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The influence of CBR value on the cost of optimal flexible pavement design.

La influencia del valor CBR en el costo del diseño óptimo de pavimento flexible.

Venkatesh Baskaran[1], Subash Raj C.[2], Subbu Sankar V.R.[2] & Blessy K.[2]

Assistant Professor, Department of Civil Engineering, Government College of Engineering, Tirunelveli, INDIA, email: venkatesh@gcetly.ac.in

Undergraduate Student, Department of Civil Engineering, Government College of Engineering, Tirunelveli, INDIA

ABSTRACT

Road transport would be arteries for the economy pulse. As a developing nation, India focuses on connecting all parts of the country through this road network. Flexible pavement is generally preferred for the road with low to medium traffic conditions. The flexible pavement design depends on the CBR of subgrade soil and design traffic for the selected road specified in IRC 37-2018. The study is limited to the road link at Tirunelveli City paved with a bituminous surface course with a granular base and sub-base between South Bypass road Junction near New bus stand – NH 44 service road intersection. Effective subgrade CBR value considered from 9% to 15% in the study area. The traffic volume detail and vehicle classification were collected with the help of an automatic vehicle classifier called MetroCount. The design starts with selecting a trial profile by considering CBR and MSA from the appropriate catalog. The stress and strain were estimated at critical locations of pavement by performing Structural Analysis in IITPAVE software. The optimal design is achieved by altering the layer thickness to minimize the gap between actual and allowable strain. An increase in CBR value decreases the thickness of the functional layer of pavement. Cost estimation has arrived from rate analysis for various work items as per IRC specification and schedule of rates. Similar studies were identified in evaluating the construction cost corresponding to different design methods. This study concluded that improvement in 1 % CBR saves about 1 to 2% of overall construction cost in optimal design.

Keyword-- CBR (California bearing ratio); MSA (Million standard axles); Optimal flexible pavement; IITPAVE; MetroCount

RESUMEN

El transporte por carretera serían las arterias del pulso económico. Como nación en desarrollo, India se enfoca en conectar todas las partes del país a través de esta red de carreteras. Por lo general, se prefiere el pavimento flexible para carreteras con condiciones de tráfico medio o bajo. El diseño de pavimento flexible depende del CBR del suelo de la subrasante y del tráfico de diseño para la carretera seleccionada especificada en el IRC 37-2018. El estudio se limita al enlace de la carretera en la ciudad de Tirunelveli pavimentado con un curso de superficie bituminosa con una base y subbase granular entre el cruce de la carretera de circunvalación sur cerca de la parada de autobús Nueva - la intersección de la carretera de servicio NH 44. Valor de CBR de subrasante efectivo considerado de 9% a 15% en el área de estudio. El detalle del volumen de tráfico y la clasificación de vehículos se recopilaron con la ayuda de un clasificador automático de vehículos llamado MetroCount. El diseño comienza con la selección de un perfil de prueba considerando CBR y MSA del catálogo apropiado. La tensión y la deformación se estimaron en ubicaciones críticas del pavimento mediante la realización de un análisis estructural en el software IITPAVE. El diseño óptimo se logra alterando el grosor de la capa para minimizar el espacio entre la deformación real y la permitida. Un aumento en el valor de CBR disminuye el espesor de la capa funcional de pavimento. La estimación de costos proviene del análisis de tarifas para varios elementos de trabajo según la especificación del IRC y el programa de tarifas. Se identificaron estudios similares al evaluar el costo de construcción correspondiente a diferentes métodos de diseño. Este estudio concluyó que la mejora en el 1% de CBR ahorra entre el 1 y el 2% del costo total de construcción en un diseño óptimo.

Palabra clave: CBR (relación de rodamiento de California); MSA (millones de ejes estándar); Pavimento flexible óptimo; IITPAVE; MetroCount

INTRODUCTION

For a country to fit into a developed status, it needs to provide various infrastructure facilities to its citizens. India has attained significant growth in infrastructure development through private and public investments. The well-planned transportation system plays a vital role in economic, social, and regional development. The cost-effective provision of infrastructure is achieved through increased private participation and technological innovation [1]. The transportation facilities such as roads, rail, port, and airports hold the country's economic momentum by connecting people and sharing goods and services through proper channels. These public utilities open up a new investment opportunity even in the rural regions [2]. Transport infrastructure promotes economic activities among various regions, which results in increased productivity and better utilization of resources [3].

The majority of road network in India is flexible pavement because of its less initial cost and local climatic conditions. Nevertheless, huge investments take part in the construction and maintenance of pavement. As the Indian sub-continent yet reaches the saturated level in transport infrastructure, the expenditure is predicted to increase yearly. Identifying proper design techniques will reduce the construction and maintenance cost of pavement [4]. The selection of techniques is generally governed by cost as well as structural capacity. A mathematical programming model can be used to minimize the cost of flexible pavement [5]. The available methods for flexible pavement design are analytical, semi-analytical, and empirical methods (based on practical experience of design engineer). However, the pavement thickness from these methods is varying widely with cost. Therefore, a standard design method called the mechanistic-empirical method, a combination of analytical and semi-analytical, is adopted by various countries [6].

The design of thickness of functional layers in the flexible pavement is confirmed as per IRC:37-2018—the guidelines deal with six categories of pavement. A granular base and sub-base with bituminous surface course pavement are considered for the study. The sectional thickness is decided based on a catalog with traffic in MSA (million standard axles) read against CBR (California Bearing Ratio) from 5% to 15%. Rutting and fatigue cracks are two distresses that are considered in this study. The critical design factors respectively for rutting and fatigue cracking are a vertical compressive strain on top of the subgrade and a horizontal tensile strain at the bottom of the bituminous layers. Environmental factors affect flexible pavement performance, especially bituminous layers (bituminous macadam and dense bituminous mix) [7]. Both durability and structural stability should be taken into account while doing the optimization process. The designer should opt for an optimal design with minimum cost without compromising reliability. A mechanistic-empirical approach is a quick and simplified optimization process to formulate cost and safe pavement design curves [8].

Optimization technique exected with the logical scientific flow which results in maximum utilization of material capacity, increase in productivity and decrease in capital investment, labor force turnover and completion period [9]. The popular optimization method adopted for engineering problems is linear programming, mixed-integer linear programming, non-linear programming, and dynamic programming [10]. Enough pavement cost optimization research has been conducted for light to denser traffic with poor and good subgrade soil combinations. Pavement designed with AI (Artificial Intelligence) technique can obtain the most cost-effective dimension for heavy and very heavy traffic with poor subgrade soil. The resisting capacity of subgrade soil highly influences the optimal design [6].

The mechanistic-empirical design approach for new flexible pavement has taken various factors into account. IRC suggests the trial layer thickness catalog by considering 90% reliability subgrade rutting and fatigue cracking. The functional layer thickness in the series of the catalogues varies only with traffic in MSA and subgrade CBR. In this study, the term optimization refers to designing the pavement with a minimum and adequate thickness for GSB (Granular Sub-base), WMM (Wet Mix Macadam), Binder or Base course, and surface course, which leads to savings in construction capital cost [11]. The opportunity for reducing the thickness of pavement by lowering traffic volume through any traffic management system is not under the scope of the study. Hence, the study focuses only on determining the cost of optimally designed flexible pavement concerning change in CBR value.

Not all existing subgrade soil is sufficient to withstand the desired traffic loads from the pavement. Soil stabilization methods like chemical and mechanical stabilization enhance the shear strength and bearing capacity of problematic strata. Replacing poor subgrade soil with the combination of any coarse or fine particles may not always be an economical solution [12]. The soil generally comprises various engineering properties, but the one widely used for dimensioning the flexible pavement is CBR. The bearing capacity of any strata can be directly related to its density or unit weight. A study concluded that CBR positively correlated with maximum dry density (R^2 = 77.2%) [13].

Flexible pavement tends to experience the traffic with repetition of axle load throughout its design period. The resilient modulus is defined as the maximum cyclic stress per unit recoverable resilient strain during one repeated dynamic loading cycle [14]. In addition to selecting trial dimensions for pavement, CBR indirectly helps in perform linear elastic analysis to measure deformation. As determining the resilient modulus of soil in the laboratory is quite expensive as per AASHTO T307-99, IRC suggested an empirical relation to determining resilient modulus with CBR value. A stretch that is aligned for pavement construction will not contain a similar kind of subgrade soil characteristics. During such conditions, 90th percentile subgrade CBR value needs to be adopted to design high-volume roads [15]. Again, investigating the variation of CBR value throughout the stretches does not come under the study's scope.

The life cycle cost assessment for pavement should be an effective method to derive optimal pavement dimensions by considering construction and maintenance. The up-gradation process in the rural part of the country increases the demand for transportation development units. The demand force the governing bodies to make a considerable investment. The total cost of flexible pavement includes initial construction cost, routine maintenance cost, periodic maintenance cost, and rehabilitation cost. The cost-benefit analysis is a perfect tool for carefully evaluating alternatives in design strategies and replacing pavement materials with their function throughout the design period [16]. A previous study has obtained the total cost pavement function in a convex shape, infers that the cost increases with overdesign and underdesigned pavement [4]. The cost savings through optimal design ensure sustainable pavement mechanism through minimal pavement construction materials [17]. For example, in a bituminous mixture, 80 to 85% of the volume is contributed by aggregates, the most abundant pavement material. The field measurement of traffic volume and the structural model to determine the optimal thickness of the functional layer are described in the methodology section.

MATERIAL AND METHODS

STUDY AREA: The investigation was performed at a stretch of Major District Road linking Palayamkottai (busiest region zone of Tirunelveli City Municipal corporation) with NH44 (Srinagar – Kanyakumari Highways). The contribution to the traffic volume on this road is by the commuters from Tirunelveli city to Kanyakumari through the mentioned national highways. In addition, the goods and service transport and allied vehicles are prominently using this stretch. This link allows such vehicles to deliver the service within the city and route back to the NH. The location of our study link, which starts with 77°43'38.7"E, 8°41'51.1"N and ends at 77°42'52.7"E, 8°39'34.2"N is clearly shown in Fig.1.

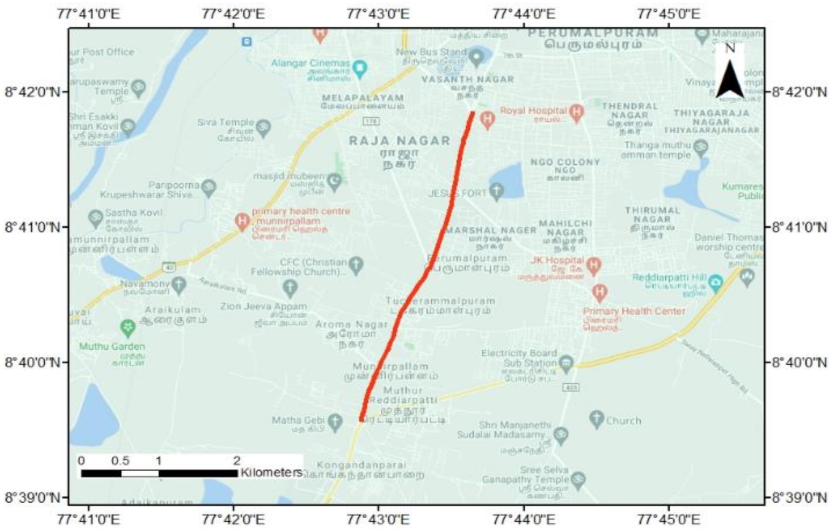


Fig. 1. Geographical location of the study area

As the traffic volume in MSA and CBR are prime data required for flexible pavement design, the work proceeds with a traffic study. Various elements need to be considered for estimating the cumulative number of axles equivalent to 80 kN single axle with dual wheels passed over the road. The inputs required to determine the design traffic for the desired design period are as follows

a) Number of initial commercial vehicles per day after the completion of road construction
b) The design life of road in years

c) The average growth rate of traffic during the design life of a pavement
d) The spectrum of axle loads
e) Estimated lateral distribution factor of commercial traffic over the carriageway

TRAFFIC VOLUME STUDY: The traffic volume determines the number and classification of the vehicle travelled through a specific point and time. Manual, automatic, and semi-automatic are the various ways to conduct a traffic study. Counting errors and classification errors are significant problems in the manual method[18]. The advancement in technology reduces the processing time between the collection of data and interpretations of results. Such a widespread, advanced, and reliable setup for traffic study are piezoelectric sensors, pneumatic road tubes, acoustic detector, and magnetic sensors. The traffic volume study for the considered road has been carried out by the MetroCount instrument (automatic traffic counter cum classifier), which uses pneumatic tube techniques. Microscopic information (time headway, speed statistics) and macroscopic information (total count, vehicle classification) can be extracted in the form of charts or tables [19], [20]. Conducting traffic surveys for about one month at four locations in the stretch provided us with CVPD. Since the road is occupied with a minimum heavy vehicle, the VDF value was confirmed with Table 4.2 (Indicative VDF value) from IRC:37-2018. The installed MetroCount set for our study area is shown in Fig.2.

Fig. 2. Installed MetroCount unit for the Traffic study

STRUCTURAL MODEL: The advanced analytical tool is used for accurate pavement design and evaluation of pavement [21]. Structural analysis of assumed linear elastic pavement layered system assesses stress, strain, and deformation within the system. The adjustment of functional layer thickness depends on the result of the layered analysis enacting the optimal pavement design [22]. IITPAVE is an updated version of the FPAVE software proposed by MoRTH to analyze the pavement for our study. The number of layers, thickness layer, and corresponding elastic moduli are inputs for the software [15]. This structural model assumes standard axle load as 80kN and uniform contact pressure as 0.56

MPa. It helps us quickly identify overdesigned pavement systems by navigating the dominant gap between permissible and allowable strain [23].

COST ESTIMATION: The previous structural analysis step results in the optimally designed flexible pavement with CBR variation between 9% to 15%. Estimating the construction cost of pavements with different CBR will be the ultimate objective of the study. Important items of work are identified for pavement completion to derive total cost. Working out rate analysis gives the cost for each work item, including material cost, labor cost, overhead charge, and contractor's profit. Due to their maximum contribution to the total cost of pavement, the construction of GSB, WMM, DBM, BC, and providing prime coat and tack coat are considered as major work items [24].

RESULT AND DISCUSSION

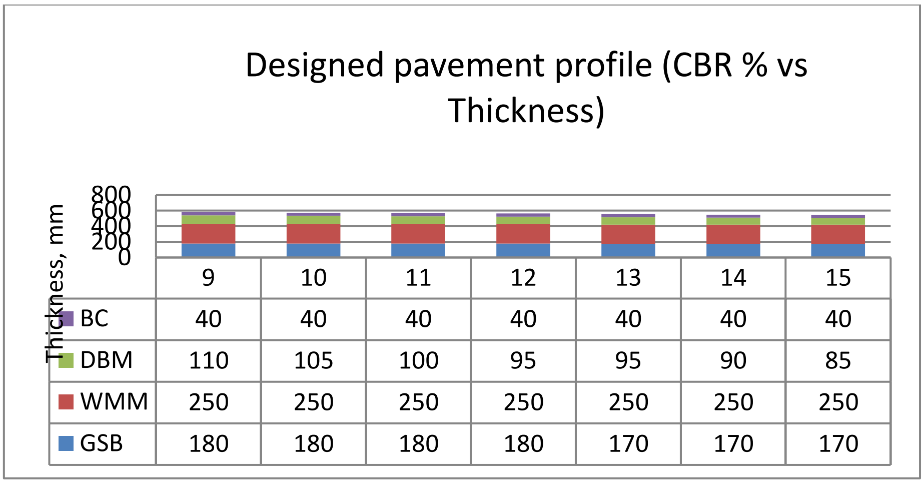
The design traffic for the study road in terms of the cumulative number of a standard axle is calculated using the expression

$$N_{Des} = \frac{365[(1+r)^n - 1]}{r} \, A \times D \times F \qquad (1)$$

Here, A is initial traffic in cvpd during the completion of a road, r is the annual growth rate of commercial vehicles, n is the design period in years, D is lateral distribution factor, and F is vehicle damage factor.

Through the traffic survey by the MetroCount vehicle classifier system, the number of commercial vehicles that passed the road per day is identified as 3080. The design life and growth rate corresponds to the urban road is 15 years and 6%. This two-lane two-way road of 14.5 meters wide takes the distribution factor as 0.5 as per standard. Since the vehicle damage factor study is tedious, we confirmed it with the indicative VDF value of 5.0. All these data together into the above expression gives design traffic as 49.06 msa. For design purposes, the cumulative axle load in millions is rounded to 50.

The field CBR test was conducted in the desired location in the stretch of the study area to determine the minimum value [25]. The minimum CBR value identified was 9% which corresponds to 2.5 mm penetration. Performing structural analysis by considering the pavement system as an elastic layer, the optimized depth has arrived for different CBR values between 9% to 15%. The chart shown in Fig. 3 displays the designed pavement thickness for CBR values.



	9	10	11	12	13	14	15
BC	40	40	40	40	40	40	40
DBM	110	105	100	95	95	90	85
WMM	250	250	250	250	250	250	250
GSB	180	180	180	180	170	170	170

Fig. 3. Variation in the thickness of pavement system with CBR value (9% to 15%)

Sub-base has the prior responsibility to protect the lower subgrade from overstressing and facilitate drainage and filter layers. The surface course thickness cannot significantly influence the tensile strength of the subbase of the asphalt-based flexural pavement system [26]. In addition to the thickness, the primary factors that affect the surface course's mechanical properties are base modulus and subgrade modulus [27]. Considering the functional requirement of GSB, the thickness of the layer should not be less than 150 mm. Similarly, the minimum thickness of the granular base course (WMM) expecting traffic greater than 2 MSA should be 250 mm [28]. The arrived overall thickness of optimized pavement varies from 580 mm (CBR – 9 %) to 545 mm (CBR – 15 %). All over the world, the overall depth of asphalt pavement varies from 280 mm to 1600 mm [29].

The cost for the construction of each layer plays a vital role in optimization. The rate analysis for listed items of works was derived based on the standard schedule of rates by PWD[30]. The arrived unit rates are listed below,

- GSB - Rs. 1350.84 per cubic meter
- WMM - Rs. 1635.10 per cubic meter
- DBM - Rs. 6209.46 per cubic meter
- BC - Rs. 6669.43 per cubic meter
- Prime Coat - Rs. 50.39 per square meter
- Tack Coat - Rs. 10.92 per square meter

IITPAVE takes GSB and WMM as one layer and DBM and BC as another layer. So while optimizing the gap between allowable strain and strain estimated by the software, the functional layer thickness was altered by taking cost into account. As the cost of DBM work is approximately 4.5 times higher than the cost of WMM work, modification of the DBM layer is preferred over GSB [8], [31]. The key steps involved in obtaining the efficient thickness through comparing strain on the CBR value 12% is briefly explained below,

Design Traffic = 50 MSA (rounded off) ; CBR = 12 %, Thickness (mm): GSB = 180, WMM=250, DBM=95, BC=40

Resilient Modulus:

Resilient Modulus of the subgrade, M_{RS} $= 17.6 * (CBR)^{0.64}$ (for CBR > 5 %) (2)

$= 17.6 * (12)^{0.64} = 86.34$ MPa

Resilient Modulus of GSB layer, M_{RGRAN} = 0.2(h)0.45* $M_{RSUPPORT}$ (3)

= 264 Mpa

Resilient Modulus for Bituminous layer = 3000 Mpa (as per Table 9.1 of IRC:37-2018)

Fatigue cracking criteria for bituminous layer:

Fatigue life of bituminous layer, N_f $= 0.5161*C*10^{-04} [1/\varepsilon_t]^{3.89}* [1/M_{Rm}]^{0.854}$ (4)

(for 90% reliability)

substituting suitable values, $1/\varepsilon t$ = 5586.34941

ε_t $= 179.01x10^{-06}$ (allowable tensile strain)

Subgrade rutting criteria:

Subgrade rutting life, N_R $= 1.4100 \times 10^{-08} [1/\varepsilon_v]^{4.5337}$ (5)

(for 90% reliability)

substituting suitable values, $1/\varepsilon_v$ = 2679.14768

ε_t $= 373.25x10^{-06}$ (allowable vertical strain)

Comparison of allowable strain with actual strain by IITPAVE:

Allowable tensile strain at the bottom of bituminous layers = 179 με

Actual tensile strain at the bottom of bituminous layer (from IITPAVE) = 179 με

Allowable vertical compressive strain at the top of subgrade = 373 με

Actual vertical compressive strain at the top of subgrade (from IITPAVE) = 281 με

Hence, the design is safe and optimized. The display screen of input and output of IITPAVE software for the analysis of pavement system belongs to CBR 12%, shown in Fig. 4 and Fig.5, respectively.

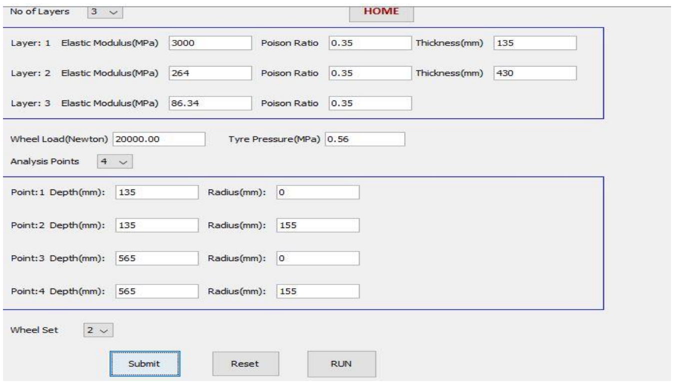


Fig. 4. Data input screen of IITPAVE software for pavement system modeled for CBR 12%

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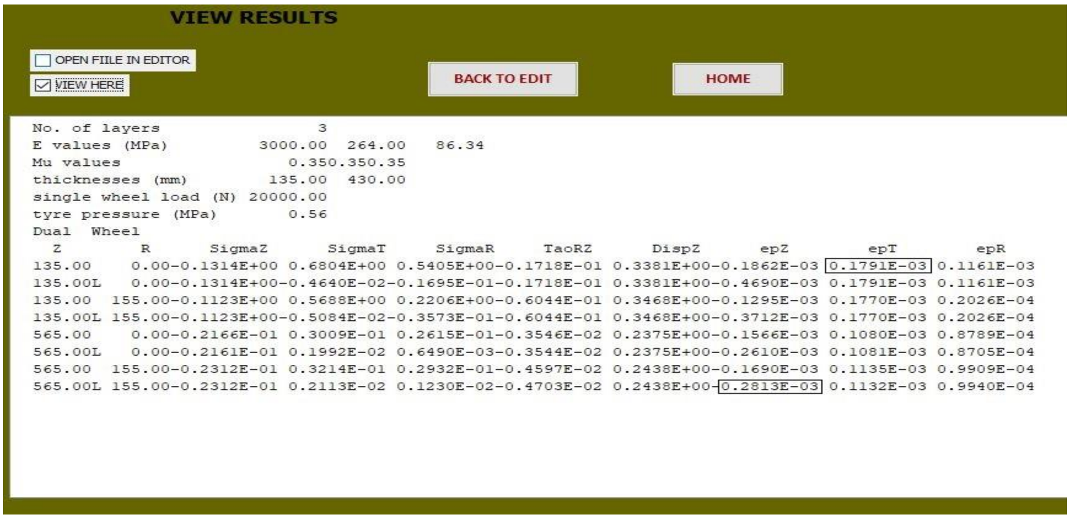

Fig. 5. Output screen of IITPAVE software for pavement system modeled for CBR 12%

Similarly, the design is obtained for CBR from 9% to 15% for a further cost comparison. The below table depicts the strain value for all our designed pavement systems.

TABLE I COMPARISON OF ALLOWABLE AND ACTUAL STRAIN WITH EFFECTIVE CBR VALUE

CBR	Tensile strain @ bottom of bituminous layer		Vertical compressive strain @ top of the subgrade	
	Allowable (micron)	Actual by IITPAVE (micron)	Allowable (micron)	Actual by IITPAVE (micron)
9%	179	178	373	301
10%	179	178	373	293
11%	179	178	373	287
12%	179	179	373	281
13%	179	176	373	277
14%	179	177	373	274
15%	179	179	373	271

The closer value in the tensile strains at the bottom of bituminous layers and compressive strains at the top of the subgrade for all CBR values disclose that the design is effective and neither overdesign nor under design [32].

The cost for construction of each layer is worked out on a volume basis, but the cost for providing coats between two layers is calculated with an area basis. The known three dimensions (length, breadth, and thickness) of pavement gave the total volume of the work and followed by multiplying the volume with appropriate unit cost, which arrived through rate analysis earlier result in a cost to be spent for pavement layer construction. Furthermore, the total cost was derived for all the so far designed pavement systems by quantity estimation. The consolidated cost for the pavement construction and decrease in cost per km and its percentage savings are displayed in Table II below.

TABLE II ABSTRACT OF PAVEMENT COST INFLUENCE ON CBR VALUE

CBR (%)	Total Cost of designed Pavement	Cost to be spent per km (L = 4.70 km)	Decrease in cost as compared to lower CBR	% decrease in cost per % CBR improvement
9	₹ 11,33,34,404	₹ 2,41,13,703.0	-	-
10	₹ 11,12,18,531	₹ 2,36,63,517.2	₹ 4,50,186	1.87
11	₹ 10,91,02,657	₹ 2,32,13,331.3	₹ 4,50,186	1.90
12	₹ 10,69,86,784	₹ 2,27,63,145.5	₹ 4,50,186	1.94
13	₹ 10,60,66,186	₹ 2,25,67,273.7	₹ 1,95,872	0.86
14	₹ 10,39,50,313	₹ 2,21,17,087.8	₹ 4,50,186	1.99
15	₹ 10,18,34,439	₹ 2,16,66,902.0	₹ 4,50,186	2.04

The average decrease in cost per kilometer for each CBR value is Rs. 4,07,800/-. The prominent savings of about 2% of project cost takes place from 14% to 15%. The average power value is near 1.70% in terms of cost-saving per kilometer in percentage. As we have rounded the thickness of DBM in fives and GSB in tens, no defined pattern is identified in the decrease in cost. The CBR value fits linearly with the cost of pavement for R^2 = 0.994. An appreciable effort to increase the effective CBR value of subgrade may result in substantial investment savings [33]. The equivalent thickness of pavement cross-section is reduced with the excellent performance of subgrade[34]. The cost-benefit analysis and cost trade-off between improvement of CBR and cost of pavement could be the best go with option. The reinforced or treated subgrade saves around 10% of construction cost[35]. A minimal change in CBR subsequently affects resilient modulus, thickness, and savings in cost and pavement material[36]. In addition to the project's cost, the various natural resource-saving opportunity was spotted in the study. Once the thickness and materials characteristics are satisfied, more attention should be paid to improving the traditional design principles and other environmental conditions [29].

As conclusion, the importance of transportation infrastructure for the country's development was discussed in the initial part of this work. As colossal government and private investments are flowing in the market, the proper planning and utilization of resources is a prerequisite. In the past decades, improving asphalt pavement capability by increasing layer thickness and material properties was mainly focused. Investigation of variation cost of pavement system to the decider by natural condition was formulated as our study's objective. Initially, the traffic volume study was conducted with the help of MetroCount setup in the considered stretch of 4.70 kilometers to estimate MSA value. CBR of soil subgrade was taken as the only variable for the optimized design of flexible pavement. The result shows clear evidence that an increase in CBR value shrinks the thickness requirement of pavement. Improvement in subgrade CBR value directly influences resilient modulus, which reduces pavement thickness and cost without compromising the structural requirement. A maximum of 2% cost saving is witnessed from the estimation of layer analysis of the pavement model. The result confirms paving of an additional 2 kilometers for every 100 kilometers at the same expenditure through an optimal design. Considering sustainability, this kind of optimization study is going to be the fundamental process for all infrastructure projects. In addition to the design, the cost-effectiveness at different levels of construction and maintenance latch the scope on better road networks even in remote rural areas.

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