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A reliability-based mechanical-empirical design method for flexible pavements containing cement-treated magnesite mine tailings as subgrade

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Abstract

The large-scale mining of magnesite generates substantial quantities of magnesite mine tailings (MMT), which pose a significant threat to soil, water, and air quality. Utilising cement-treated MMT as a subgrade material presents a promising solution to address this environmental challenge. However, the existing mechanical-empirical design methods cannot be directly employed due to the uncertainties associated with the various design parameters particularly the behaviour of cemented MMT. This research introduces a novel reliability-based MEM design method to design flexible pavements incorporating cemented MMT as subgrade. A three-layered flexible pavement configuration, with a middle granular layer sandwiched between the top bituminous layer and the bottom stabilised subgrade, was examined. The response surface model and finite element model were developed to determine the fatigue and rutting strains of the pavement. Monte Carlo simulation was adopted to compute reliability. Further, a sensitivity analysis was performed to probe the contribution of input parameters on the reliability of pavement. The developed methodology was illustrated with a case study. Reliability analysis revealed that the cemented MMT pavement achieved reliabilities of 97.44% and 96.27% for fatigue and rutting criteria, respectively, under a design traffic load of 30 million standard axles (msa). Additionally, the sensitivity analysis identified the modulus of elasticity of the granular layer and bituminous layer as the most critical input variables. Thus, the developed design methodology for pavements incorporating MMT enables the engineers to design MMT-based flexible pavements considering the uncertainties.

Keywords: Reliability analysis, Magnesite mine tailings, Subgrade, Monte Carlo simulation, Fatigue, Rutting

Introduction

Magnesite mine tailings (MMT) are the waste material produced during the extraction and processing of magnesite, a magnesium carbonate mineral that is used in various industrial applications such as the production of refractory materials and fertilisers. The tailings are typically a by-product of the crushing, grinding, and flotation processes used in the extraction of magnesite. As the production of magnesite has risen over time, a huge amount of MMT has been created and disposed of in open landfills. This has a major impact on the ecosystem in the areas surrounding the dumpsite. Past studies have shown that utilising MMT as a construction material would be a beneficial solution [32].

Cement-treated magnesite mine tailings can be used as a subgrade material in various construction projects, such as roads and bridges. The tailings were treated with cement to improve their mechanical properties, such as strength and stability. A previous study has indicated that the MMT blends containing 8% Ordinary Portland Cement (OPC), and 10% OPC demonstrated resilience through 12 wetting–drying cycles, with residual unconfined compressive strength (UCS) values reaching 28.41% and 46.93% of the 28th-day UCS [33]. Additionally, the leachates from these mixtures adhere to the Indian standards for drinking water [5]. This is important for preventing the infiltration of contaminants into the subgrade and maintaining its stability over time. The use of cement-treated magnesite mine tailings as a subgrade material has several benefits. Firstly, it can reduce the amount of waste generated by magnesite mining operations, as the tailings are utilised instead of discarded. Secondly, it can provide an economical alternative to traditional subgrade materials, such as gravel and crushed rock, which can be more expensive to obtain and transport. Moreover, using mine tailings as a subgrade can reduce the demand for virgin materials, helping to conserve natural resources [33].

Flexible pavements are composed of multiple layers, typically including a bituminous surface layer, base course, and subgrade. These pavements distribute loads through their flexible nature, adapting to traffic-induced stresses. The flexibility allows for efficient load distribution, resilience to temperature variations, and ease of maintenance, making them a popular choice for many road construction projects. Pavement design methods involve a systematic approach to determining the appropriate thickness and composition of road surfaces to withstand traffic loads and environmental conditions [28] & [16]).

Pavement design methods are broadly categorised into mechanistic-empirical and empirical approaches. Mechanistic-empirical methods (MEM) employ mathematical models to analyse the structural response of pavement layers, considering factors like traffic loads and environmental conditions. In contrast, empirical methods rely on historical data and experience to establish design guidelines. While these design methods are deterministic in nature with fixed input parameters such as traffic and material responses, it is crucial to acknowledge that uncertainties are inherent in these parameters, introducing a probabilistic aspect to pavement design. More specifically, the uncertainties influencing the performance of pavements could be classified into four groups such as spatial variability in material properties, inaccurate estimation of design inputs, errors from model complexity or inefficient model, and statistical error from fitting the data [21].

The theory of reliability offers well-established methodologies that address the performance of any engineering structure designed with uncertainty in its design parameters [14]. The American Association of State Highway and Transportation Officials (AASHTO) [1] defines the reliability of pavement as the probability of a designed pavement that successfully sustains the designed number of load repetitions without undergoing any kind of serviceability and structural failure during its designed lifetime. Further, AASHTO [26] mandates a specified level of probability for each category of the road together with traffic requirements.

In the past, the uncertainties were incorporated into the design through safety factors. These factors were applied based on experience and arbitrary guidelines, which led to the failure of a few pavements [15]. The reliability-based pavement deterioration model was proposed by Lemer and Moavenzadeh [23] which defined the limit state function as the difference between logarithms of the allowable number of axle load and actual number of axle load. Further, Alsherri and George [3] developed various indices for measuring pavement serviceability based on reliability. Kim and Lee [22] utilised load and resistance factors for designing pavement based on reliability, and the level of performance was indicated by the reliability index. The study further recommended that the target reliabilities could be varied in accordance with traffic loads. Maji and Das [25] developed design charts for designing pavements for targeted reliability. The sensitivity analysis indicated that the thickness of the bituminous layer considerably influenced the reliability.

Reliability analysis was also used for scheduling maintenance work of pavements. Deshpande et al. [7] have developed three reliability-based models such as constrained reliability, constrained budget, and multi-object optimisation to determine optimum rehabilitation strategies. Chou and Le [6] utilised the particle swarm optimisation technique to develop a budget-reliability maintenance model which strategically increased the efficiency of road maintenance plans. Xin et al. [39] employed a neural networks-based reliability approach to optimise preventive maintenance of asphalt pavement during their service period. The road users and agency benefits were maximised, and life cycle cost was reduced to schedule preventive maintenance.

The MEM employs a suite of models to systematically analyse the degradation of flexible pavement structures under the influences of traffic, climate, and materials. These models encompass the forecasting of rutting and fatigue strains [18]. The precision of reliability analysis is significantly contingent on the effectiveness and accuracy of the models utilised for predicting the deterioration of flexible pavement. The viscoelastic continuum damage was initially adopted to compute pavement distress [31, 37, 40]. The limitations of performance forecasts only based on material testing became evident when attempting to comprehensively understand the behaviour of pavement [29]. Given that pavements are intricate layered structures, the stress and strain distributions exhibited variability throughout the pavement section, leading to the emergence of difficult shear and flow areas [13].

The prevailing approach in the stress–strain analysis involved layered elastic analysis, wherein pavement layers were treated as an elastic medium under the action of static point loads. Nonetheless, this method proved to be less accurate for asphalt pavement, as it displayed viscoelastic behaviour, particularly under the influence of traffic loading. In response to this limitation, layered viscoelastic moving load analysis emerged as an enhanced methodology [17]. By incorporating the dynamic nature of traffic-induced loading and the viscoelastic properties of asphalt concrete, this approach provided a more realistic representation of the stress and strain distribution within the pavement layers [12, 38].

Based on historical and laboratory experiments, statistical models are also employed to predict strains in the pavement [11, 17, 30]. Various design codes were also adopted statistical models [19]. However, these models yielded low accurate results due to the variations in characteristics of materials, traffic loads, and climatic actions. The finite element analysis was proven to be effective in determining pavement strains [2, 34]. Sudhakaran et al. [34] probed the effects of bottom ash and areca fibre on improving the properties of cohesive soil and performed a reliability analysis to estimate the allowable traffic load. In this study, a three-layered road section was modelled in a finite element programme called ANSYS 3D. The strains at the bottommost of the surface layer and topmost of the subgrade were determined using ANSYS 3D. The simulations were performed using MATLAB software. Syed and GuhaRay [35] studied the alkali-stabilisation of an expansive soil added with chemically treated hemp fibre and performed a reliability analysis to account for various uncertainties. Based on the experimental datum, the UCS and split tensile strength were modelled using nonlinear equations as a function of binder and fibre contents and fly ash to slag ratios. Monte Carlo simulations were performed on 30,000 samples using MATLAB software. Toan et al. [36] investigated the impact of variations in modulus of elasticity and layer thickness on the reliability of flexible pavement under rutting failure conditions. The probability functions were generated using Monte Carlo simulations with MATLAB. The data collected from the national highways of Vietnam were used to develop statistical distributions.

Monte Carlo simulation (MCS), first-order reliability method (FORM), and second-order reliability method (SORM) are widely employed techniques in reliability analysis, each offering distinct advantages and considerations in the context of pavement reliability computation. MCS operates by generating numerous random samples for uncertain variables, simulating system performance, and deriving reliability from the fraction of simulations meeting specific criteria. This method is adaptable and capable of handling complex, nonlinear models with multiple sources of uncertainty. However, its computational intensity and resource requirements can be prohibitive, particularly for real-time or large-scale applications [8, 9].

FORM, on the other hand, approximates the limit state function using a first-order Taylor series expansion to compute the probability of failure. It is more computationally efficient than MCS and is suitable for systems with relatively small uncertainties. Despite its simplicity and ease of implementation, FORM may be less accurate for highly nonlinear systems or those characterised by significant uncertainties. It relies on the assumption that the limit state function is adequately represented by a first-order Taylor series [10, 20].

SORM builds upon the principles of FORM but offers improved accuracy by considering the second-order expansion of the limit state function. This method strikes a balance between accuracy and computational cost, making it suitable for systems with moderate levels of uncertainty and nonlinearity. While being more complex than FORM, SORM provides a more refined estimation of the probability of failure. However, it may still be computationally intensive compared to FORM [4, 10].

In the analysis of pavements, the complex interrelationship between various failure modes posed a significant challenge. The primary modes of failure, fatigue cracking and rutting, were traditionally treated as independent and occurring in series, suggesting that pavement failure could result from either mode independently [19]. Limited studies indicated a potential correlation between fatigue cracking and rutting. These studies showed the existence of a possible connection between the two failure modes, challenging the notion of complete independence [8, 24]. Recognition of this potential correlation became crucial for reliability analysis. However, the challenge lay in the lack of precise knowledge regarding the extent of correlation, as it depended on numerous factors and remained a subject of ongoing research.

It is evident from past studies that the incorporation of reliability in pavement design is inventible. As the cemented MMT is a relatively new pavement material, the existing deterioration models cannot be employed. Moreover, designing the pavement with available designing techniques may not provide optimum design. By addressing this issue, a better understanding of the reliability performance of this specific pavement type can be achieved, leading to improved design and maintenance strategies for such pavements.

Methods

This research introduces an MCS-based methodology for the reliability-oriented design of MMT pavement, utilising the Indian Roads Congress (IRC) guidelines as per the current standards. The analysis involves a nonlinear elastic examination conducted through a finite element model to determine axle load-produced fatigue and rutting strains in a three-layer flexible pavement system incorporating cemented MMT as subgrade. A mechanics-based model for estimating these strains is established using the response surface method (RSM). To enhance computational accuracy, Monte Carlo simulation is incorporated in MATLAB to precisely compute reliability. The proposed approach is illustrated through a case study involving the performance assessment of a three-layer pavement with cemented MMT as subgrade, considering varying traffic demands. This ideology is illustrated in Fig. 1

The proposed methodology for the reliability-oriented design of cemented MMT pavement offers several novel contributions to the field of pavement engineering. The research demonstrates a significant advancement in pavement design by incorporating viscoelastic and elastoplastic behaviours into a three-layered model, surpassing traditional linear elastic

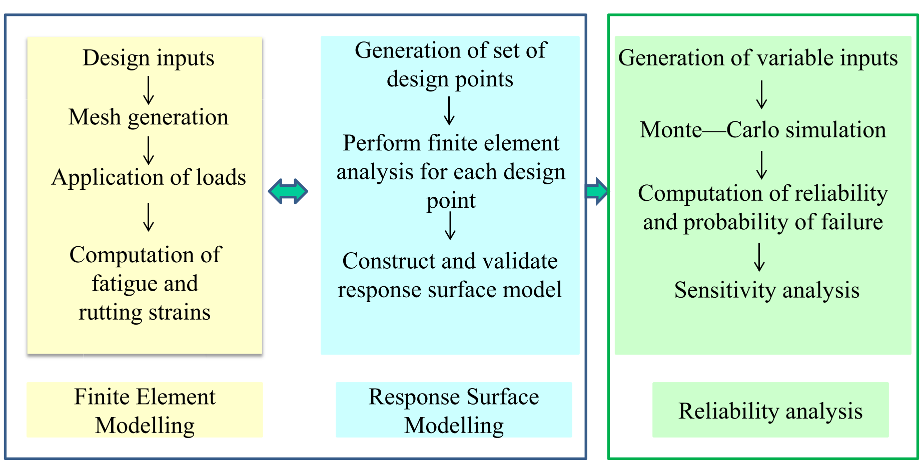

Fig. 1 Conceptual map of the proposed methodology

approaches. By utilising a multi-model approach combining response surface methods and finite element analysis, the study offers a comprehensive understanding of fatigue and rutting failure modes. Furthermore, the inclusion of Monte Carlo simulation for uncertainty quantification enhances the realism of reliability assessments by accounting for variations in material properties and loading conditions.

Limit state function

In pavement engineering, the reliability of a pavement system is closely tied to the accuracy of its predictive models for assessing pavement performance. One crucial component of these models is the limit state function, which plays a key role in determining whether the pavement system is considered safe or has failed. The limit state function was defined in this study as the difference between the number of cumulative standard axles corresponding to the fatigue strain (Nf) or rutting strain (Nr) and the intended number of cumulative standard axles (Nd).

$$f_f(x) = N_f - N_d \tag{1}$$

$$f_r(x) = N_r - N_d \tag{2}$$

where $f_f(x)$ and $f_r(x)$ are the limit state functions for fatigue and rutting failure modes respectively.

Pavement section

The components of pavements were designed as per IRC by incorporating the average soaked CBR of the MMT subgrade. A three-layered flexible payment system with a middle granular layer with a top bituminous layer and bottom stabilised MMT subgrade is analysed in this study. Figure 2 shows the pavement cross section of the cemented MMT subgrade.

Modelling of pavement response

There are several factors influencing the fatigue and rutting strains including elastic moduli, Poisson's ratio and thicknesses of each layer, spacing of wheels, and contact pressure [9]. Thus, mathematically,

$$\varepsilon = f\left(E_b, E_g, E_s, T_b, T_g, T_s, \mu_b, \mu_g, \mu_s, ws, p\right) \tag{3}$$

where E_b, E_g, E_s, T_b, T_g, T_s, μ_b, μ_g, and μ_s are elastic moduli (MPa), Poisson's ratio and thickness (cm) of bituminous layer, granular layer, and stabilised subgrade. w_s denotes wheel spacing, and p denotes contact pressure.

Previous studies have shown that Poisson's ratio had a negligible impact on pavement performance, and hence, the present study considered Poisson's ratio as constant. Further, the thickness of stabilised subgrade, wheel spacing, and contact pressure were treated as constants with the values of 500 mm, 310 mm and 560 kPa respectively as per IRC [19]. Thus, Eq. (1) became as follows:

$$\varepsilon = f\left(E_b, E_g, E_s, T_b, T_g\right) \tag{4}$$

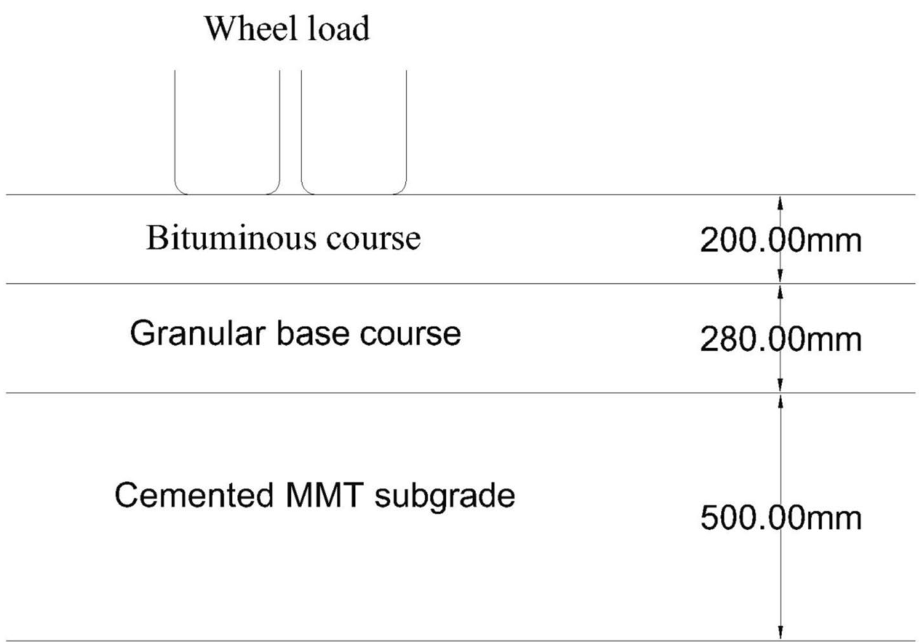

Fig. 2 Cross section of cemented MMT subgrade

Table 1 Design parameters of the stabilised MMT subgrade pavement

Pavement component	Input parameters	Unit	Mean	Standard deviation	Reference
Bituminous layer	Thickness	cm	20	1	Noureldin et al. [27]
	Modulus of elasticity	MPa	2771	415.8	Noureldin et al. [27]
Granular layer	Thickness	cm	28	2.8	Noureldin et al. [27]
	Modulus of elasticity	MPa	554	110.8	Noureldin et al. [27]
Stabilised subgrade	Modulus of elasticity	MPa	146.24	10.54	Present research

Table 1 summarises the design input parameters along with their mean and standard deviations for the cemented MMT subgrade pavement. The failure criteria consisted of fatigue and rutting strains.

The three-layered flexible pavement system with a middle granular layer with a top bituminous layer and bottom stabilised MMT subgrade was modelled in PLAXIS 2D, a finite element analysis software. The geometry and material properties of the pavement system were defined, including the thicknesses of the bituminous layer, granular layer, and subgrade, as well as their material properties as shown in Fig. 2 and Table 1. A finite element mesh was created that was fine enough to accurately represent the behaviour of the pavement system without being computationally expensive to solve. Loads and boundary conditions were applied, including a vertical load to the top of the pavement system to simulate the weight of traffic and fix the bottom of the subgrade in place to prevent it from moving. The fatigue and rutting strains were analysed to assess the performance of the pavement system.

In this study, response surface methodology (RSM) is employed to develop a statistical model of the results of finite element analysis of the three-layered flexible pavement system.

RSM is fundamentally rooted in statistical and mathematical techniques, which are indispensable for comprehending and optimising complex systems. In our context, RSM facilitates the modelling of intricate relationships between various input variables, including elastic moduli (E) and the thicknesses of each pavement layer (T_b, T_g), and the critical output variables of fatigue (ε_f) and rutting (ε_r) strains. These relationships are often expressed through mathematical equations, typically in the form of response surface models. For example, a simple linear response surface model for fatigue strain might be represented as follows:

$$\varepsilon_f = \beta_0 + \beta_1\beta_b + \beta_2E_g + \beta_3E + \beta_4T_b + \beta_5T_g \tag{5}$$

Here, β_0, β_1, β_2, β_3, β_4, and β_5 are coefficients determined through regression analysis. The input variables are weighted according to these coefficients, reflecting their impact on fatigue strain. The analysis encompasses the design of experiments to efficiently sample the input parameter space, validation of the response surface models through experimental data comparison, and optimization to identify the combination of input variables that minimises fatigue and rutting strains or satisfies specified criteria.

To validate the accuracy of the statistical model developed using RSM, a comparison was made between the predicted values of the fatigue and rutting strains obtained from the statistical model and the actual values obtained from finite element analysis. The comparison showed that the predicted values were in good agreement with the actual values, with an average absolute percentage error of less than 3%. This indicates that the statistical model is a reliable tool for predicting the critical responses of the three-layered flexible pavement system.

Computation of reliability

For computation reliability, Monte Carlo simulation was used. To construct a set of 'N' randomly distributed input parameters, a 'N' number of pseudo-random numbers was generated. To return zero for the safe condition and unity for the failure condition, a binary function was utilised for a sample size of 10^6.

$$B_f(x) = \begin{Bmatrix} 1 & \text{if} f_f(x_i) \leq 0 \\ 0 & \text{otherwise} \end{Bmatrix} \tag{6}$$

$$B_r(x) = \begin{Bmatrix} 1 & \text{if} f_r(x_i) \leq 0 \\ 0 & \text{otherwise} \end{Bmatrix} \tag{7}$$

where $B_f(x)$ and $B_r(x)$ are the binary functions for fatigue and rutting criteria respectively. The following equations can be used to calculate the probability of failure and reliability.

$$F_{Pf} = \frac{1}{N}\sum_{i=1}^{N} B_f(x) \tag{8}$$

$$F_{Pr} = \frac{1}{N}\sum_{i=1}^{N} B_r(x) \tag{9}$$

$$R_f = (1 - F_{Pf}) \times 100\% \tag{10}$$

$$R_r = (1 - F_{Pr}) \times 100\% \tag{11}$$

where P_{ff} and P_{fr} represent the failure probabilities of fatigue and rutting criteria respectively and R_f and R_r represent the reliabilities of fatigue and rutting criteria respectively. The Matlab software was utilised to perform reliability analysis.

Sensitivity analysis

The gamma sensitivity index is a measure of the relative importance of an input variable to the estimated probability of failure in reliability-based analysis. It is calculated as the partial derivative of the probability of failure with respect to the standard deviation of the input variable. Higher gamma values indicate greater sensitivity, highlighting variables that significantly contribute to the variability in the probability of failure.

The gamma sensitivity index, denoted by γ_i, measures the relative importance of an input variable x_i in influencing the system's probability of failure, P_f. It can be calculated using the following formula:

$$\gamma_i = \frac{\partial P_f}{\partial x_i} \tag{12}$$

where $\partial P_f/\partial x_i$ represents the partial derivative of the probability of failure with respect to the input variable x_i.

In the context of Monte Carlo simulation, the gamma sensitivity index can be approximated using the following expression:

$$\gamma_i = \frac{P_{f(x_i+\Delta x_i)} - P_{f(x_i)}}{\Delta x_i} \tag{13}$$

where x_i is the standard deviation of the input variable x_i, Δx_i is a small perturbation in x_i, and $Pf(x_i)$ and $Pf(x_i + \Delta x_i)$ represent the probabilities of failure calculated using Monte Carlo simulations with the original and perturbed input variables, respectively.

Results and discussion

Sensitivity analysis

The result of the gamma sensitivity index study is presented in Fig. 3 which displays the gamma sensitivity index of thickness of pavement layers and their modulus of elasticity. The gamma sensitivity index study found that the modulus of elasticity of the granular layer has the highest gamma sensitivity index (0.33), followed by the modulus of elasticity of the bituminous layer (0.29), the modulus of elasticity of the stabilised mine tailings subgrade (0.28), the thickness of the bituminous layer (0.23) and the thickness of the granular layer (0.07).

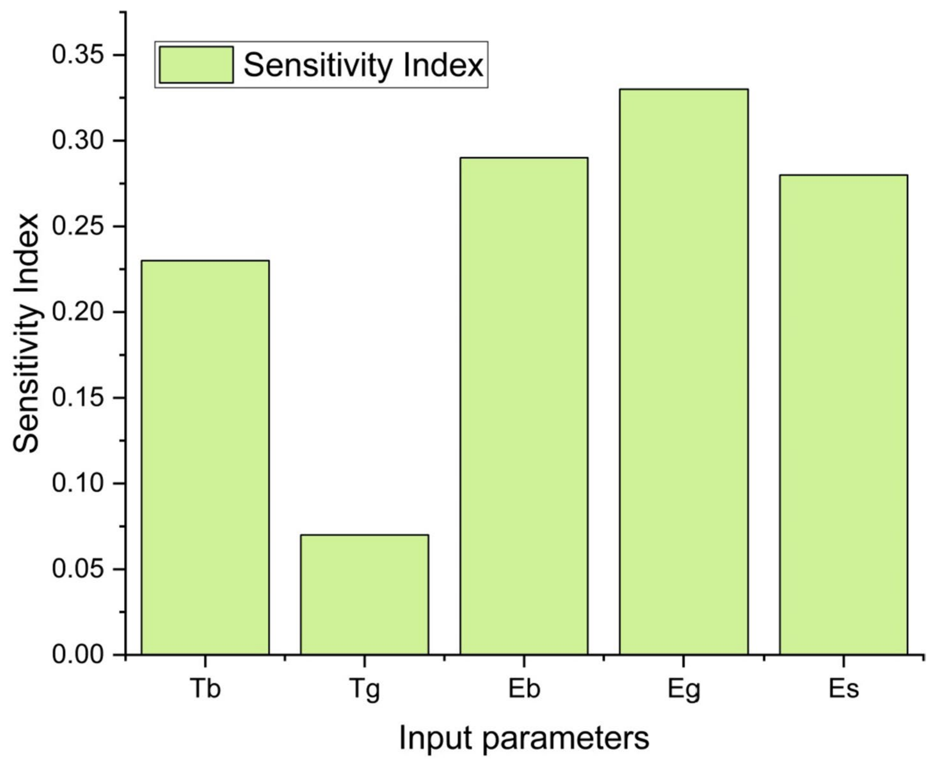

Fig. 3 Gamma sensitivity index of various design parameters

The results of the gamma sensitivity index study indicate that the modulus of elasticity of the granular layer and the modulus of elasticity of the bituminous layer are the most important input variables in the finite element model of the three-layered flexible pavement system. This means that changes in these two input variables will have the greatest impact on the predicted pavement deflection, vertical compressive stress and tensile strain. The thickness of the bituminous layer and the thickness of the granular layer are also important input variables, but they have a smaller impact on the predicted pavement responses than the modulus of elasticity of the granular layer and the modulus of elasticity of the bituminous layer.

The modulus of elasticity of the stabilised mine tailings subgrade has the least impact on the predicted pavement responses. This is because the stabilised mine tailings subgrade is a relatively stiff material, and changes in its modulus of elasticity will not have a large effect on the behaviour of the pavement system.

The gamma sensitivity index study provides valuable insights into the relative importance of the input variables in the finite element model of the three-layered flexible pavement system. These insights can be used to prioritise input variables for data collection and to focus design efforts on the most critical factors.

Reliability of pavements

This section provides an illustrative example of the developed reliability-oriented design of cemented MMT pavement based on the inputs presented in Table 1. The target reliability and expected traffic were first assumed based on the design code. The pavement

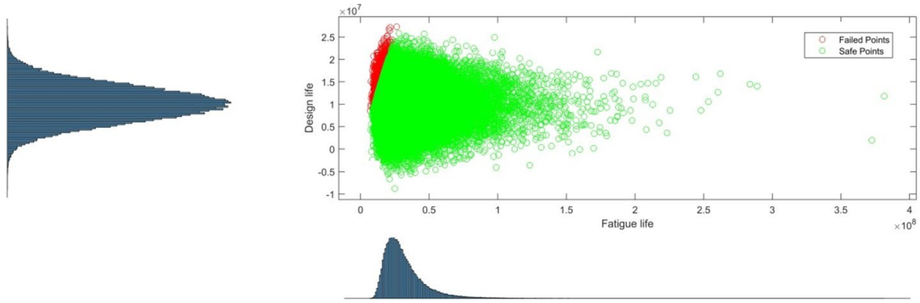

Fig. 4 Monte Carlo simulation of fatigue criteria of cemented MMT pavement

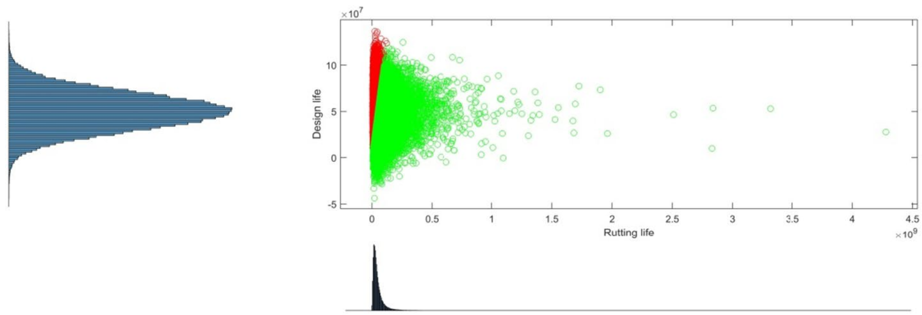

Fig. 5 Monte Carlo simulation of rutting criteria of cemented MMT pavement

was designed based on trial and error method. The limiting and designed load cycles were computed using the developed RSM equation, and the reliability of the particular section against the induced fatigue and rutting strains was calculated using MCS. The pavement section meeting the reliability limits would further be considered for cost optimisation.

Figures 4 and 5 show the fatigue failure pattern and rutting failure pattern of cemented MMT pavement obtained from Monte Carlo simulation respectively. In the case of fatigue failure, the distribution of the number of cumulative standard axles followed a log-normal distribution. This distribution accurately represents the variability and uncertainty associated with fatigue failure in pavements. Fatigue failure occurs when the demand for the total number of standard axles exceeds the permissible number. The reliability analysis revealed that the reliability of cemented MMT pavement in terms of fatigue criterion was 97.44%. This high reliability indicates that the pavement is expected to perform well under fatigue-loading conditions.

On the other hand, rutting failure was found to have a nonparametric distribution. Similar to fatigue failure, the demand for the total number of standard axles exceeding the permissible number leads to rutting failure. The reliability analysis demonstrated that the cemented MMT pavement had a reliability of 96.27% in terms of the rutting criterion. This high reliability suggests that the pavement is expected to resist rutting and maintain its structural integrity under the specified design traffic loads.

It is worth noting that the distribution of traffic demand, in terms of the total number of standard axles, followed a normal distribution. This distribution assumption aligns well with previous investigations in the field of pavement engineering [8, 25]. By considering the statistical properties of traffic demand, the reliability analysis provides a comprehensive evaluation of the pavement's performance and its ability to withstand traffic loading.

The higher design traffic and reliability of cemented MMT pavements can be attributed to their superior characteristics, particularly their higher soaked CBR values. The higher CBR values indicate a stronger and more stable subgrade, which contributes to enhanced pavement performance and durability. The use of cement-treated MMT as a subgrade material offers several advantages, including the safe disposal of tailings generated from magnesite extraction and reduced demand for natural aggregates.

Influence of traffic demand on reliability

The influence of traffic demand on the reliability of cemented MMT pavement is a critical aspect examined in this study. While a mean traffic demand of 30 million standard axle repetitions (msa) was considered, it is important to acknowledge that inherent uncertainties exist in estimating traffic demand, including factors like initial traffic estimates, variations in traffic growth rates, and other unpredictable factors. Therefore, the reliability of the pavement was evaluated by raising the mean traffic demand from 20 to 45 msa to assess its performance under different traffic scenarios.

Figure 6 illustrates the variation in the reliability of cemented MMT pavement with respect to design traffic demand. The results show that the reliability of the cemented MMT pavement decreases as traffic demand increases. At a mean traffic demand of 20

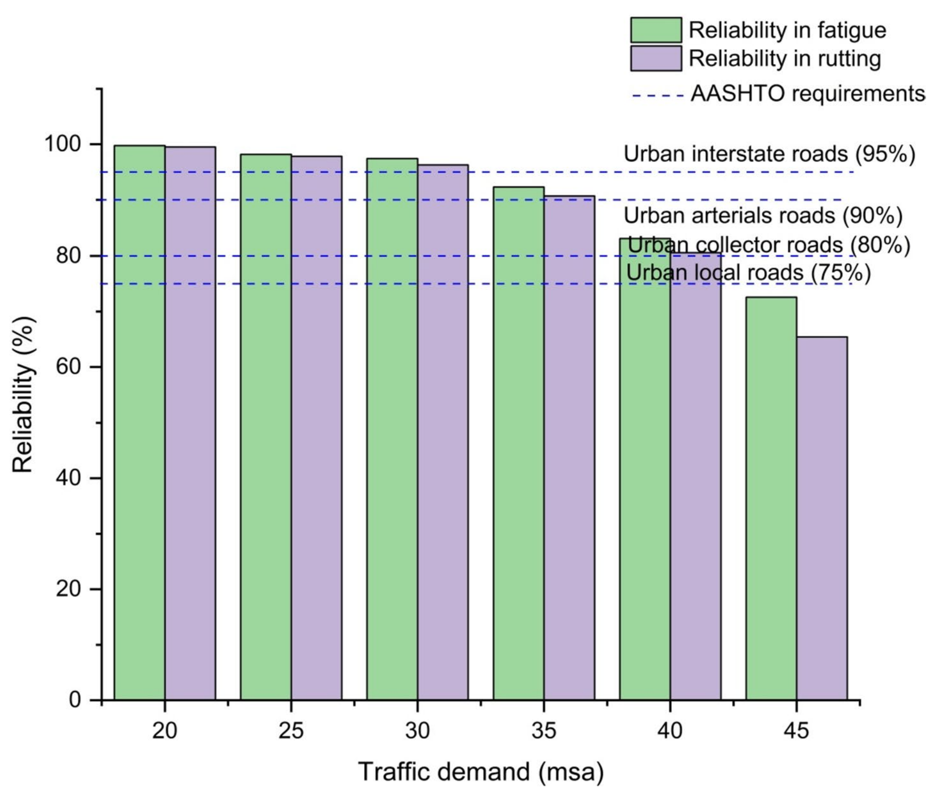

Fig. 6 Influence of traffic demand on the reliability of cemented MMT pavement

msa, the reliability in fatigue is 99.78%, and the reliability in rutting is 99.52%. However, at a mean traffic demand of 45 msa, the reliability in fatigue decreases to 72.58%, and the reliability in rutting decreases to 65.43%. As the design traffic demand reached 45 msa, the reliability of the pavement decreased significantly, falling below the threshold set by the AASHTO [26] guidelines.

The AASHTO guidelines provide recommendations and standards for pavement design, ensuring the safety and reliability of road infrastructure. According to these guidelines, the cemented MMT pavement can accommodate a maximum traffic demand of 40 msa when used for collector roads. This means that the pavement can adequately handle traffic loads within this limit while maintaining the required reliability levels. However, for applications on interstate and arterial roads, the design traffic should not exceed 30 msa to ensure the desired reliability. Similarly, IRC specifications [19] offer guidelines for pavement design in India. According to these specifications, the cemented MMT pavement can be utilised on expressways, national highways, state highways, and urban roads for a design traffic demand of 30 msa. This suggests that the pavement meets the reliability requirements and can be effectively employed in these road categories.

The findings of this study emphasise the significance of incorporating traffic demand uncertainties into the design and maintenance of cemented MMT pavements. By accounting for the potential for higher traffic volumes, pavements can be engineered to withstand increased stress and strain, extending their service life and reducing the likelihood of premature failure.

Limitations

Despite its advancements, this study has limitations that need consideration. Primarily, there is a lack of validation against field data, undermining the real-world applicability of the proposed methodologies. Simplifications and assumptions, like constant parameters and limited scope, may compromise the accuracy and generalizability of the findings. Moreover, uncertainties in estimating traffic demand introduce potential inaccuracies. Addressing these limitations through field validation, broader scope investigations and improved modelling techniques would enhance the reliability and applicability of the outcomes of the study.

Conclusions

This study proposed a reliability-based MEM design methodology for the pavement with a cemented MMT subgrade. The rutting and fatigue strains were considered failure modes. The MCS technique was employed to compute reliability. The proposed method was demonstrated using a case study. The important findings of the study are summarised as follows.

- A new RSM model based on the FEA was developed to determine fatigue and rutting strains when cemented MMT was utilised as a subgrade.
- The sensitivity analysis showed that the modulus of elasticity of the granular layer and the modulus of elasticity of the bituminous layer are the most important input variables.

- The traffic demand for the cemented MMT pavement follows a normal distribution, while fatigue traffic displays a log-normal distribution and rutting traffic exhibits a nonparametric distribution.
- The reliability analysis reveals that the cemented MMT pavement achieves high reliabilities of 97.44% and 96.27% for fatigue and rutting criteria, respectively, under a design traffic load of 30 msa. These results demonstrate the ability of the pavement to withstand significant traffic loads while maintaining satisfactory performance levels.
- According to the guidelines set by the AASHTO, the cemented MMT pavement is suitable for use as interstate and arterial roads, considering the design traffic load of 30 msa. This indicates its potential for accommodating heavy traffic volumes and providing reliable transportation infrastructure.
- In accordance with the specifications provided by the IRC, the cemented MMT pavement can be utilised for expressways, national highways, state highways, and urban roads, all falling under the design traffic load of 30 msa.

The outcomes of this study can be employed to ascertain the fatigue and rutting load-carrying capacity of bituminous pavements constructed with cemented MMT subgrade, enabling an evaluation of their performance levels. This study is anticipated to contribute to the selection of target reliability analysis methodologies tailored to the properties of specific pavement sections. Consequently, the methodology developed in this study can be integrated into MEM.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
BIS	Bureau of Indian Standards
CBR	California bearing ratio
FORM	First-order reliability method
IRC	Indian Roads Congress
MCS	Monte Carlo simulation
MEM	Mechanistic-empirical methods
msa	Million standard axle
OPC	Ordinary Portland Cement
RSM	Response surface method
SORM	Second-order reliability method
UCS	Unconfined compressive strength

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Authors' contributions
VS, conceptualization, methodology, investigation and writing—original and revised draft. BS, resources, supervision and project administration and writing—original and revised draft. PK, investigation and writing—original and revised draft. MTS, investigation and writing—original and revised draft. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests

The authors declare that they have no competing interests.

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