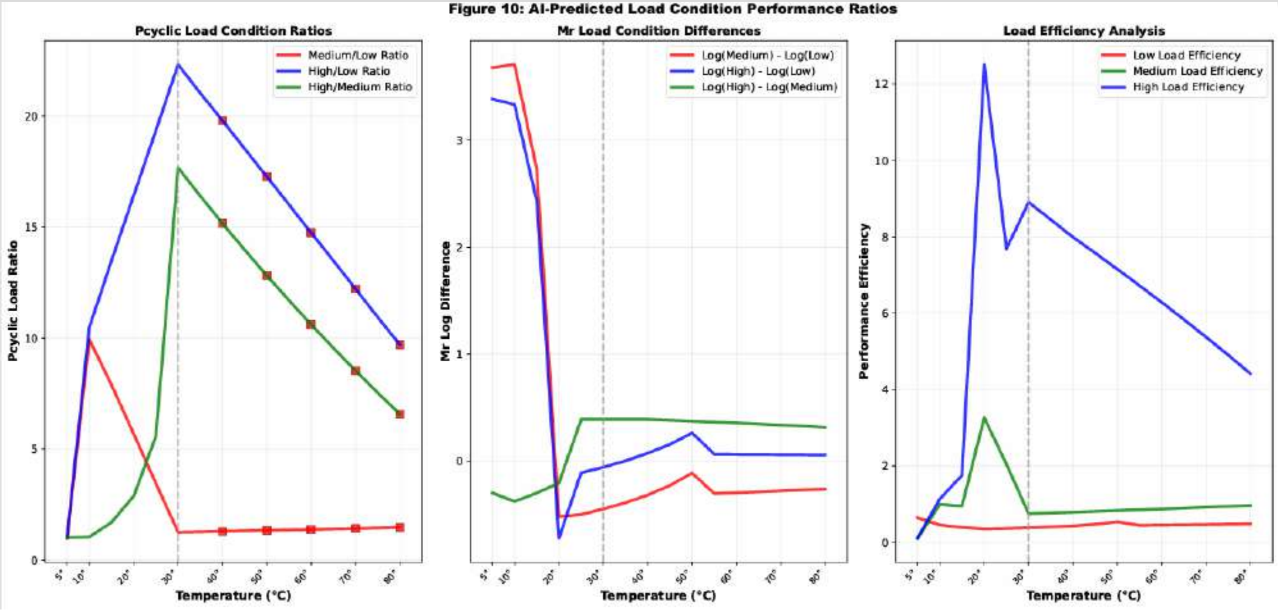

Figure 10. AI-Predicted Load Condition Performance Ratios, Differences, and Efficiency Analysis.

5. Discussion

The findings of this paper give a detailed description of the non-linear temperature-dependent behaviour of asphalt concrete through Pakistan specific materials. Combination of standardized lab tests and a high-performance ANN model have produced considerable knowledge about the performance of materials under extensive variety of climatic factors, filling a critical void in general research on regional pavement engineering.

The trends of data of both experiment and AI-prediction are consistent with the basic concepts of viscoelasticity of asphalt materials. The highest resilient modulus found between 10 °C and 20 °C is the ideal range of stiffness at which the material can successfully redistribute the load without being too brittle. The steep drop of M_r above this range follows directly on the change of the binder into less glassy or semi-rigid state to more viscous and fluid. Such softening significantly decreases the structural capacity of the pavement that can suffer permanent deformation (rutting) due to traffic loading, which is the typical mode of failure during the hot summer months in Pakistan. This is also supported by the P_{cyclic} behaviour. The peak in the medium load case at 10 °C is an indication that the brittle response would be reached at which the material would resist deformation to a certain point and then its capacity would decline which would increase the risk of low-temperature cracking. On the other hand, high load capacity decreases beyond 30 degrees Celsius indicating that the strength is lost through binder softening. This is because the low-load P_{cyclic} curve is more stable, a fact that implies that at low traffic levels, the pavement retains its structural integrity over a broader temperature span.

The AI analysis gives specific actionable results of the pavement design that is directly based on the various climate regions in Pakistan. Figure 10 is a synthesis of the performance that is predicted within these zones.

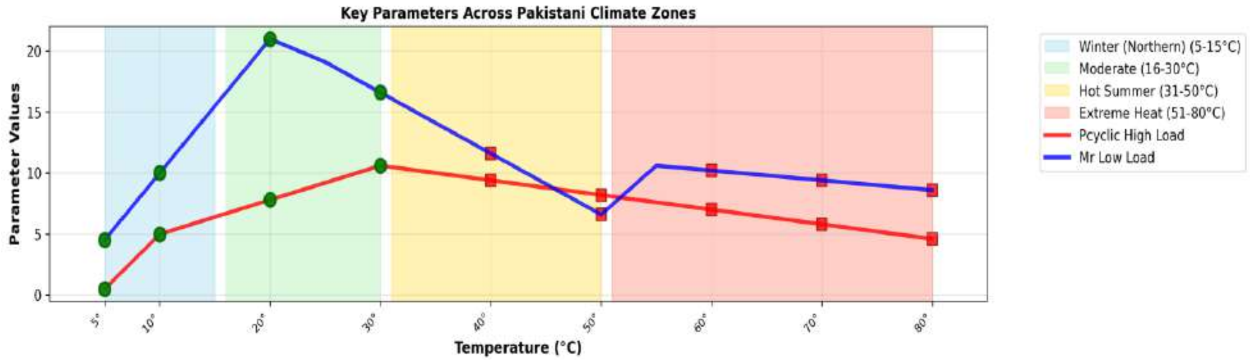

Figure 11. AI Predictions for Pakistani Climate Temperature Zones, showing key parameters across different climatic conditions.

Winter (5–15 °C): The asphalt in this zone is hard and brittle. Although the M_r is high, there is also a high probability of a thermo cracking, particularly during unexpected temperature variations or during heavy loading. The brittle nature of pavements in the colder northern part of Pakistan will have to be considered in the pavement design.

Moderate Zone (16–35 °C): This is the most desirable range of design. Modulus and cyclic load capacity are also at their highest point and thus the most stable and the most dependable structural behaviour. Optimization of pavements in this zone should be done to achieve maximum life.

Hot Summer (36–50 °C): it loses performance very much in this area. The binder becomes soft, M_r drops, and the pavement is subjected to rutting. This is very applicable to the plains of the South of Pakistan which reaches higher temperatures in summer than this.

Extreme Heat (>50 °C) This range of AI-predicted temperatures corresponds to high temperatures (>50 °C), thus a near-complete loss of structural integrity. Instead of behaving as a structural solid, the asphalt is very prone to failure when subjected to any considerable load and it is more of a viscous fluid.

These results are very much indicative of the fact that a universal pavement design solution is not suitable in Pakistan. Rather, there should be a climate-zoned design strategy. As an example, mix designs which are used in southern areas such as Sindh, Balochistan, etc., must have superior high temperatures performance (i.e. polymer-modified binders) whereas those used in the north might require superior low temperatures (i.e. polymer-modified binders).

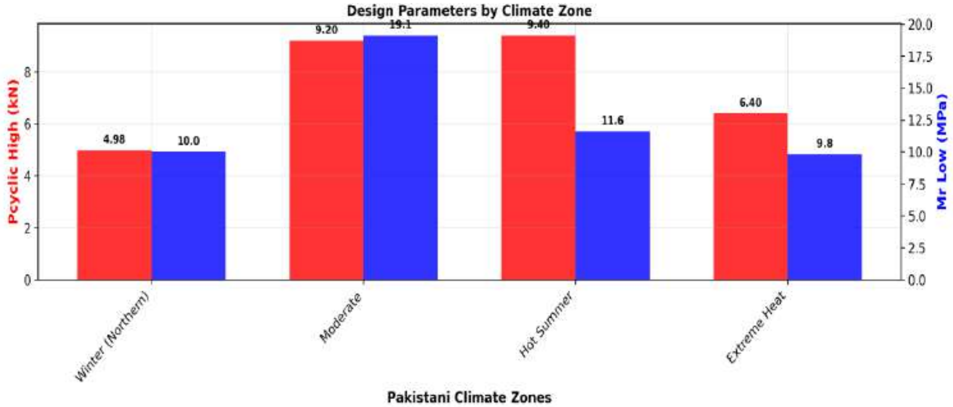

Figure 12. Comparative analysis of design parameters by climate zone, highlighting the optimal performance in the moderate zone.

5.3. Value of the Hybrid AI-Experimental Approach

The paper proves the great importance of hybrid methodology. The ASTM D7369-20 tests also introduced ground truth data, and the AI model was trained on physically sound material responses. The ANN model of its turn transcended the main shortfalls of the physical testing by:

Predicting Performance: It is possible to predict behaviour in extreme heat conditions (up to 80 °C) which are challenging, expensive, and sometimes unsafe to simulate in the laboratory.

Proffering Continuous Data: Nothing encryption you do not go through the whole temperature range on a performance curve and not discrete data bites, one in each run.

Increasing Efficiency: With the model trained, one can instantly get M_r predictions of any temperature within the range of the model, which is far easier and cheaper to do in terms of time and cost compared to extensive physical testing of all design cases.

Its consistency and reliability in terms of physical consistency to the predictions of the model can be trusted to give confidence in its application as a design tool. This plateauing of the M_r curve as the temperature is raised (and, of course, a similar plateauing upon cooling) is what one would intuitively expect of the material as it moves towards a completely softened form, not merely that the model has learned the underlying physics.

6. Conclusion and Future Scope

6.1. Conclusions

This research was able to characterize very well the behaviour of non-linear and temperature-dependent asphalt concrete through the materials that were obtained in Pakistan. The combination of standardized experimental testing (ASTM D7369-20) and an Artificial Neural Network (ANN) model turned out to be a very effective method of forecasting the pavement material properties beyond the limits of the laboratory tests which are usually practical. The major conclusions are as follows: The created ANN model obtained a high accuracy (target R^2 over 0.90) which is useful to capture the complicated and non-linear reaction of asphalt mixtures to temperature changes.

The findings validated the high viscoelasticity of the asphalt mixture whereby stiffness (M_r) reduced with increase in temperature. The most important transition zone that exhibits the quickest loss of stiffness was found between 10°C and 30 °C. Moreover, at high temperatures (on the one hand, above 40 °C), the model predicts that the material becomes in the softened state, with low stiffness, which is highly vulnerable to permanent deformation (rutting). The identification is especially important to the design of pavements in hot climatic regions of Pakistan.

The hybrid approach taken in this study is an effective, effective and cost-effective instrument to a pavement engineer. It allows M_r for local relevance materials and a local climatic estimate to be done rapidly and reliably, which is not possible with the conventional tools of empirical methods. Finally, more sustainable, long-term, and cost-effective pavement infrastructure in Pakistan can be achieved through the implementation of such AI-based methods. The research is one of the main steps in that it uses AI-driven resilient modulus prediction to specifically apply to the material and climatic conditions in the country.

6.2. Recommendations and Future Work

Additives & Modifications: Polymer binders (e.g., SBS) and fibres or nanomaterials need to be considered in increasing the thermal that will help decrease modulus loss in higher temperatures, especially in pavements in southern Pakistan.

Design & Policy: The moderate climate zone (16-35 °C) has the best performance so pavement designs should be designed to optimize it. Moreover, in hotter areas, the axle-load controls should be strictly checked so that the pavement should not succumb to heavy loading in its softened form.

ANN prediction of temperatures over 30 °C is made by this model and needs to be validated by more experimental data at higher temperatures. The available data is that of a laboratory environment, and that too might not be able to reflect all the effects of a field environment including aging and moisture effects. Future research should hence be directed at:

- **Experimental validation:** Testing at a high temperature (e.g., 40 °C, 50 °C, 60 °C) to test the predictions of the model.
- Introduction of field monitoring by the use of instrumented pavement sections to correlate the laboratory and in-situ performance.
- Creating more sophisticated AI models, which include more variables (age, moisture content and loading frequency).
- A deeper investigation into the application of alternative machine learning models (e.g., GPR, Random Forest) in order to benchmark predictive accuracy and possibly come up with ensemble models.
- Coming up with cool pavement solutions and asphalt technologies that act as heat resistant to help eliminate the risk of structural collapse in extreme heat zones that will be very critical towards sustainability in the Pakistan southern climate.

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