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Optimal boosted framework for fatigue cracking prediction in polyethylene terephthalate pavement

Anand Prakash Chaturvedi* and Sanjeev Kumar Suman

Department of Civil Engineering, National Institute of Technology, Patna, Bihar - 800005, India

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Abstract

Depleting natural resources for construction purposes and research needs in the field of civil engineering is becoming a dependable process. To minimize this degradation process several techniques are implemented, one such method is using software approaches in research fields. In the consideration of the former investigation works, the focus point of the works is mainly on Crack Prediction on bitumen pavements. Since the bitumen pavement undergoes repeated loading under wheel loads in static conditions during traffic, and is dynamically loaded during the movement of fast moving vehicles. The strength parameters related to the fatigue limit of the bitumen are not analysed. Hence the fatigue limit of the bitumen should also be analysed. To analyze such conditions, deep learning with standardizing features is implemented to estimate the effective Strength parameters and to forecast the essential outcomes. In this study, the Fatigue Cracking Prediction of the Polymer Modified Bitumen (PMB) of grade 40 in Polyethylene Terephthalate (PET) Pavement is carried out. The Suggested Methodology is termed as Hyena based Curriculum Learning (HbCL). It is implemented in the Accuracy Prediction of Fatigue Cracking behaviour of PET pavement at different temperatures in dynamic and static load conditions. The fitness function in the optimization was triggered initially, to determine the ideal strength parameters of the Polymer Modified Bitumen as well as the PET. The tensile strength of the proposed model is 410 KPa in dynamic loading. The compression strength of the proposed model decreases with an increase in temperature. The rutting depth of the proposed model is between 1.7728mm and 1.6870mm. The Marshall Coefficient value gained was 2.7 KN/mm as the maximum for static loading. A value of 1.77mm in maximum is achieved by fatigue crack depth under dynamical load. The mean fatigue crack prediction accuracy estimated was 96.1%.

Keywords: Hyena optimization, Polymer modified bitumen, Marshall coefficient, Fatigue crack prediction

1. Introduction

Fatigue cracking and permanent distortion are the two different kinds of asphalt pavement distress [1]. The road surface layer of flexible pavement is formed of asphalt concrete mixture, a visco-elastic substance consisting of aggregates, bitumen, filler, and performance-enhancing addictive [2]. One of the main problems that reduce the life of flexible pavement is fatigue cracking, which usually results from continuous tensile strain brought on by wheel loads at the base of the asphalt mix layer [3]. To clarify, the fatigue failure mode of asphalt pavements is caused by the proliferation of micro- and macro-cracks, which are brought on by vehicles [4]. Several other elements also contribute to flexible pavement fatigue failure, including aging, moisture content, and temperature [5]. The capacity of flexible pavement to withstand repeated bending without breaking or cracking is known as its fatigue resistance; small cracks that appear are the first signs of larger fatigue distress when traffic loads are applied [6]. Tensile training causes fatigue fractures to start at the base of the asphalt layer and spread to the surface [7]. When applied wheel loads fall below the ultimate stress failure level, fatigue cracks begin to form [8]. These fractures eventually lead to potholes, which can cause traffic accidents [9]. The fatigue resistance of asphalt concrete is typically characterized in a laboratory setting using either constant strain loadings or constant stress loadings [10]. It is more difficult to characterize using constant strain loading than constant stress [11].

The definition of fatigue failure under continuous stress is based on the event of a sample failing due to excessive tensile strain following a test [12]. To mitigate fatigue and build a long-lasting pavement, researchers and engineers have developed several methods [13]. Using fibre as a reinforcing ingredient is one alternative for improving asphalt concrete; several kinds of fibre are being employed [14]. The distortion found across blacktop pavement includes two design conditions, retrievable deformity (temporary deformity under load) together with the non-retrievable deformity (permanent deformity). The most generally used designing criteria are the retrievable deformity avoiding the non-retrievable conditions [15]. The rutting pattern in the top surface of pavements is due to poor gradation in the bottom pavement layers [16]. The fatigue crack in flexible pavement develops due to non-retrievable deformity, which develops due to repeated loading in the pavement. The fatigue crack develops due to repeated loading is depends on the quality of materials used in the layers of flexible pavement [17].

The proposed polyethylene terephthalate pavement has resistance to the plastic behaviour strain under repeated cyclic loads [18]. Considering this statement the pavement with low bitumen content will easily subjected to plastic deformity [19]. Hence minimum bitumen content in the mix design of bitumen should be taken into consideration [20]. On the contrary, the bottom layers in pavement

*Corresponding author.
Email address: anand2616@gmail.com; anandchaturvedi2616@gmail.com
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play a vital role in the propagation of rutting depth to the bottom [21]. The strain energy stored in the flexible pavement under the impact of cyclic load provides benefits in regaining to its original shape once the load is removed in the initial stages [22]. As the cycles of load continue, the strain energy absorption is reduced and the fatigue property of the material starts to develop after a certain stage [23]. This condition is the same for both static and dynamic load conditions. In the dynamic load condition fatigue appears often than in the static load condition. This investigation in fatigue prediction of PET pavement occurs due to repeated cyclic loads. The rutting depth, tensile, and compressive parameters of the PET pavement are discussed along with the Fatigue Prediction Accuracy. In the end, the PMB mix and analysis is carried out based on the standard code limited values and is demonstrated under the assistance of prior investigation reports.

The key contribution about this current investigation is specified below,

- At the beginning, the properties of bitumen layer as well as Polyethylene terephthalate bitumen layer were examined owing to their parameters and their limits.
- Afterwards, a novel Hyena based Curriculum Learning (HbCL) mechanism is intended through adequate ideal qualities as well as fatigue estimation.
- Moreover, the Marshall Coefficient and Fatigue Crack Prediction are analyzed by applying both static and dynamic loads individually.
- Finally, the strength of the bitumen layer is evaluated with various temperature and PET percentages.
- At the end, the toughness about the suggested approach was assessed considering the analysis such as estimation of accuracy in fatigue damage, Toughness under tensile load, and compression load, rutting depth, Coefficient in Marshall Stability test and tensile stiffness.

In order to frame the results about the process of this study, the second section of this paper includes recent research works, the third section consists of overcoming of difficulties explained in the third section. The Fourth part consists of an evaluation of outcomes and their correlation with the recent papers. Finally, the Fifth section consists of the fulfilment of the research conflicts.

2. Related works

Some of the recent related literatures are described as follows,

Baradaran et al. [18] evaluated the physical function of the asphalt mixture that contains Polyethylene Terephthalate. The PET was recycled chemically. The experiments include creep due to dynamical loading, Tensile Toughnessm and Modulus of Tensile Parameter to evaluate the modulus of resilient and rutting. The outcomes express that adding Polyethylene Terephthalate increases opposition to rutting and humidity related defects. It also shows reduced crack behaviour. The factor of confidence is 95%. Hence it is known that adding PET components in bitumen enhances its physical properties.

Heidarian et al. [24] introduce the uses of waste carbon fibres from a sustainable waste management system. Recently carbon has been the most demanding fibers because of their mechanical properties. Meanwhile, addressing the reclamation and reformatting the properties is the most challenging task. To know more, the lifecycle and applications of carbon are investigated as well as the potential of waste and recycled products. At last, the highlights and applications are explored to further usages. In some rare cases, while using carbon it is a brittle and easily broken substance.

Zhang et al. [25] have analyzed the performance of the bitumen pavement in Norwegian limits. Only the wearing course is considered in this study. The variables in bitumen are divided into mechanical compositional and elastic-visco. The aging parameter of the bitumen is based on type, functional time, and temperature conditions. The prediction model has high accuracy in which the outcome of the model matches with the lab test values. In conclusion, the modulus of dynamic load resistance capacity of the pavement lowers with an increase in aging.

Aldagari et al. [26] examined the durability parameters of flexible pavements made with Polyethylene terephthalate in highways. The durability index evaluated is based on triggered energy. When the temperature goes to a higher level the pavement shows enhancing opposition to the plastic behaviour. The oil treated plastic grained plastic pavement illustrated in this investigation has higher durable parameters than ordinary PET pavements. Correlating with pure binder the oil treated plastic granules have a low chemical durability index.

Hossain et al. [27] emphasize the need for next–generation polymers, polypropylene (PP), a flexible polymer with a wide range of applications, has experienced significant modifications in recent years. This paper offers a thorough analysis of current PP research and its sophisticated functional applications. To direct future research and encourage innovation in polymer applications, the study highlights the exciting potential of PP while addressing open-ended issues. However, it has poor temperature capability.

The most typical type of cracking is fatigue cracking. It is caused by lowing-amplitude cyclic loads associated with traffic loads. Therefore, the repetitive passage of these loads rather than the load magnitude causes deterioration to the pavement structure. When the climate loads are paired with repetition, they can cause fatigue that eventually results in cracks. Since trucks carry more than 60% of all products and services, maintaining roadway infrastructure is critical to the economy. The responsibility of keeping roads in good shape at the lowest possible cost has grown more difficult due to rising traffic volumes and tight finances. The performance and service life of the pavement is particularly negatively impacted by pavement cracking. High building and maintenance expenses result from this. Consequently, it is crucial to adopt high-performance materials that can enhance pavement performance while lowering maintenance costs and frequency.

3. Proposed methodology

A novel Hyena based Curriculum Learning (HbCL) is introduced for fatigue estimation in the present work by incorporating the Polyethylene Terephthalate (PET) bituminous layer. In many cases, the fatigue is not determined while estimating the rutting behavior. But the fatigue crack also damage associated in the bitumen pavement. In the primary phase, PET bituminous substances were taken with the desirable conditions and needed concentrations. Then the static and dynamic load is applied for the strength evaluation. Then the optimal mechanical and fatigue cracking is predicted by the Hyena fitness process.

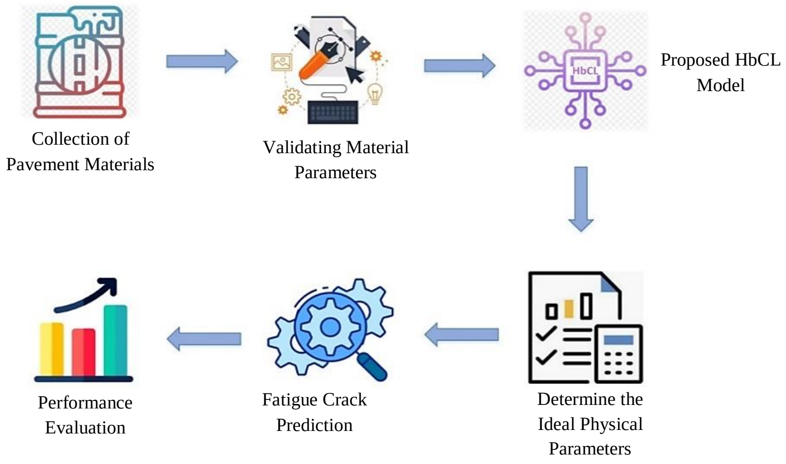

Figure 1 Suggested Methodology

Figure 1 defines the suggested methodology to predict the fatigue cracking in bitumen. Initially, the bitumen parameters are evaluated and checked whether it is within their standard limits [28]. Then Modelling takes place in Hyena based Curriculum Learning and the physical strength parameters are determined. Then the static and dynamic loads are implemented with different temperatures and analysed. Afterwards the Prediction of Fracture Cracking takes place. Then the results are compared with the recent study papers.

3.1 Polymer modified bitumen

The Bitumen employed for the investigation is of grade PMB 40; Where PMB stands for Polymer Modified Bitumen. As per IS 15462 2004 the PMB defines Type A Elastomeric Thermoplastics based Bitumen whose penetration value lies among 31mm to 40mm [28]. The preliminary tests such as Penetration Value, Softening Point, Automatic Breaking Point, Flash Point, and Viscosity tests studied, and their standard values are taken as input. Their optimal values are illustrated in Table 1.

Table 1 Characteristics of Polymer Modified Bitumen Grade 40

Reference	Characteristics	Optimal values	Range
IS 1203	25°C Penetration Value (mm)	40	30 to 50
IS 1205	Softening Point (°C)	60	60
IS 1206	Viscosity Ratio	4	4
IS1206 Part 1	Viscosity at 150°C (Poise)	6	3 to 9
IS 1208	Ductility at 25°C (cm)	25	5 to 100
IS 1209	Flash Point (°C)	220	220
IS 9381	FRAASS Breaking Point (°C)	-12	-12

The PMB 40 must be in homogenous colour when its temperature is raised above 169°C. The PMB must be in its natural state and should have an absence of other foreign minerals which will change its properties. The Thin Film oven test and Tests on residue tests are standard values are denoted in Table 2 below.

Table 2 Thin Film Oven Test Requirements on PMB 40

Reference	Characteristics	Optimal values
IS 1203	Minimum Reduction in Penetration (mm)	35
IS 1205	Increase in softening Point (°C)	5
IS 9382	Loss in Mass (%)	1
IS 15462	Elastic Recovery at 25 °C	35
IS 15462	Complex Modulus	70

Thin Film oven test optimal values are taken from IS 15462 2004. These values are used as input in the Optimization. Normally the range values are utilized as input in Optimization and the output emerged as Optimal Values.

3.2 Preparation of sample

Polymer Modified Bitumen (PMB) sample is made with reference to the parameters mentioned in the Indian Standard Code Book 15462 - 2004. Merely the Polymer Modified Bitumen of elastomeric Type A in which the sample made should have a recovery in elastic as 74.5% at 14°C. With Consideration of Viscosity Grade, the bitumen designed should have assumed as Traditional Refining method. So that the Standard Value in Optimization is maintained within the required limits. The Aggregate used along with Bitumen in Polyethylene Terephthalate Pavement should be within their parameters. Table 3 provides the data about the Mechanical Parameters of Coarse Aggregate.

Fine aggregates are natural or manufactured finer material or their merged material passing IS sieve number 8 and should not pass through sieve number 200. The amount of natural sand used in the surface course of pavement is limited to 10%. They are majorly allowed in Base Courses. The fine matrix used should be free of organic matter and other lumps. The abrasion value of fine aggregates should not exceed 30% with accordance to IS 383 1983. The filler material employed in this study is the dust of rocks. And its plastic index is less than 4% as per IRC 105 2019. The amount of Bitumen to be used in pavement and the grade of aggregate utilized in this study are denoted in Table 4.

Table 3 Mechanical Parameters of Coarse Aggregate

Reference	Parameter	Method	Range
IS 2386 Part 1	Fineness	Grain Size Distribution	0.35% passing 0.0075mm sieve
IS 2386 Part 1	Shape Parameter	Merged Flakiness and Elongation Index	30%
IS 2386 Part 3	Water Withholding Capacity	Water Retention Capacity	1%
IS 2386 Part 4	Toughness	Abrasion Value	30%
IS 2386 Part 4	Toughness	Impact Value	24%
IS 2386 Part 5	Endurance	Sodium Sulphate	12%
IS 2386 Part 5	Endurance	Magnesium Sulphate	18%

Table 4 Dosage of PMB and Grading of Aggregates

Reference	Parameter	Binder Course	Surface Layer
IRC 105 2019	Nominal Maximum Size of Aggregates	19mm	13.20mm
	Layer Thickness	50 to 75mm	40-50mm
	Minimum Bitumen Dosage	5.41%	5.62%

Once the Dosage of bitumen and Aggregate grades are determined, the homogenous mixing procedure takes place and it is made to the specified thickness with optimum binder dosage. Afterwards, this mixture is compacted and checked for flow for their standard limits using suggested optimization. The Specification for making the required mix is mentioned in Table 5.

Table 5 Specification of design Mixes

Reference	Parameter	Range
IRC 105 2019	Level of Compaction	75 blows
	Flow value	2mm to 4mm
	Total Air Voids	3% to 5%
	Voids Filled with Bitumen	65% to 75%

In the end, the mix made with Polymer Modified Bitumen is within the standard limit. The acceptable voids in mineral aggregate were 13% in the binding course and 14% in the surface course as per IS 105 2019. Afterwards, the sample is subjected for theexperimental evaluation in the proposed approach.

3.3 Optimized PMB parameters: HbCL

The Hyena based Curriculum Learning was implemented while merging Curriculum Learning Technique along with Hyena Optimization. This dual technique merged model develops a composite prediction approach tool as Hyena based Curriculum Learning (HbCL). For this optimum reason, it is defined as an innovative technique for determining the Fatigue Cracking Prediction Accuracy. Generally, the Hyena based Curriculum Learning was considered for its supreme predatory behaviour with its prey. At this point, the ideal purpose of this optimization is utilized for concluding the ideal physical parameters of the basic source material. The ideal bitumen physical parameters are analysed in several recurrences by the evaluation function which is initially triggered by the optimizer. Therefore this behaviour along with the prediction behaviour of this optimization is employed for the estimation of fatigue cracking patterns under the loading techniques. The optimal fatigue cracking level was fixed in the memory function of Hyena optimal model based on the fixed optimal fatigue range, the bitumen dosage was regulated. This process has been iterated continuously till the optimal fatigue crack was recorded. In addition, the curriculum function of this proposed model is utilized to train the data input parameters data for finding the optimal level. In the hyena optimal algorithm, finding the best optimal hunting is determined as the best solution. In this present work, this optimal solution finding process is utilized to determine the optimum fatigue crack level.

The inlet governing was illustrated in Eqn. (1).

$$E(J_o) = \{W_b, A_s, VFB\} \tag{1}$$

Where J_o represents the data with consideration of the ideal technique, $E(J_o)$ portrays the governing technique, W_b denotes the minimum amount of polymer modified bitumen, A_s gives the maximum size of aggregates, VFB is the amount of voids to be filled by bitumen. The evaluation function from the optimizer initially triggered will analyze the optimum values in the mix design of bitumen. Moreover, adequacy in the physical parameter outcome is developed through the evaluation in the outcomes in accordance with several errors taken into consideration. The Minimum bitumen content (W_b) as 5.41% for the binder course, 5.62% for surface course, and how this amount of bitumen binds with the maximum aggregate size (A_s) 13.2mm for surface course and 19mm for binder course and how much in total these bitumen binds the voids (VFB) as 65% to 75%. This above provided data is the limiting factor in determining the strength parameter of bitumen. Thus these binding parameters are standardised by the optimal function in the proposed HbCL and the fatigue cracking prediction is evaluated. The optimal function enhances the compression toughness, tensile toughness, and tensile stiffness of the mix and the new mix percentages will be obtained. These properties reduce the Fatigue Cracking that minimizes the depth of rutting. The idealised Physical parameters are set in stationary by utilizing Eqn. (2).

$$Cm_p = \begin{cases} W_b = 5.62\% \text{ , } 5.41\% \\ As = 13.2mm, 19mm \\ VFB = 65\% \text{ } to \text{ } 75\% \end{cases} \tag{2}$$

Considering the above equation, the selected strength determining properties of bitumen is denoted asCm_p. The minimum bitumen content in the bitumen is denoted asW_b, the maximum size of nominal aggregate for the mix is represented as As, The voids to be filled by bitumen is expressed asVFB. Many repetitions are performed by the evaluation function for determining the minimum bitumen dosage, Size of aggregate and the voids of aggregate to be filled by bitumen. Afterwards, the fatigue cracking is determined by implementing dynamic as well as static loads with respect to dissimilar temperatures. The bulk relative density obtained from the evaluation function of HbCL is expressed in Eqn. (3).

$$H_m = \frac{V_m}{V_m - V_w} \tag{3}$$

While considering Equation 3, it gives the bulk relative density of the bitumen as H_m, V_m denotes the normal mix weight, and V_w represents the mix weight in water. The detection function in the HbCL is activated and it predicts the voids in total bitumen sample by the Eqn. (4),

$$W_v = \frac{(H_t - H_m)\,100}{H_t} \tag{4}$$

Where H_t is the conceptual relative density of the mix provided by the fitness function of HbCL, usually as 2.35, the resisting factor in the HbCL fixes this value based on the values obtained by the detection function in H_m, the Mineral Aggregate Voids (MAV) plays a secondary role in strength properties of bitumen hence the evaluation function estimates it as expressed in Eqn. (5),

$$MAV = W_v + W_b \tag{5}$$

Where W_b indicates the minimum bitumen content and W_v represents the air voids in the mix. Hence the evaluation function provides the W_b and the detection function provides the MAV Fixing the minimum bitumen content the proposed HbCL provides us the voids filled by bitumen and is given in Eqn. (6),

$$VFB = \frac{W_b \times 100}{MAV} \tag{6}$$

Eqn. (6) determines the voids to be filled by bitumen. Here, W_b and MAV are taken from Eqn. (5) in order to predict the effective toughness outcomes of the bitumen. When the load is applied to the specimen for experimentation the detection function is again initiated in predicting the effective outcomes. The ideal value is fixed by the fitness function of the hyena hunting behavior, based on that fatigue crack was optimized.

$$F_p = \frac{Estimated\,Value}{Ideal\,Value} \tag{7}$$

Eqn. (7) provides us the optimal Fatigue Cracking Prediction which is denoted as F_p, it is made using Eqn. (6) the loads are implemented under dissimilar temperature conditions and the Fatigue crack prediction analysis is performed. It is defined as the ratio of estimated value and the ideal value. The ideal value in cracking of bituminous pavement lies among 5% to 10% of the pavement surface as per IRC 82 2015. Thus the Fatigue Crack Prediction Accuracy is determined.

Algorithm 1: HbCL

```
Start
{       initialization()
        {
                int W_b, A_s, VFB;
                //Initialize the evaluation function
        }
        ideal strength determining parameters()
        {
                fix → Ideal Input
                W_b = 5.41% , 5.62% ;
                A_s = 13.2mm , 19mm ;
                VFB = 65% to 75%;
                //initialize the detection function
        }
        Implementing Bitumen Dosage()
        {
                int VFB;
                //initialize the minimum bitumen dosage
                VFB = (W_b × 100) / MAV
                // Applying Bitumen for Aggregate Voids
```

```
        }
        Fatigue Crack Prediction Accuracy()
        {
                int F_p,;
                //initialize the fitness function
                Fix → Ideal value
                // fixing the Ideal Fatigue value
```

$$F_p = \frac{Estimated\ value}{Ideal\ value}$$

```
        }
}
End
```

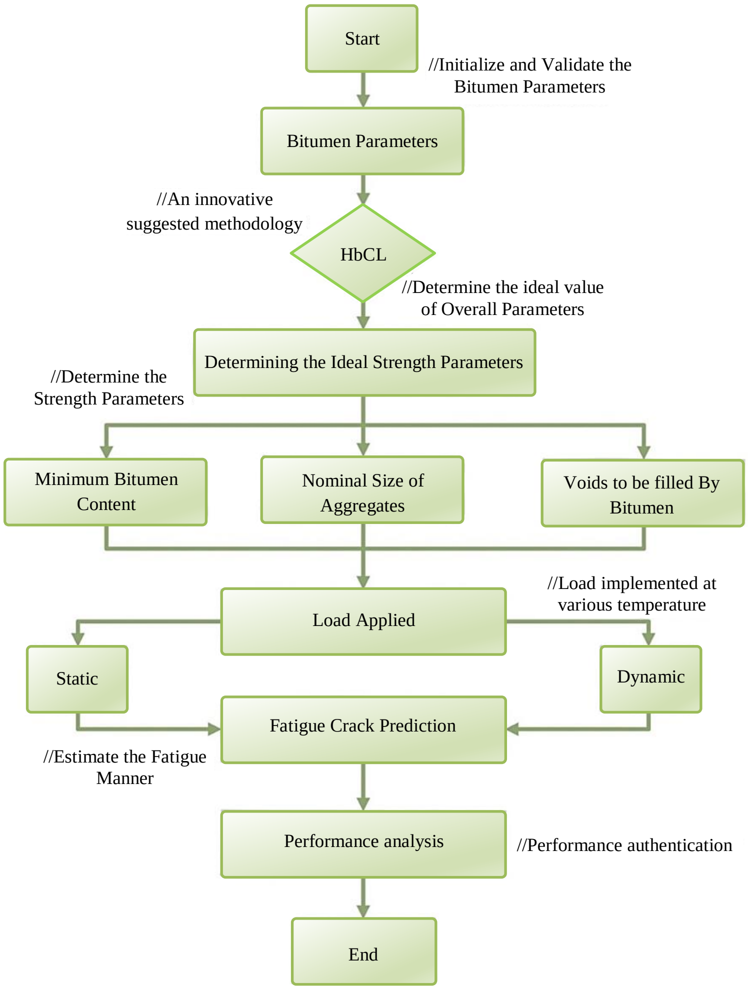

Figure 2 Flow Chart of Suggested HbCL

The Suggested Approach HbCL process is explained in Figure 2. In which the PMB 40 physical parameters limits are determined. From the physical parameter limits the strength parameters are determined and the mix design is modelled and load is applied in static and dynamic conditions with dissimilar temperatures and the Fatigue Crack Prediction is carried out. And the performance of our proposed model is correlated with the recent studies.

4. Results and discussion

The intended approach functions in Windows 10 Operating System. The tests will be performed in MATLAB R2021a Software. MATLAB is matrix based software utilizing strings as well as arrays to estimate the outcome in total or in part. It provides directional point programming as well as multiple layers in programming that include operative directives and functional directive. The Hyena based Curriculum Learning optimization provides the ideal strength parameters effectively, which includes minimum bitumen content and the voids which need to be filled by this minimum bitumen content. Polyethylene Terephthalate (PET) was included in the mix for enhancing the toughness properties of the bitumen. The amount of Polyethylene Terephthalate varies from 2% to 10% in the bitumen content for making the polymer modified bitumen [29]. Afterwards the parameters of the PMB 40 are evaluated for dissimilar physical parameters like tensile stiffness, tensile toughness, Marshall Coefficient, and Compressive Toughness. Then the operational element of the Hyena based Curriculum Learning is triggered to determine the ideal strength parameters. Once the strength parameters are determined the Fatigue Crack Prediction Accuracy is evaluated considering dissimilar dynamic as well as static loading terms.

4.1 Case study

For determining the function behaviour of Suggested approach, test substantiation must be done. The outcomes are illustrated orderly. Experiments such as incursion, Fire point and viscosity ball tests are sustained and validated within their standard limits. Then the axial load from the single direction is implemented on static as well as dynamic terms in dissimilar temperatures. The mixes are prepared and are correlated and sustained for the functional enhancement rate. The Suggested Approach secured an excellent outcome with the correlated techniques.

4.1.1 Tensile strength

The tensile toughness in the Polyethylene Terephthalate Pavement is evaluated under stagnant as well as dynamical loading environments. The apex load in which the model can withhold without yielding is termed as the outcome load to determine the tensile strength of the sample with respect to its loading condition. Usually, the test is carried out in a cylindrical sample. The Stagnant loading condition is where the load is implemented in a low rate with a long duration of time. Under this loading condition, the PET pavement has an additional duration to regain its original shape in accordance to the dynamical loading.

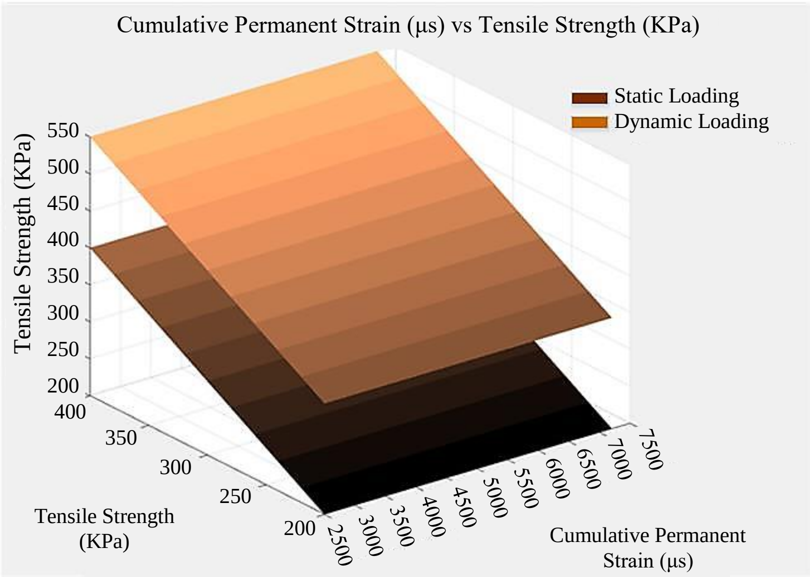

Figure 3 Tensile Strength of PMB 40

In opposition, the dynamical load is implemented in a high rate and with a short duration, that provides the PET pavement to regain its original shape within short duration. In conclusion, the tensile strength under the stagnant load condition is better than the dynamical loading condition. This specifies that the PET pavement will endure the stagnant load to a viable limit. However, could not endure the dynamic load to the point same as the stagnant load. The correlation among the stagnant and dynamical loading conditions of the PET pavement is illustrated in Figure 3.

The tensile strength of the sample specimen in static load varies from 200 KPa to 400 KPa which is low when correlating with the dynamical loading condition it varies from 375 KPa to 550 KPa for 2500μs Cumulative Permanent strain and slightly increases till reaching 7250μs. Where, μs is the micro-strain. The tensile strength of the proposed model is represented in Table 6.

Table 6 Tensile Strength of Proposed Model

	Tensile Strength (KPa)	
Cumulative Permanent Strain (μs)	**Static Loading**	**Dynamic Loading**
2500	370	330
3100	392	346
3800	414	362
4100	436	378
4900	458	394
6000	480	410

4.1.2 Compressive strength

The Compression Toughness in the PET pavement is the opposition behaviour to compressive load. It is employed to determine the load in which the pavement turns to a plastic state and changes its shape everlastingly. This state happens in the lower yield point in the stress strain behaviour of this PET pavement. The compression toughness is determined as the load, at which the sample yields by the cross section area of the sample that should be orthogonal to the load. The compression strength of the specimen is carried out only for static load condition. Moreover, the test is conducted for 60°C due to reason that bitumen reaches its softening point at 60°C.

The compression toughness of the specimen is tested with different temperature conditions and illustrated in Figure 4. When the compression strength of the specimen is tested at 5°C the noted compression strength was 40 N/mm^2. And at 60°C the noted compression strength was 20 N/mm^2.

From Table 7 it can be observed that the compression strength of the specimen decreases with an increase in temperature. Hence the temperature in bitumen is indirectly proportional to the compression toughness of bitumen.

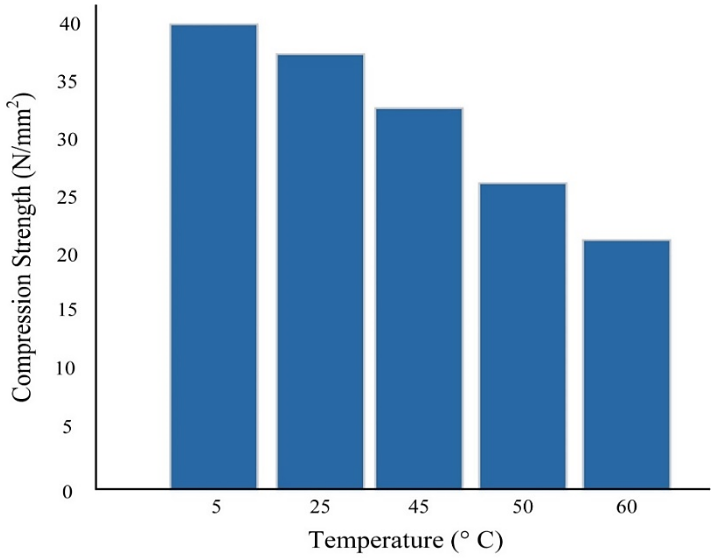

Figure 4 Compression Strength of PMB 40

Table 7 Compression Strength of Proposed Model

Temperature (°C)	Compression Strength (N/mm^2)
5	40
25	38
45	32
50	25
60	20

4.1.3 Rutting depth

The total vertical distance in a straight line from the wearing surface of pavement to the maximum deformation point is termed as rutting depth. It is caused in pavements by both stagnation of heavy load in long duration or dynamical load applied in short duration for long time. The Stagnation Loading condition is pretentious by environmental elements like temperature and Pavement shape elements like material quality and depth of pavement.

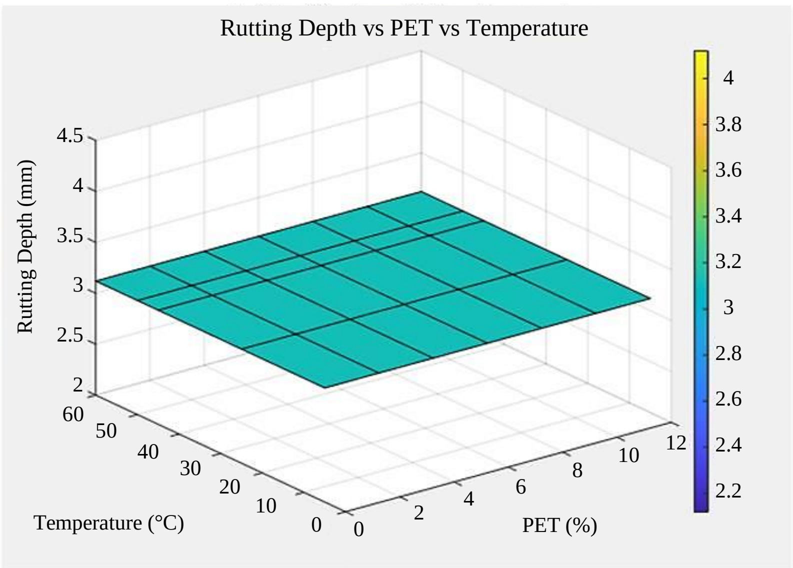

Figure 5 Rutting Depth of PMB 40

The rutting depth due to dynamic loading is determined as same as the stagnation loading condition. But, it differs in the vulnerability condition. The Rutting depth due to dynamical loading is a more severe condition than the stagnation loading. Hence the dynamical loading condition of the PMD 40 specimen ranges between 1.7728 mm and 1.6870 mm. Hence the deformation in the layers of pavement is minimal as illustrated in Figure 5.

4.1.4 Marshall coefficient

The PET pavement opposes the plastic deformation behaviour according to the loading condition. This opposition to plastic deformation behaviour is determined by Marshall Coefficient. The Tensile Toughness of the sample by its flow value provides the Marshall coefficient of that pavement. The Tensile toughness provides the material resistance to deformation and the flow value gives the ductility behaviour of the material. The Marshall Coefficient is directly proportional to the plastic deformation of the material, which leads to a higher Marshall Coefficient Value giving better resistance to plastic deformation. The Marshall coefficient is determined by dividing the stability of the specimen by the flow value of the specimen.

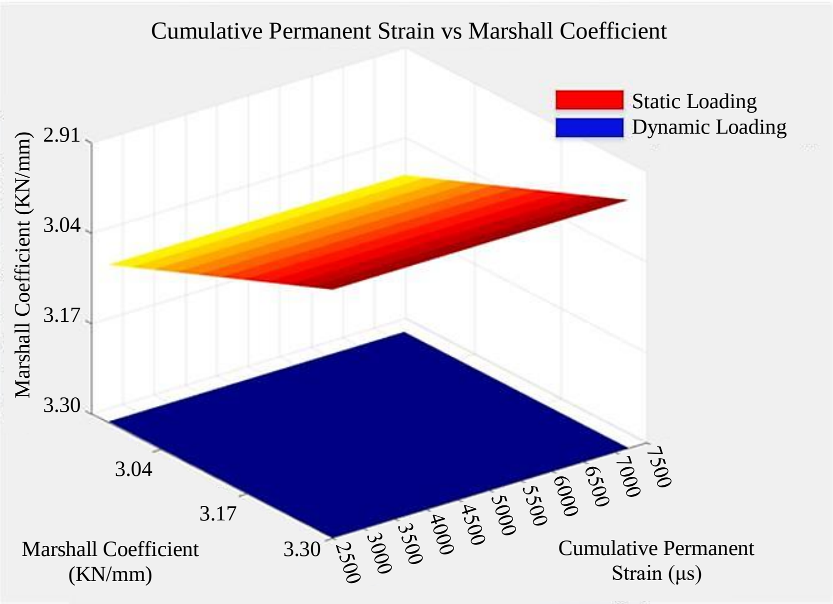

Figure 6 Marshall Coefficient of PMB 40

The Marshall Coefficient of the specimen under static load condition is lower than the dynamic loading condition. The static loading condition lies above the value of 3.5 KN/mm hence the graphical representation shows small deformations. The specimen under dynamic loading conditions the values are from 2.7 KN/mm to 1.78 KN/mm for the Cumulative permanent strain 2500μs to 7200μs. The output of Marshall Coefficient is represented in Figure 6.

Table 8 Marshall Coefficient of specimen under static and dynamic loading condition

	Marshall Coefficient (KN/mm)	
Cumulative Permanent Strain (μs)	**Static Loading**	**Dynamic Loading**
2500	3.5	1.78
3100	3.2	1.96
3800	2.9	2.15
4100	2.6	2.33
4900	2.3	2.52
6000	2	2.7

From Table 8 it can be identified that the specimen under dynamic loading has less Marshall Coefficient value and the specimen under static loading has a high Marshall Value when correlating. Hence due to static loading during traffic conditions, the PET pavement has a higher stiffness resistance than the dynamic fast moving vehicles.

4.1.5 Fatigue crack depth

The Fatigue Crack Prediction Accuracy was a significant technique across material technology. The deep learning approaches turned out to be implemented in impulsive rupture detection within substantial material elements. Several smart retrieving models are employed to predict the fatigue crack in accordance with loading conditions as well as dissimilar temperatures. Some sample models have exhibited utmost accuracy during evaluating crack dispersion. This accuracy is utilized in evaluating the width of crack in the accuracy of the validated outcomes. This innovative mechanism helps in the experimentation of designing, implementing, functioning, and maintenance of the samples, enhancing their toughness and durability behaviour.

Figure 7 represents the relation among fatigue crack depth and Marshall Coefficients along with varying PET percentages under the static loading condition. Initially, before loading the pavement is denoted as purple colour. When the loading starts the Marshall coefficient of the pavement decreases and in which the fatigue crack depth under increasing PET % it increases. With the increase in PET %, the Marshall Coefficient decreases which indicates resistance to stiffness has been reduced. Hence the fatigue crack depth formation is resisted. At 8% PET, the minimum Marshall coefficient attained is 2.25 KN/mm with fatigue crack depth of 1.7087mm. The highest Marshall Coefficient value obtained was 1.9 KN/mm with a fatigue crack of 1.6925mm.

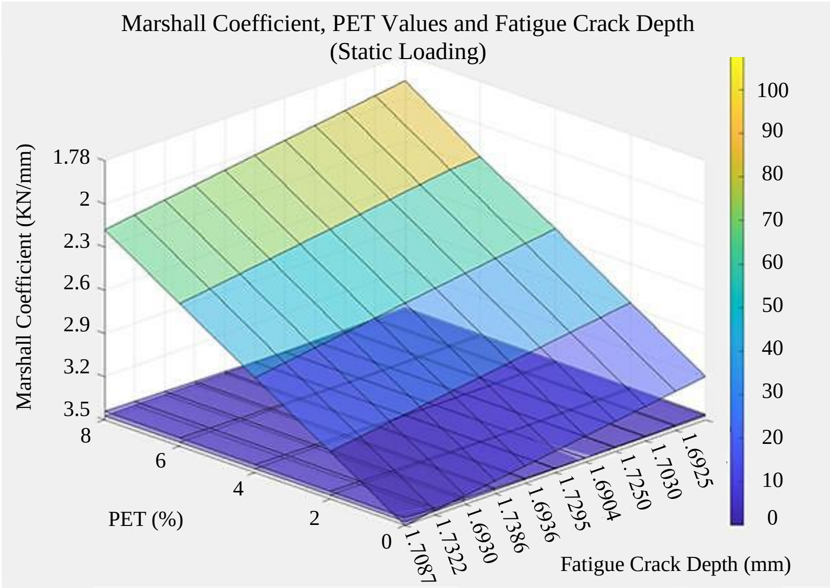

Figure 7 Fatigue Crack Prediction of PMB 40 in Static Loading

The behavior pattern of the PMB 40 with different PET % and Marshall Coefficient values and their fatigue crack depth under dynamic loading are expressed in Figure 8. Since under dynamic loading, the behaviour pattern of the pavement changes hence the Marshall Coefficient, PET%, and Fatigue Crack Depth are expressed in three different ways. The PET % increases with the mix shown as pale red colour; it also increases the Marshall Coefficient.

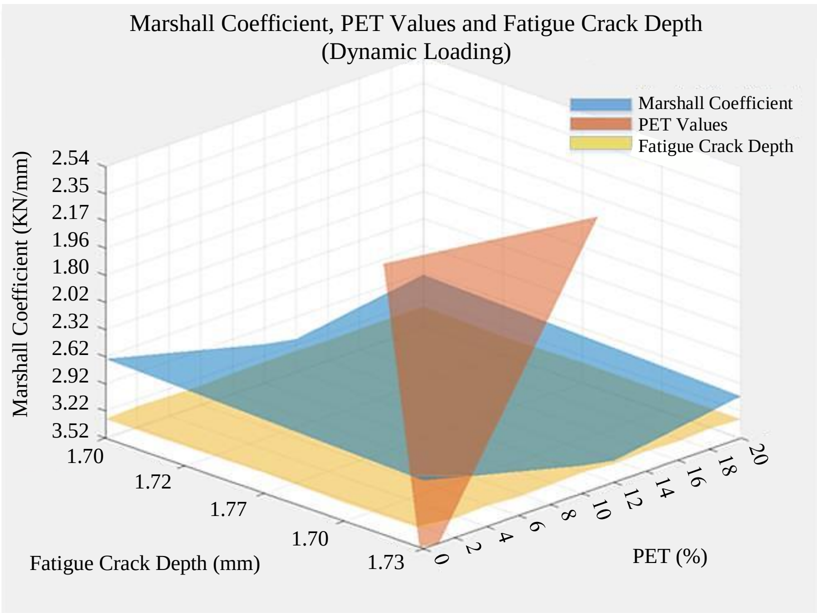

Figure 8 Fatigue Crack Prediction of PMB 40 in Dynamic Loading

Table 9 Fatigue Crack Prediction Accuracy

Fatigue Crack Prediction Accuracy (%)	
Static Loading	**Dynamic Loading**
96.1	95.3
96.2	95.5
96.5	95.7
96.7	95.9
96.9	96

The Marshall coefficient is denoted in blue colour. The fatigue crack depth lies between 1.7691mm and 1.6787mm hence it forms in flat yellow layer. The PET% limits the fatigue depth as 1.77mm as the maximum and the Marshall Coefficient as 3.5KN/mm. During the analysis of fatigue crack, the prediction accuracy is also evaluated and expressed in Table 9. The highest crack prediction accuracy obtained was 96% in dynamic loading and 96.9% in static loading.

4.2 Comparison

The Compression toughness, Tensile strength, Marshall Coefficient and Fatigue Crack Depth outcomes depends on the Accuracy value obtained by the fatigue crack prediction accuracy. The tensile strength of the proposed model is correlated with bitumen made with antimony trioxide and tested on multiple stress creep recovery (MSCR) [30], Plastic Asphalt Mixture which is examined on Adaboost Regressor (ABR) [31], cold recycled bitumen mix tested on falling weight deflectometer (FWD) [31]. The compression strength of the PMB is analyzed along with the mixes of recent investigations in which all correlation tests are carried out in 0°C. The recent investigations include De-asphalted hydrocarbon bitumen Mix (DA-BM) [32], Reclaimed Asphalt Pavement (RE-AP) [33], and Nano Silica Asphalt Mixture (NS-AM) [34]. The Marshall coefficient of the proposed model is correlated among the Silicon Rubber Modified Bitumen (SRMB) [35], Modified asphalt analyzed in Gauss Progression Regression (GPR) [36], and Crumble Rubber Bitumen (CRB) [37]. The Fatigue Crack Prediction Accuracy value is validated in comparing with recent models and latest techniques. The recent models include CrackNet II [38], VGG 16 FCN [39], Deep Conventional Neural Network (DCNN) [39], MobileNet [40] are correlated with our proposed model. The implementation of the suggested model is carried out in MATLAB R2021a Software with optimal mix ratio as well as cross section and the accuracy prediction was conducted. Finally the comparison is carried out to provide certainty. Here, all the existing methods were tested in the same proposed platform with similar bitumen ratio. Only thing to attain the finest outcome for the proposed model is due to the hybrid optimization model. The optimal function of the hyena was worked continuously till attaining the finest expected outcome. All the parameter ranges are also fixed in the hyena optimal algorithm (best hyena selecting) function, which helps to earn the finest outcome. The key advantages of the proposed model are tuning behaviour and iteration process for gaining the finest outcome. The limitations of the past traditional methods are finding the best and optimal outcome due to the lack of optimal features.

4.2.1 Tensile strength

To predict the initiation of fatigue crack and fatigue strength, the tensile strength was measured. Moreover, the crack growth is highly depends on the tensile stress. Based on the tensile strength, the fatigue crack propagation was determined. For this reason, the tensile strength was valued in this study.

The tensile strength of the proposed model is analyzed in Matlab environment in both static and dynamic conditions. The highest tensile strength obtained was 480 KPa in static loading condition and this optimal value is utilized in this correlation. The tensile strength of the FWD [31] is 380 KPa. The tensile strength of the ABR model [31] is 150 KPa.

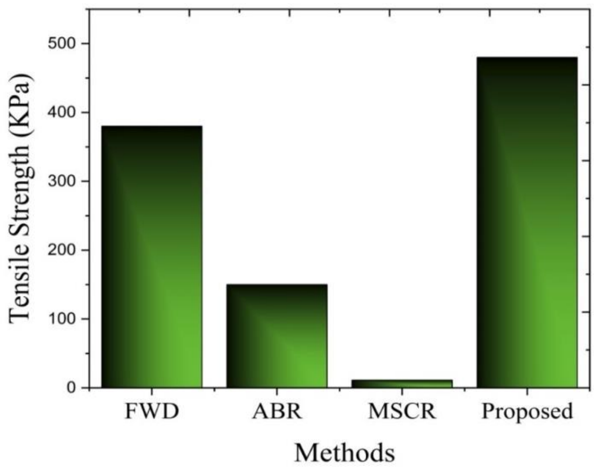

Figure 9 Correlation Assessment of Tensile Toughness of PMB

The PMB made with antimony trioxide is analyzed in multiple stress creep theory and the obtained value is 11.23 KPa which is the least gained value in all the correlation. The proposed model has a tensile strength of 480KPa in static loading conditions. It is obtained at the mean PET% of 6 with test conducted at temperature of 25°C. The Correlation among the models is illustrated in Figure 9.

Table 10 Correlation of Tensile strength

Methods	Tensile Strength (KPa)
FWD	380
ABR	150
MSCR	11.23
Proposed Model	480

From Table 10 it can be expressed that the high tensile strength of the proposed model is achieved by adding PET. Materials like Antimony trioxide in multiple stress creep recovery methods does not bind with bitumen properly hence resulting in the least tensile strength in correlation. Therefore it can be concluded that the PET addition to Bitumen binds well with it and enhances the tensile properties of bitumen.

4.2.2 Compression strength

In addition, there is a major reason for measuring the compressive strength for this study. Based on the compressive loading, crack initiation and growth was happened that can lead unexpected component damage. A lower stress ratio generates a net compressive strain in every use, leading to fewer components degradation and an extended fatigue life.

The Compression strength of the proposed model is analyzed for temperature up to the softening point of the bitumen. With rising in temperatures the compression strength of the mix decreases. Hence the compression strength at 25°C is taken for correlation. The compression strength of the recent mixes in the investigated paper is taken for reference. The compression strength of the NS-AM mix is 9MPa [32], DA-BM mix is 11MPa [33], and the RE-AP mix is 9.5MPa [34].

The compression strength of the proposed model is 38 MPa. This high strength is obtained due to the addition of Polyethylene Terethaphalate at an optimum level in the bitumen mix. The test is conducted on the specimen having PET% of 6. The correlation among the different mixes of bitumen is shown in Figure 10.

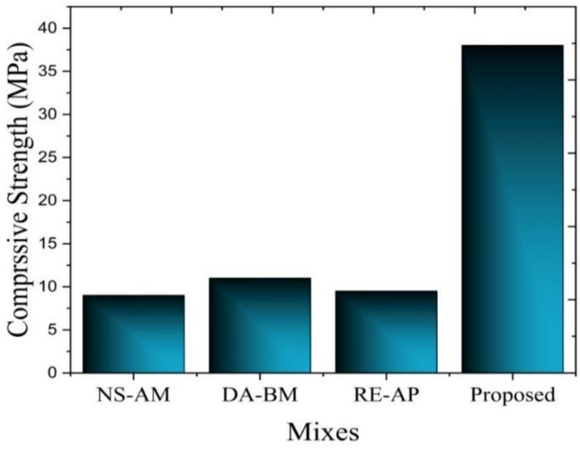

Figure 10 Correlation Assessment of Compression Toughness in PMB

Table 11 Correlation of Compression Strength

Methods	Compression Strength (MPa)
NS-AM	9
DA-BM	11
RE-AP	9.5
Proposed Model	38

From Table 11, it is noted that adding PET to the optimum percentage can improve the compression strength of the modified bitumen mix. The Compression strength obtained is of supreme grade when compared with the recent developed mixes. Hence adding PET % improves the compression as well as tensile toughness in bitumen.

4.2.3 Marshall coefficient

The Marshall coefficient is the ratio of Marshall Stability value to flow. The Marshall stability of the mix is tested under static and dynamic loading conditions. In which the specimen has an optimum PET value of 6% at temperature of 25°C.

The Marshall coefficient obtained in the GPR technique is 3.1KN/mm. The SRMB has Marshall Coefficient of 3.4 KN/mm and the CRM mix has a Marshall coefficient of 3.3 KN/mm. The Proposed Model has a high Marshall Coefficient value of 3.5 KN/mm at 6000µs Cumulative Permanent Strain. The comparative assessment is illustrated in Figure 11.

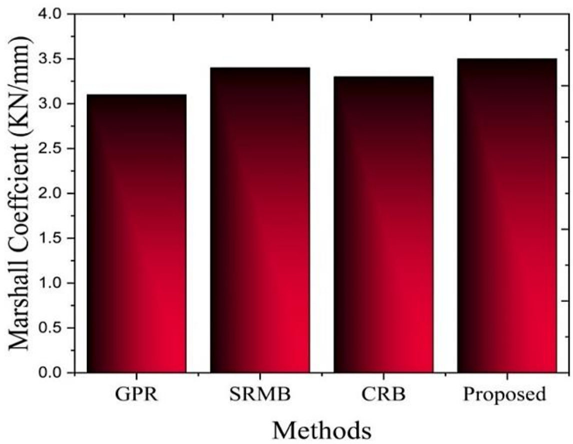

Figure 11 Correlation Assessment of Marshall Coefficient in PMB

In Table 12, the Marshall Coefficient of the proposed mix is slightly higher than the other mixes due to the reason that the added PET to bitumen enhances the load carrying capacity of the polymer modified bitumen pavement in both static and dynamic conditions.

Table 12 Correlation of Marshall Coefficient

Methods	Marshall Coefficient (KN/mm)
GPR	3.1
SRMB	3.4
CRB	3.3
Proposed Model	3.5

4.2.4 Fatigue crack prediction accuracy

The essential requirement in modelling construction materials and their experimental implementation is how accurately the values are obtained. In the suggested approach, the fatigue crack prediction accuracy is carried out to determine the precision of the study. The deep learning functions such as the fitness function and evaluation function of the HbCL are implemented in sensing the fatigue crack. Several stimulated models are considered with static and dynamical loading conditions.

The static loading term denotes a higher load than the dynamic condition applied for a long duration and the dynamic loading provides a lower repeated load for specified duration. Prototypes showed high precision during the estimation of Fatigue Crack. The fatigue crack obtained thus benefits in mix design, implementation, and maintenance of pavement during its lifespan. The accuracy of the CrackNet II Model is 92.6% [38], VGG 16 FCN is 74.1% [38], DCNN is 96% [39], MobileNet is 95.3 [40] and the proposed model has an average accuracy of 96.1%. The Statics are revealed in Figure 12.

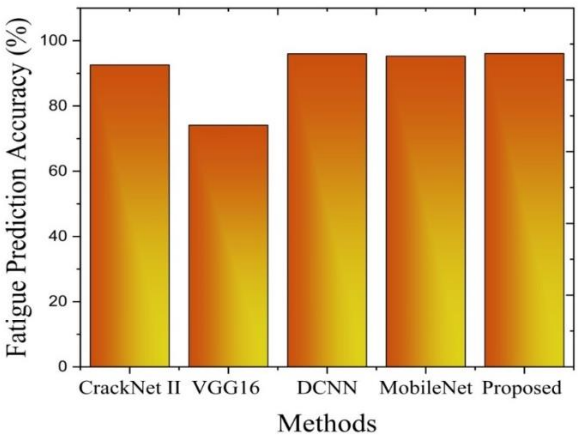

Figure 12 Comparison Assessment of Fatigue Prediction Accuracy

Table 13 Correlation of Crack Prediction Accuracy

Methods	Crack Prediction Accuracy (%)
CrackNet II	92.6
VGG 16 FCN	74.1
DCNN	96
MobileNet	95.3
Proposed Model	96.1

In correlation with alternate approaches the prime focus of selecting HbCL is due to the reason expressed in Table 13. Several developing approaches were implemented with many stages for validating the enhancing behaviour in the estimation of fatigue crack prediction accuracy.

4.3 Separation degree

The separation tendency of the PET in the bitumen is analysed in terms of Plastic Granule of Hybrid Type (PGHT), Plastic Granule of Non-Treated (PGNT), and Plastic Granule of Oil Treated (PGOT). The test was carried out in cigar tube sample. Raman intensity and Raman shift of the bitumen along with the three different granules are determined for different Raman shift values as shown in Figure 13.

The PGOT has Raman intensity of low value in the bitumen in correlation with the PGHT and PGNT. This indicates within low intensity this granule can be removed from the bitumen. The PGNT Raman intensity value is slightly higher than the PGOT indicating that it possesses higher resistance than PGOT. The PGHT possesses higher resistance to separation than the other two plastic granules in bitumen. From the Raman shift value from 1700 to 1760 cm^{-1}, the PGHT has a higher intensity value and the peak intensity is also higher than the PGNT and PGOT as shown in Figure 14. All the bitumen has a peak value near 1730 cm^{-1} Raman shift indicating that the plastic granules separation point. The PGHT has a higher resistance to separation than PGOT and PGNT. The separation index of the PGNT, PGOT and PGHT is represented in Figure 15.

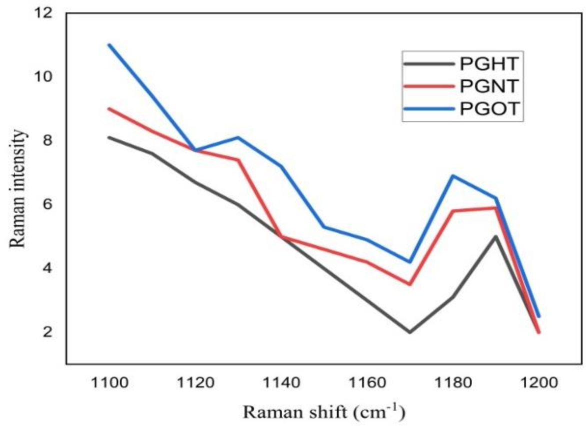

Figure 13 Raman intensity in the PGHT, PGNT, PGOT granules for the Raman shift value from 1100 to 1200 cm^{-1}.

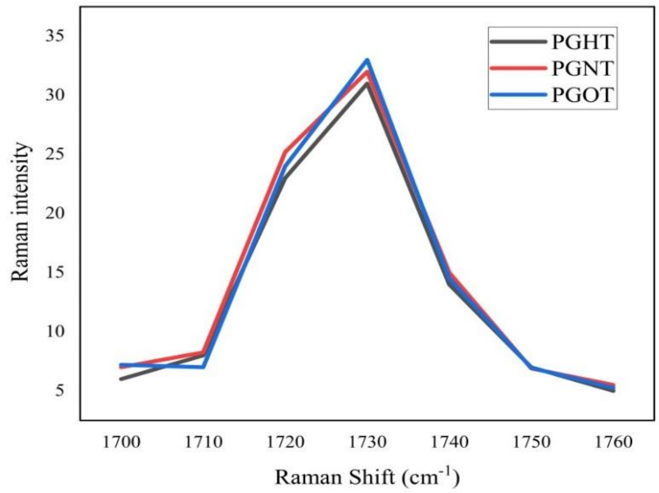

Figure 14 Raman intensity in the PGHT, PGNT, PGOT granules for the Raman shift value from 1700 to 1760 cm^{-1}

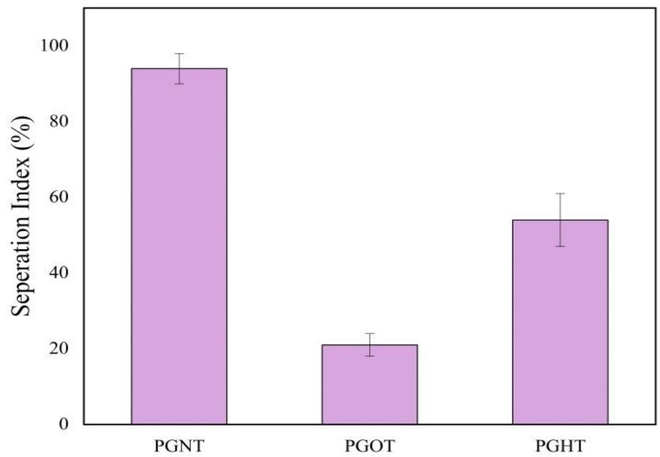

Figure 15 Overall seperatin index of PGNT, PGOT and PGHT

The PGHT has high raman intensity value, in the meantime, the overall seperation index of the PGNT sample is 94% higher than PGOT and PGHT. The PGOT has a separation index of 21% and the PGNT has a separation index of 54%. The overall separation index of the plastic granules in bitumen is represented in Table 14.

Table 14 Overall seperation index of plastic granules in bitumen

Plastic Granule	Seperation Index (%)
PGNT	94
PGOT	21
PGHT	54

4.4 Potential for carbon sequestration

Given the current pollution levels [41], using recycled plastic trash in asphalt mixtures may facilitate the establishment of circular economies and diminish carbon footprints. The progress of the green economy in multiple fields of civil engineering, especially in the development of roads, has attracted considerable attention. The incorporation of recycled asphalt pavement (RAP) for fresh developments has become a central issue, due to its economic advantages and its role in diminishing carbon emissions. Furthermore, the integration of various additives, including recycled and rejuvenator Polymers includes oupled with the reduction of environmental pollutants in RAP, highlights the importance of this initiative. This comprehensive strategy not only reduces environmental pollutants and carbon emissions but also improves the performance of asphalt mixtures using RAP. Given the current pollution levels, using recycled plastic trash into asphalt mixtures may facilitate the establishment of a circular economy and diminish carbon footprints.

Currently, the progress of the ecological economy in several fields of civil engineering, especially in the development of roads, has received considerable focus. The incorporation of recycled RAP in building projects has become a central focus, due to potential cost-saving advantages and its role in mitigating carbon emissions. Furthermore, the integration of various additives, including rejuvenators and recycled polymers, coupled with the reduction of outside pollutants in RAP, highlights the importance of this initiative. This comprehensive strategy not only reduces greenhouse gases and carbon dioxide emissions but also improves the efficiency of asphalt mixtures using RAP. So, in the upcoming work considering the carbon components in the PET pavement will increase efficiency score.

5. Conclusion

The Presented Work points to explain the innovative Hyena based Curriculum Learning (HbCL) to estimate the Fatigue Crack Prediction accuracy in the Polyethylene Terephthalate (PET) Pavement with considerable layers, implementing dynamic as well as static forces with respect to altered temperatures. The HbCL executes its deep learning technique for determining the Polymer Modified Bitumen Parameters and its behavior under stagnant and dynamical load conditions. Furthermore, to enhance the strength parameters of the pavement, Polyethylene Terephthalate is included in the mix. Then the strength parameter of the PET bituminous pavement is standardized by the HbCL. The evaluation function in the Optimization is activated for enhancing the bitumen properties and in the prediction of fatigue damage. The maximum tensile strength of the proposed model at static and dynamic loading is 480 KPa and 410 KPa which is 26.5% high when correlated with other models. The Compression Strength of the Proposed PMB 40 decreases from 40 MPa to 20 MPa in temperature from 0°C to Softening Point. The rutting depth values obtained are between 1.7728 mm and 1.6870 mm. The Maximum Marshall Coefficient value obtained was 3.5 KN/mm in static loading which is 2.95% higher than other models and secured 2.7 KN/mm in dynamic loading. The fatigue crack depth of the pavement model is limited to 1.77mm in dynamic loading conditions. In static loading conditions, the fatigue crack depth lies among 1.7087mm and 1.6925mm. The average fatigue crack prediction accuracy obtained by the proposed model was 96.1% including static and dynamic loading that is 0.104% higher accuracy than other models. Afterwards, the outcomes are validated by correlating the proposed model outcome with recent investigation papers. In consideration with other approaches, the proposed technique has better Fatigue Prediction in comparison in both static and dynamical loading conditions. With the better strength properties of bitumen such as tensile strength, compression toughness and Marshall Coefficient, the proposed model has enhanced durable parameters within the range of PET. Combining the model with live fatigue monitoring predictor in the future provides better maintenance and improved pavement lifespan.

6. References

[1] Khedaywi T, Haddad M, Bataineh H. Effect of waste plastic polyethylene terephthalate on properties of asphalt cement. Innov Infrastruct Solut. 2023;8:232.

[2] Al-Hadithi AI, Almawla SA, Mohammed MK. Fresh, mechanical and impact properties of self-compacting lightweight concrete containing waste PET fibers. Innov Infrastruct Solut. 2023;8:268.

[3] Dereje B, Rath B, Gatkuoth K, Getachew K, Praveenkumar TR, Garoma S, et al. Thermal stress–strain analysis of CFRP-laminated concrete beam with partial replacement of fine aggregate by PET granules. Innov Infrastruct Solut. 2023;8:249.

[4] Matarneh S, Elghaish F, Rahimian FP, Abdellatef E, Abrishami S. Evaluation and optimisation of pre-trained CNN models for asphalt pavement crack detection and classification. Autom Constr. 2024;160:105297.

[5] Xiong Y, Wang H. Analysis of the grouting fullness and road performance of hot-recycled semi-flexible pavement materials. Case Stud Constr Mater. 2024;20:e02755.

[6] Maljaars J, Leander J, Nussbaumer A, Sørensen JD, Straub D. Models and methods for probabilistic safety assessment of steel structures subject to fatigue. Struct Saf. 2024:102446.

[7] Gu X, Xu X, Zhang Q, Sun L, Zhou Z. Study on the correlation between spatial variability of asphalt mixture material parameters and fracture performance. Case Stud Constr Mater. 2024;20:e02989.

[8] Fletcher DI, Corteen J, Wilby A. Rough surface rolling contact fatigue crack stress intensity factor calculation for modern rail steels. Wear. 2024;540-541:205231.

[9] Vinodhini KA, Sidhaarth KRA. Pothole detection in bituminous road using CNN with transfer learning. Meas: Sens. 2024;31:100940.

[10] Al Ashaibi A, Wang Y, Albayati A, Weekes L, Haynes J. Uni-and tri-axial tests and property characterization for thermomechanical effect on hydrated lime modified asphalt concrete. Constr Build Mater. 2024;418:135307.

[11] Chunping W, Jianfeng L, Liang C, Jian L, Lu W, Yilin L. Creep constitutive model considering nonlinear creep degradation of fractured rock. Int J Min Sci Technol. 2024;34(1):105-16.

[12] Ren S, Liu X, Erkens S. Insight into the critical evaluation indicators for fatigue performance recovery of rejuvenated bitumen under different rejuvenation conditions. Int J Fatigue. 2023;175:107753.

[13] Li X, Fu J, Yang F, Cao HL, Zhang Z, Liu F, et al. Laboratory investigation for the bridge deck pavement performance of conventional asphalt mixtures based on fuzzy comprehensive evaluation method. Case Stud Constr Mater. 2024;20:e02784.

[14] Upadhya A, Thakur MS, Sihag P, Kumar R, Kumar S, Afeeza A, et al. Modelling and prediction of binder content using latest intelligent machine learning algorithms in carbon fiber reinforced asphalt concrete. Alex Eng J. 2023;65:131-49.

[15] Zhu L, Li J, Xiao F. Carbon emission quantification and reduction in pavement use phase: a review. J Traffic Transp Eng. (Engl Ed). 2024;11(1):69-91.

[16] Maha Madakalapuge C, Dutta TT, Kodikara J. Evaluation of climatic effects on moisture variation and performance of unbound pavements with sprayed seals. Acta Geotech. 2024;19:5481-502.
[17] Bhandari S, Luo X, Wang F. Understanding the effects of structural factors and traffic loading on flexible pavement performance. Int J Transp Sci Technol. 2023;12(1):258-72.
[18] Baradaran S, Rahimi J, Ameri M, Maleki A. Mechanical performance of asphalt mixture containing eco-friendly additive by recycling PET. Case Stud Constr Mater. 2024;20:e02740.
[19] Genet MB, Sendekie ZB, Jembere AL. Investigation and optimization of waste LDPE plastic as a modifier of asphalt mix for highway asphalt: case of Ethiopian roads. Case Stud Chem Environ Eng. 2021;4:100150.
[20] Yaro NSA, Sutanto MH, Habib NZ, Napiah M, Usman A, Al-Sabaeei AM, et al. Mixture design-based performance optimization via response surface methodology and moisture durability study for palm oil clinker fine modified bitumen asphalt mixtures. Int J Pavement Res Technol. 2024;17:123-50.
[21] Li N, Zhan H, Yu X, Tang W, Yu H, Dong F. Research on the high temperature performance of asphalt pavement based on field cores with different rutting development levels. Mater Struct. 2021;54:70.
[22] Jwaida Z, Dulaimi A, Bahrami A, Mydin MAO, Özkılıç YO, Jaya RP, et al. Analytical review on potential use of waste engine oil in asphalt and pavement engineering. Case Stud Constr Mater. 2024;20:e02930.
[23] Benedetti M, du Plessis A, Ritchie RO, Dallago M, Razavi N, Berto F. Architected cellular materials: a review on their mechanical properties towards fatigue-tolerant design and fabrication. Mater Sci Eng R: Rep. 2021;144:100606.
[24] Heidarian P, Mokhtari F, Naebe M, Henderson LC, Varley RJ. Reclamation and reformatting of waste carbon fibers: a paradigm shift towards sustainable waste management. Resour Conserv Recycl. 2024;203:107465.
[25] Zhang X, Saba RG, Chen H, Hoff I, Liu J, Wang F. Research on asphalt surface layer performance over service time and establishment of ageing model for in-service bitumen under Norwegian conditions. Case Stud Constr Mater. 2024;20:e02824.
[26] Aldagari S, Kabir SF, Fini EH. Investigating aging properties of bitumen modified with polyethylene-terephthalate waste plastic. Resour Conserv Recycl. 2021;173:105687.
[27] Hossain MT, Shahid MA, Mahmud N, Habib A, Rana MM, Khan SA, et al. Research and application of polypropylene: a review. Discov Nano. 2024;19(1):1-21.
[28] Chaturvedi AP, Suman SK. Rutting behavior estimation of polyethylene terephthalate bituminous layers under static and dynamic load at different temperature ranges. Innov Infrastruct Solut. 2024;9(1):18.
[29] Ahmad MS, Ahmad SA. The impact of polyethylene terephthalate waste on different bituminous designs. J Eng Appl Sci. 2022;69(1):53.
[30] Akbas MY, Karahancer S, Enieb M. Study on the effects of nano Sb_2O_3 on early and long-term aging behaviour of bitumen and asphalt mixtures. Ain Shams Eng J. 2021;12(4):3531-42.
[31] Arifuzzaman M, Qureshi HJ, Al Fuhaid AF, Alanazi F, Javed MF, Eldin SM. Novel ensemble modelling for prediction of fundamental properties of bitumen incorporating plastic waste. J Mater Res Technol. 2023;24:3334-51.
[32] Khusnutdinov I, Goncharova I, Safiulina A. Extractive deasphalting as a method of obtaining asphalt binders and low-viscosity deasphalted hydrocarbon feedstock from natural bitumen. Egypt J Pet. 2021;30(2):69-73.
[33] Almusawi A, Shoman S, Lupanov AP. Assessment of the effectiveness and the initial cost efficiency of hot recycled asphalt using polymer modified bitumen. Case Stud Constr Mater. 2023;18:e02145.
[34] Mirabdolazimi SM, Kargari AH, Pakenari MM. New achievement in moisture sensitivity of nano-silica modified asphalt mixture with a combined effect of bitumen type and traffic condition. Int J Pavement Res Technol. 2021;14:105-15.
[35] Akbulut H, Gürer C. Investigation of the performance of silicone rubber modified bitumen. Silicon. 2022;14(15):9721-31.
[36] Usanga IN, Ikeagwuani CC, Etim RK, Attah IC. Predictive modeling of modified asphalt mixture rutting potentials: machine learning approach. Iran J Sci Technol Trans Civ Eng. 2023;47(6):4087-101.
[37] Rashed AM, Al-Hadidy AI. Comparative performance of DG mixes and SMA mixes with waste crumb rubber as aggregate replacement. Case Stud Constr Mater. 2023;19:e02615.
[38] Zhou S, Song W. Crack segmentation through deep convolutional neural networks and heterogeneous image fusion. Autom Constr. 2021;125:103605.
[39] Long XY, Zhao SK, Jiang C, Li WP, Liu CH. Deep learning-based planar crack damage evaluation using convolutional neural networks. Eng Fract Mech. 2021;246:107604.
[40] Dais D, Bal İE, Smyrou E, Sarhosis V. Automatic crack classification and segmentation on masonry surfaces using convolutional neural networks and transfer learning. Autom Constr. 2021;125:103606.
[41] Aldagari S, Kabir SF, Lamanna A, Fini EH. Functionalized waste plastic granules to enhance sustainability of bituminous composites. Resour Conserv Recycl. 2022;183:106353.