American Journal of Civil Engineering
2024, Vol. 12, No. 3, pp. 86-94
https://doi.org/10.11648/j.ajce.20241203.12

Research Article

Pavement Service Life Prediction with PLAXIS 3D in Bangladesh

Muhammad Akhtar Hossain, Shahriar Ahammed Shakil*, Hritu Raj Barua, Kazi Shahed Ahmed Shoeb

Department of Civil Engineering, Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh

Abstract

This research aims to forecast the service life of the flexible pavement in Bangladesh. The service life of flexible pavement is greatly affected by the climate and traffic load. Pavements are severely deteriorated by the overweight trucks, shortening their lifespan. The study aims to predict the service life of a flexible road using the PLAXIS 3D software. The PYTHON algorithm was utilized for the pre- and post-processing of new mechanistic empirical approach based on the AASHTO 2008 design standard. PLAXIS 3D was used for realistic soil & damage modelling and to obtain a reliable service life. Rajshahi City Bypass Nowhata Road was chosen as the study area for this study because the road condition of Nowhata is defected day by day and the number of moving vehicles with high axle load also increasing. This research has established to give the valid data to the authority according to the construction materials of flexible pavement to get better performance and proper use of materials. This road is constructed under the Road & Highway Department (RHD), Rajshahi Zone. This study shows realistic results based on temperature, soil data of subgrade and the materials property used in the PLAXIS 3D software and PYTHON programming language.

Keywords

Flexible Pavement, Pavement Service Life, PLAXIS 3D, Asphalt Concrete, PYTHON

1. Introduction

The growth of a nation mostly relies on secure and effective communication facilities with enough road net-work infrastructure and Bangladesh is no exception in this situation. The government has been implementing large-scale infrastructure development initiatives to strengthen the road sector over the previous 10 years.

However, the initiatives were unable to provide the anticipated outcomes because there was insufficient forward-thinking planning and parallel maintenance programs. Approximately 95% of new roads built in Bangladesh are now made of bituminous pavement. Like all other nations, Bangladesh experiences early failure of flexible pavements due to limited supply and rising cost of construction materials, heavy axle loads, environmental factors, inadequate design, and improper construction technique. This forces engineers to think of more practical and long-lasting pavement design approaches in order to construct roads using local pavement materials and modern construction techniques. [9]. For developing nations, the situation worsens even more [4]. One of North Bengal's principal urban, commercial, and educational hubs is Rajshahi, a metropolitan city in Bangladesh. The research is being conducted in Rajshahi City Corporation, which is situated in Bangladesh's northwest.

*Corresponding author: sas.ruet.ce@gmail.com (Shahriar Ahammed Shakil)

Received: 14 May 2024; **Accepted:** 6 June 2024; **Published:** 2 July 2024

Service life prediction of flexible pavement refers to the estimation of the duration for which a flexible pavement structure will remain functional and serviceable under anticipated traffic and environmental conditions. Flexible pavements are composed of multiple layers, including the surface course, base course, and sub-base course, with the surface course typically consisting of asphalt or bitumen. Predicting the service life of flexible pavements in Rajshahi, or any other location, involves considering various factors such as climate, traffic load, materials used, construction quality, and maintenance practices [8].

The particular aims of this study were to establish a model for forecasting service life of flexible pavements considering stiffness of pavement. It is envisaged that the conclusion of this study effort would aid understanding the challenges related with the design, construction and maintenance of flexible pavements in connection with the tremendous traffic load being put on the pavements in Bangladesh.

2. Data Collection and Study Area

There are many highways in Rajshahi. Among these roads, the Rajshahi City Bypass Nowhata Road (20.96 km) was selected because this road is under the Road & Highway Department (RHD), Rajshahi Zone. The data was found in the Field Level Quality Control Laboratory office, Road Circle, Rajshahi. The road was constructed in good condition which is overlay 50 mm in several years.

2.1. Preparing Traffic Data

The overall number and composition of cars that will traverse the pavement over the next 20 years is determined by analyzing both current and projected statistics. The Annual Average Daily Traffic (AADT) value is considered 4563 and the traffic growth rate is considered 7% per annum from the Maintenance and Rehabilitation Needs Report of 2021- 2022. The total number of loadings of different vehicles is then converted to an equivalent number related to the one having the heaviest applied tire load which is the Equivalent Single Axle Load (ESAL). This data is found in the Maintenance and Rehabilitation Needs Report of 2021- 2022 for RHD Paved Roads which is organized by The Highway Development and Management (HDM4) Model (HDM-4 software), mainly an economic tool, has been used to project the total maintenance need of RHD Road network and also to select and prioritize maintenance work based on Net present value (NPV)/Cost ratio.

2.2. Preparation of Finite Element Model Data

A three-dimensional model of the flexible pavement is developed in PLAXIS 3D. Due to the symmetry of the single axle truck (H20 truck loading), it is feasible to simulate only one quadrant of the pavement, and the symmetry boundary requirements are implemented appropriately. Fourteen The model dimensions of 12 x 8 x 6 m (depth) are used in order to minimize the impact of the boundary conditions on the calculated results.

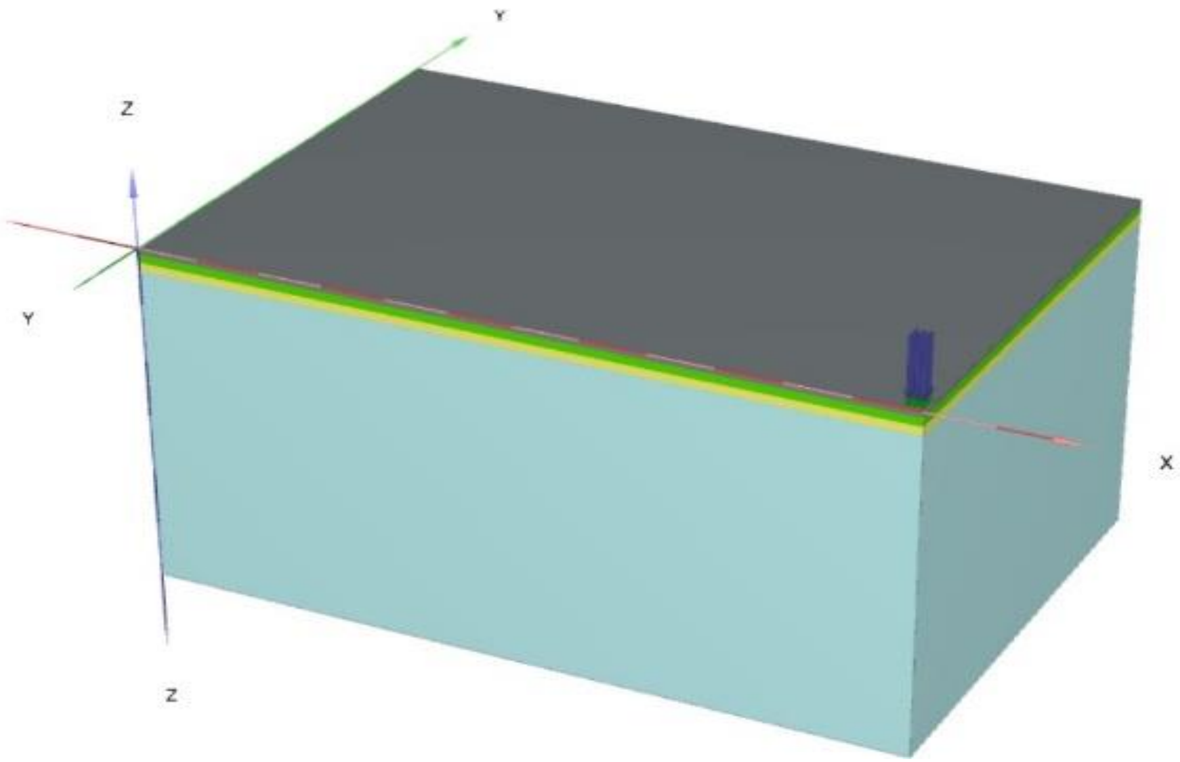

Figure 1. *Finite element model.*

Table 1. *Parametric study for the pavement layer.*

Material	Layer thickness [m]	Soil Model	Elastic Modulus E at 28.5 ℃ [kPa]	Poisson's Ratio ν [-]	Dry Density [kN/m^3]	Initial Damage [%]
Asphalt	0.1	Linear Elastic	$2.1 \times E6$	0.40	24	0
Base	0.15	Mohr Columb	$100 \times E3$	0.35	20	0
Sub-base	0.15	Mohr Columb	$50 \times E3$	0.30	18	0
Sub-grade	5.6	Mohr Columb	$20 \times E3$	0.30	17	0

2.3. Preparing Climate Data

The temperature was taken from the Bangladesh Meteorological Department (BMD) website. The average temperature of Rajshahi is 28.5 ℃. Based on air temperatures, asphalt temperatures were then determined, according to the Asphalt Institute equation (1982) [2].

$$T_{asp} = T_{air}\left(1 + \frac{1}{z+4}\right) - \frac{34}{z+4} + 6 \tag{1}$$

Where:

T_{asp} = The average monthly pavement temperature (℃) at the depth z,

T_{air} = The average monthly air temperature (℃),

z = is the depth under the pavement surface on which temperature is to be determined (in)

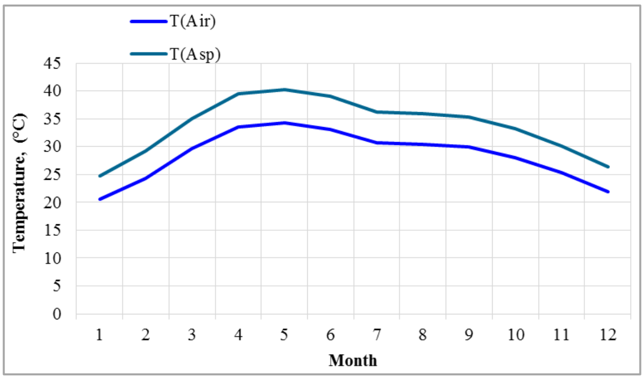

Figure 2. *Air & asphalt monthly mean temperature.*

2.4. Implemented Incremental Functions

The developed incremental functions quantify the variations in material qualities in response to traffic and climate. The impact of temperature on the rigidity of asphalt is calculated based on the model outlined. [5]

Based on the revised damage function, as seen in Figure 4, the material incremental damage ΔD is computed. To begin at the same damage level as in the i increment on the prior function, an identical amount of loads must be computed from the revised incremental function at i+1. The modified transfer function (for strain εi+1) is used to compute the damage Di+1 at a new increment i+1. The material stiffness S $(S_{i+1} = S_i * (1 - \Delta D_i))$ is then updated using the incremental damage ΔD damage in accordance with a designated transfer function [7] (Figure 4).

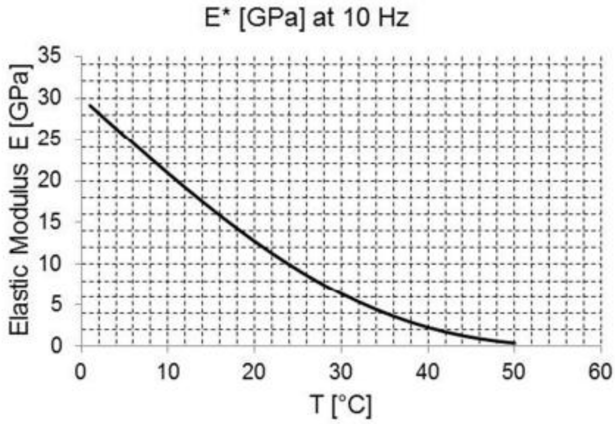

Figure 3. *The stiffness of asphalt varies with temperature, as described by Collop and Cebon (1995).*

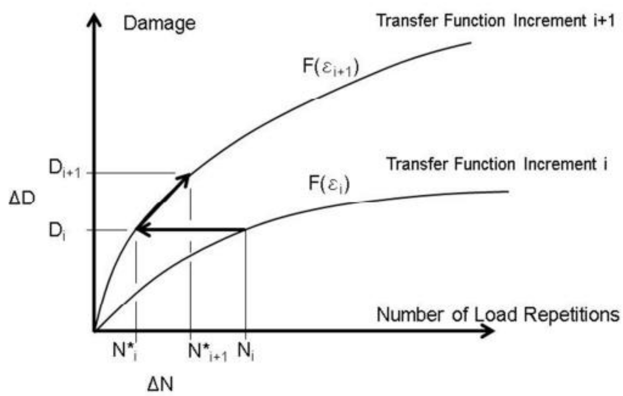

Figure 4. *Modified incremental damage methodology for the transfer functions.*

The suggested asphalt damage model is taken from the AASHTO 2008 design guide [1]. The formula's numerical values closely mirror the original Asphalt Institute model, which is the foundation for the AASHTO 2008 model, because the bottom-up cracking correction factor has been set to 1.

In the approved technique, damage in asphalt is determined based on the number of cycles to failure (N_F) that are acquired as a consequence of fatigue testing. The number of cycles to failure for the asphalt is instead anticipated according to the semi-empirical fatigue law that is presented in the AASHTO 2008 pavement design guide for alligator cracking [10].

$$N_F = k_{f1}(C)(C_H)\beta_{f1}(\varepsilon_t)^{k_{f2}\beta_{f2}}(E_b)^{k_{f3}\beta_{f3}} \quad (2)$$

N_F = Allowable number of axle-load applications for a flexible pavement

ε_t = Tensile strain at critical locations and calculated by the structural response model, in./in.,

E_b = Dynamic modulus of the Asphalt measured in compressions psi,

k_{f1}, k_{f2}, k_{f3} = Global field calibration parameters (from the NCHRP 1-40D recalibration;

k_{f1} = 0.007566, k_{f2} = –3.9492, and k_{f3} = –1.281)

$\beta_{f1}, \beta_{f2}, \beta_{f3}$ = Local or mixture-specific field calibration constants; for the global calibration effort set to 1.0.

$$C = 10^M$$

$$M = 4.84\left(\frac{V_{be}}{V_a+V_{be}} - 0.69\right)$$

Where,

V_{be} = Effective asphalt content by volume, %.

V_a = Percent air voids in the Asphalt mixture and

C_H = Thickness correction term, dependent on type of cracking.

For bottom-up or alligator cracking:

$$C_H = \frac{1}{0.000398+\frac{0.003602}{1+e^{(11.02-3.49H_{asp})}}}$$

H_{asp} = Total asphalt thickness, in.

This prediction equation (Eq. 2) depends on the maximum (critical) tensile strain level at the bottom of the asphalt base layer ε_t, the elastic modulus E and empirical coefficients. The total damage D is derived by adding the increments (Eq. 3) after each repetition according to Miner's rule [12].

$$D = \sum_{i=1}^{l} \Delta D_i \quad (3)$$

Material deterioration is responsible for the loss of stiffness in asphalt. In literature, there are different approaches to connect damage to stiffness in asphalt [5]. According to a well-known criterion, fatigue failure (100% damage) in asphalt is defined as the number of cycles to failure NF after which the material stiffness (elastic modulus) approaches half of its starting value. Therefore, in the technique followed in this work, the stiffness decay is calculated by multiplying the asphalt elastic modulus by a factor:

$$1 - \frac{\sum \Delta D_i}{2} \quad (4)$$

The well-known Van der Pool monographs state that the asphalt stiffness is also adjusted at each phase depending on the average layer temperature. The elastic modulus of the bituminous binder E_b (MPa) was calculated using the following equation derived from the Van der Pool monograph [6].

$$E_b = 1.157 \times 10^{-7} t_1^{-0.368} 2.718^{-PI^{(R)}} \left(T_{RB}^R - T_{asp}\right)^5 \quad (5)$$

Where,

T_{RB}^R = The recovered bitumen 'Ring and Ball' softening temperature (℃)

T_{asp}= The temperature of the asphalt layer (℃)

$PI^{(R)}$ = The recovered bitumen 'Penetration Index'

t_1= The loading time (secs)

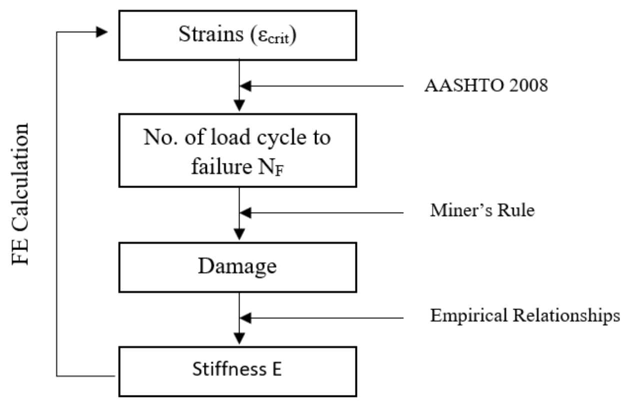

Figure 5. *Simulation of the damage process due to fatigue in asphalt.*

The asphalt stiffness for the next calculation is obtained, as already mentioned, by considering the damage level and the average monthly temperature during service hours of the airport. The procedure is illustrated in Figure 6.

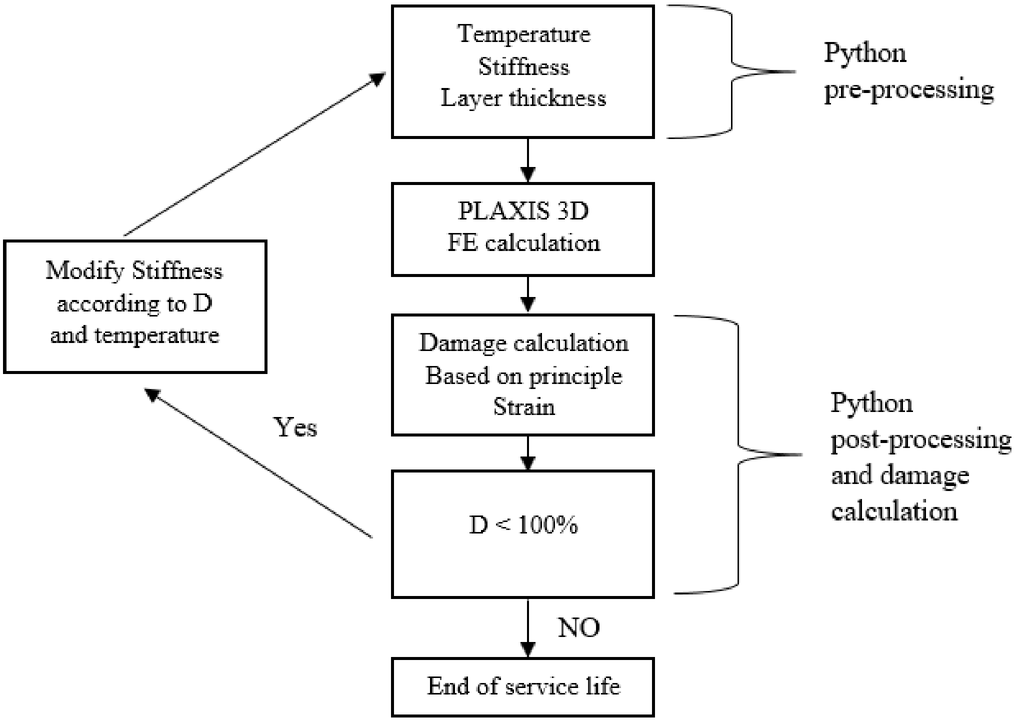

Figure 6. Implemented procedure for estimating service life (fatigue) with PYTHON and PLAXIS 3D.

3. Research Methodology

The three-dimensional finite element programs PLAXIS 3D and PYTHON are the two pieces of software utilized to construct the approach. After the calculation finishes, PYTHON runs the translating output software cbin.exe and reads the stresses in the Gauss points. PYTHON calculates the strains from the stresses according to the elastic constitutive model adopted for modelling the asphalt behavior.

The damage functions were selected to accurately mimic the material's degradation in stiffness brought on by repetitive loading. The chapter "Implemented incremental functions" describes the selection and key features of these functions. The chapter "Finite Element Model" contains a thorough explanation of the finite element model used in PLAXIS 3D.

In the present, the new method's overall updated incremental procedure is explained. Here is a thorough explanation of the revised process for the first six steps of the computation.

Steps 1 & 2: An FE model in PLAXIS 3D is used to determine the mechanical reaction, namely the major strains caused by a loading and unloading calculation step. The stresses that are significant are the major strains in the asphalt, which are the biggest (compression) and the base layer, which is the third smallest (tension). After loading (step 1), the PLAXIS 3D findings are converted into binary files using a PYTHON algorithm, which then reads the stresses in the pavement's critical places. The governing factor for the fatigue behavior of soil materials is the translation of critical stresses into critical strains in an intermediary stage. The stiffness decrease of each layer is then determined by a Python algorithm based on specified damage functions, critical stresses, mean monthly temperature and water conditions, and the amount of load applications each month [12].

Steps 3 & 4: The finite element model is updated with the new stiffness values, and two additional computation steps—loading and unloading—are added. To maximize the distribution of data, the outcomes of the last two stages are kept, but the results of steps one and two are erased. The model is updated once more once the model parameters are computed in accordance with the damage functions.

Steps 5 & 6: Beginning with step 4, the final computation, new loading and unloading stages are introduced (unloading).

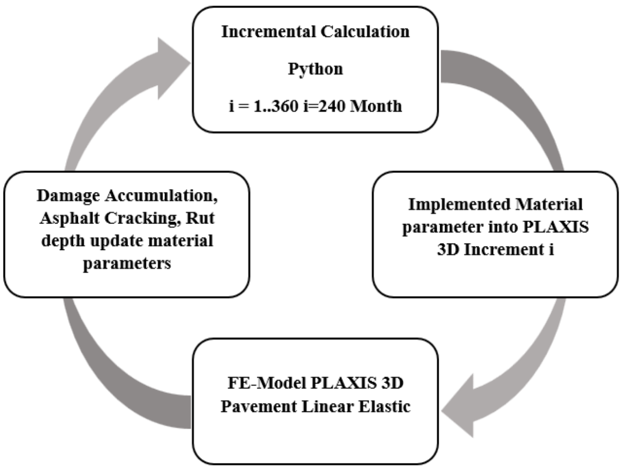

Figure 7. Calculation scheme of the implemented algorithm.

Within this procedure, it is possible to calculate permanent strains in the bound layers due to the plastic deformation in the subgrade.

At each level of the computation, the damage functions are updated based on the number of loads, current stiffness, and calculated strains. In order to determine the residual service life, factors such as fractures, plastic deformations in the subgrade, and stiffness decrease (damage) are considered. The chapter on the implemented incremental functions provides a description of the chosen end-of-service life criterion.

4. Model Calibration and Validation

The term "calibration" refers those interactions where chosen boundaries and factors of the model are acclimated to mention the model yield coordinate observable facts. Predicting the service life of flexible pavement using finite element mode is new in Bangladesh. In Bangladesh usually international roughness index is used for predicting service life of flexible pavement. So, there was some difficulties to validate our model. The service life of Zurich International Airport rehabilitation design has been studied by adopting a new mechanistic-empirical technique based on the AASHTO 2008 design guide, but certain enhancements have been implemented: 1) three-dimensional finite element modeling (FE) using an elastoplastic strain hardening material behavior model for the subgrade [13]. This model was also same to our model. The damage with respect to no. of month graph was similar to this research result which validate this model.

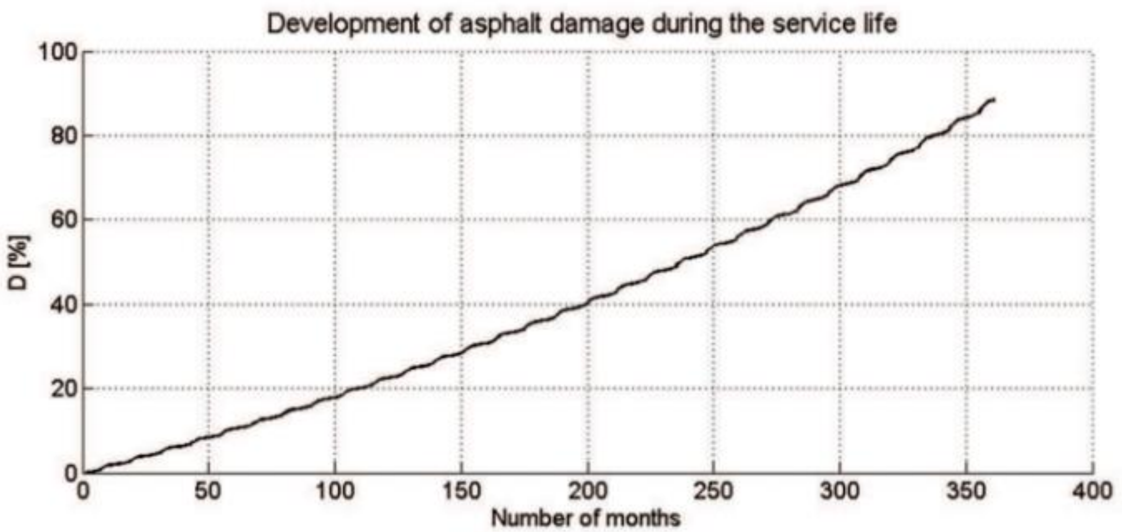

Figure 8. *Accumulation of damage during runway 14/32 service life.*

5. Result and Discussions

Cumulative fatigue damage is a complex phenomenon influenced by various factors, including traffic volume, material properties, environmental conditions, and construction practices. Understanding these causes is essential for implementing effective pavement management strategies and prolonging pavement service life. The effects of cumulative fatigue damage are crucial for implementing proactive pavement management strategies which are reduced service life, increased cracking, safety hazards, and traffic disruption aimed at minimizing deterioration and ensuring the safety and functionality of road networks.

For 10% cumulative fatigue damage

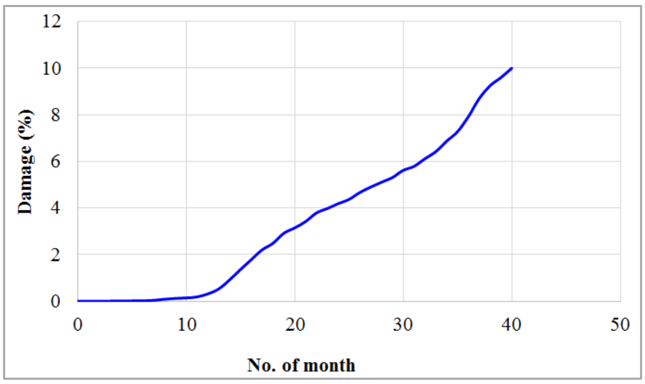

Figure 9. *Accumulation of 10% damage during pavement service life.*

The time required for first 10% damage is approximately

40 months. The effect of the repetitive load in the first 10 month is quite less and the reduction of stiffness is less.

For 50% cumulative fatigue damage

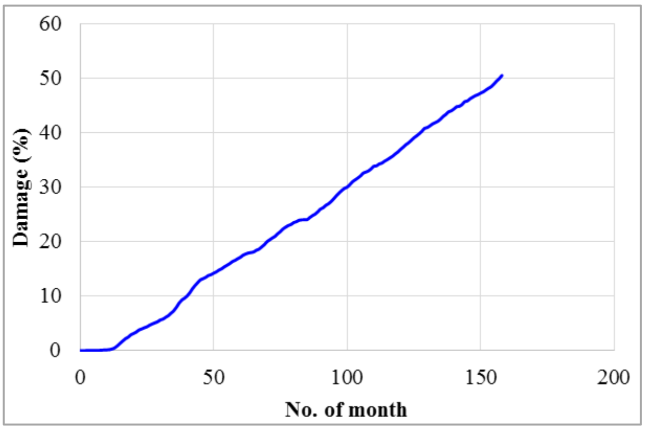

Figure 10. *Accumulation of 50% damage during pavement service life.*

The time required for first 50% damage is approximately 158 months. After the first 25% damage (case 2), the next 25% damage takes only 70 months. The incremental damage effects greatly on the stiffness and reduce the stiffness at a higher rate than previous case.

For 100% cumulative fatigue damage

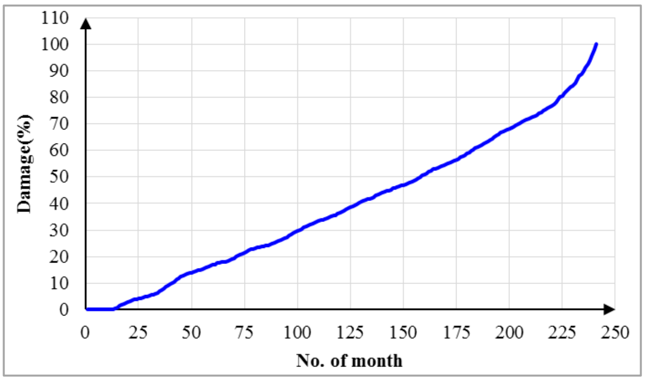

Figure 11. *Accumulation of 50% damage during pavement service life.*

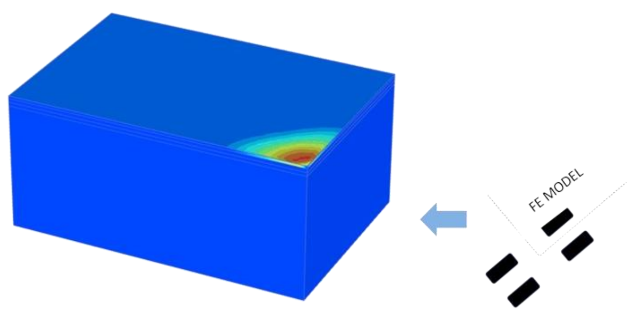

Figure 12. *Symmetrical 3D finite element model of the pavement.*

The time required for first 100% damage is more than 240 months. The last 50% damage takes 82 months where the first 50% damage takes 158 months. It affects the stiffness greatly and reduce it to almost 50% of its initial value.

A realistic soil modelling was created by PLAXIS 3D after moving repetitive loads.

Stiffness reduction

Temperature fluctuations significantly impact the stiffness of asphalt and pavement materials [3]. As temperatures rise, asphalt mixtures experience a reduction in stiffness due to decreased viscosity and cohesion, leading to a softer and more flexible pavement surface. Conversely, at lower temperatures, asphalt stiffness increases, making the pavement more brittle and susceptible to cracking under loading conditions. This phenomenon is attributed to the thermal expansion and contraction of asphalt binders, affecting the overall structural integrity of pavements. Understanding the relationship between temperature and stiffness is crucial for designing durable and resilient pavement systems that can withstand varying environmental conditions and traffic loads [11].

Damage effects on stiffness reduction are applied in a linear fashion akin to Collop and Cebon's (1995) description of the Ullidtz model. As in the standard failure criteria for fatigue testing on asphalt, the Ullidtz model equation is changed, assuming that 100% damage (number of cycles to failure = total number of applied loads up to the final step) corresponds to 50% decrease of the starting stiffness (Figure 12).

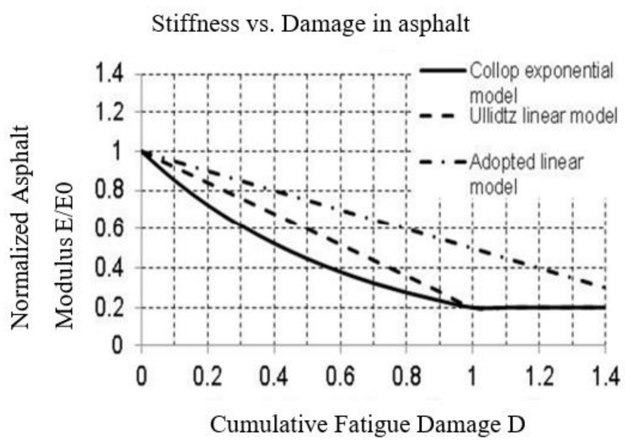

Figure 13. *Preferred the Collop and Ullidtz model above the linear damage approach model (the Collop exponential model was found especially for asphalt overlay).*

The stiffness reduction cut-off value was set at E = 50 MPa, which is the theoretical modulus of a badly compacted gravel. The AASHTO 2008 model illustrates the progression of deterioration and bottom-up fractures in asphalt in Figure 14.

It is possible to see that for every 50% of a cracked region in Figure 14, the damage to the asphalt layer is equivalent to 100% by comparing the dashed and continuous lines. Hence, 50% of the original stiffness of the asphalt is considered to be the definition of pavement failure.

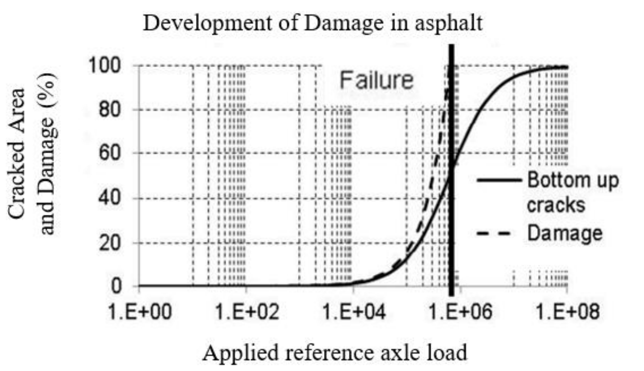

Figure 14. The AASHTO 2008 design guide and the selected asphalt damage percentage (stiffness decrease) model were used to determine the development of the cracked area in relation to the number of reference axle loads (the reference wheel in this technique).

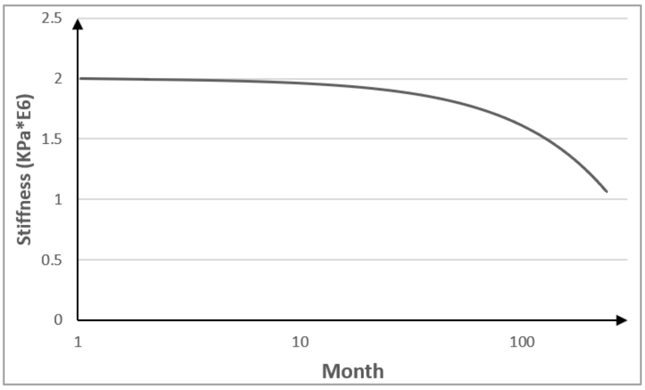

Figure 15. The development of asphalt stiffness throughout a 20-year service life is as follows: 1 month = 11800 reference landing repetitions with 7% annual increase.

End of service life criterion

A pavement's end of service life can be determined by a variety of factors, such as the maximum rut depth, the acceptable number of cracks, evenness, or other signs.

Rutting was not considered as a criterion for the end of service life as it will be altered far in advance of the pavement's useful life ending. The criteria that were used to signify the end of the service life was 100% damage to the base asphalt layer and bottom-up cracking. In this case, after this layer has sustained 100% damage, 50% of the original stiffness and 50% of the cracked region will also be diminished.

It is notice that 50% loss in initial stiffness may also be a credible predictor of the end of the pavement's service life, since it is noted that this is a traditional failure indicator for fatigue testing on asphalt [6].

6. Conclusions

The road sector in Bangladesh is expanding in response to the rising demand for transportation, but the overall growth of the road communication sector is relatively underdeveloped as a result of inadequate planning and execution at the field level. Similar to other emerging nations, this nation chooses flexible pavement over other types of pavements when building new roads.

A realistic soil modelling of Rajshahi Nowhata Highway was obtained from this research. When the damage reached 100% stiffness reached almost its half value which validated the damage modelling. This work then produced a realistic updated incremental damage technique for the stiffness parameters and transfer functions. The predicted service life of this study was 20 years which was similar to the predicted service life of RHD. So, reliable service life was obtained by this study.

Abbreviations

AADT	Annual Average Daily Traffic
RHD	Road & Highway Department
ESAL	Equivalent Single Axle Load
AASHTO	American Association of State Highway and Transportation Officials
HDM4	The Highway Development and Management
NPV	Net Present Value

Acknowledgments

The author expresses his heartiest gratitude and sincere indebtedness to his supervisor Dr. Md. Akhtar Hossain, Professor, Department of Civil Engineering, RUET for his continuous guidance, relentless discussions, helpful suggestions, affectionate encouragement, and generous help at every stage of this study.

Author Contributions

Muhammad Akhtar Hossain: Conceptualization, Formal Analysis, Project administration, Supervision

Shahriar Ahammed Shakil: Software, Formal Analysis, Writing – original draft

Hritu Raj Barua: Software**,** Investigation, Visualization, Resources, Data curation, Methodology, Validation

Kazi Shahed Ahmed Shoeb: Data curation, Methodology, Validation

Funding

The research was carried out without the help of any specific funding. The study was finished as a part of the authors'

acknowledged independent research projects.

Data Availability Statement

The data available from the corresponding author can be provided for verification purposes.

This publication has also included references to the data that support the findings of this investigation.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] American Association of State Highway and Transportation Official's (AASHTO) (2008). Mechanistic-Empirical Pavement Design Guide, A Manual of Practice, Interim Edition.

[2] American Association of State Highway and Transportation Officials (AASHTO). (1993). Guide for Design of Pavement Structures.

[3] AUSTROADS. (2012). Guide to Pavement Technology. Part 2: Pavement Structural Design. Austroads Publication No. AGPT02-12.

[4] Ali, G., Elniema, A. and El-Obeid, H. (2012). "Feasibility of Using Concrete Pavements in Developing, Hot-Climate Countries: A Case Study for Conditions of Khartoum State in Sudan." 9th International Conference on Concrete, Bahrain, 12-14 Feb 2012.

[5] Collop A. and Cebon D. (1995). "Modelling Whole-Life Pavement Performance". Road Transport Technology 4, *University of Michigan Transportation Research Institute*. 201–212. https://doi.org/10.1243/pime_proc_1995_209_170_02

[6] Di Benedetto, H., Baaj, H., Pronk, A. C., & Lundström, R. (2004). Fatigue of bituminous mixtures. *Materials and Structures*, *37*(3), 202–216. https://doi.org/10.1007/bf02481620

[7] Fatemi, A. and Yang, L. (1998). "Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials*". Int. J. Fatigue*, *Vol. 20, No. 1*. 9–34. https://doi.org/10.1016/s0142-1123(97)00081-9

[8] Hamim, O. F., & Hoque, S. (2019). Prediction of Pavement Life of Flexible Pavements under the Traffic Loading Conditions of Bangladesh. *Airfield and Highway Pavements 2019*. https://doi.org/10.1061/9780784482452.003

[9] Hamim, O. F. (2017). "Comparative study of rigid and flexible pavements construction in Bangladesh." B. Sc. thesis, Bangladesh University of Engineering and Technology, Dhaka.

[10] Li, J., Xiao, D. X., Wang, K. C. P., Hall, K. D., & Qiu, Y. (2011). Mechanistic-empirical pavement design guide (MEPDG): a bird's-eye view. *Journal of Modern Transportation*, *19*(2), 114–133. https://doi.org/10.1007/bf03325749

[11] Lundström, R., Di Benedetto, H., & Isacsson, U. (2004). Influence of asphalt mixture stiffness on fatigue failure. *Journal of Materials in Civil Engineering*, *16*(6), 516–525. https://doi.org/10.1061/(asce)0899-1561(2004)16:6(516)

[12] Rabaiotti, C., Amstad, M., and Schnyder, M. (2013) Pavement Rehabilitation of Runway 14/32 at Zürich International Airport: Service Life Prediction Based on Updated Incremental Damage Approach. Airfield and Highway Pavement 2013, pp. 609–627. https://doi.org/10.1061/9780784413005.049

[13] Rabaiotti, C., Puzrin, A. M., Caprez, M., & Ozan, C. (2013). Pavement structural health evaluation based on inverse analysis of three-dimensional deflection bowl. *International Journal of Pavement Engineering*, *14*(4), 374–387. https://doi.org/10.1080/10298436.2012.684055

Biography

Muhammad Akhtar Hossain is currently working as a Professor at Rajshahi University of Engineering & Technology, Department of Civil Engineering. He acquired his B.Sc. in Civil Engineering from Rajshahi University of Engineering & Technology in 2001. He has published various research works and conference papers.

Hritu Raj Barua has just completed undergraduate studies in the Civil Engineering Department at Rajshahi University of Engineering & Technology. He will acquire his B.Sc. in Civil Engineering degree from Rajshahi University of Engineering & Technology in 2024.

Shahriar Ahammed Shakil has just completed undergraduate studies in the Civil Engineering Department at Rajshahi University of Engineering & Technology. He will acquire his B.Sc. in Civil Engineering degree from Rajshahi University of Engineering & Technology in 2024.

Kazi Shahed Ahmed Shoeb has just completed undergraduate studies in the Civil Engineering Department at Rajshahi University of Engineering & Technology. He will acquire his B.Sc. in Civil Engineering degree from Rajshahi University of Engineering & Technology in 2024.