Determination of Compacted Subgrade Thickness on Weak Subgrade using Odemark's Method Based on Mechanistic- Empirical Design Approach

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Abstract. Subgrade in flexible pavement is considered as the foundation of pavement structure. Improvement in subgrade stiffness in terms of California Bearing Ratio (CBR) is done by placing suitable thickness of compacted subgrade with higher CBR. Such increase in subgrade CBR reduces the total pavement thickness and increases the durability of pavement against rutting failure. Present paper deals with formulation of a methodology for determination of suitable thickness of compacted subgrade on the top of weak natural subgrade using mechanistic-empirical design approach. In this paper, the allowable vertical stress on top of compacted subgrade has been determined from the CBR - depth relationship corresponding to axle load and tyre pressure developed by Yoder and Witczak. Moreover, the vertical compressive strain on the top of the natural subgrade has been determined from the rutting criteria as recommended in IRC-37:2018. The two layered system with compacted subgrade with higher CBR on weak natural subgrade with lower CBR has been transformed in this paper in to a homogenous system by Odemark's method to use the formulations of mechanistic approach. The thickness of compacted subgrade thus has been back calculated so that the layered system can withstand the design load repetitions by limiting the vertical compressive strain on the top of natural subgrade. It has been found that, appropriate thickness of compacted subgrade is necessary to achieve the specified CBR when placed over the weak natural subgrade for specified axle load repetitions. Such layer thickness significantly varies with the ratio of elastic modulus in a two layered system. In this backdrop, the concept of effective CBR as recommended in IRC:37-2018 and the provision of SP:72-2015 specification for adopting a fixed thickness of compacted subgrade in low volume rural road need to be revisited.

Keywords: Compacted Subgrade, Odemark's Method, Rutting, Compressive Strain, CBR.

1 Introduction

The failure of bituminous road pavement is largely guided by the failure criteria of rutting on pavement surface, which can be compared as foundation failure of a structure. The weakness in any of the constituent layers in a flexible pavement increases the vertical stress and strain on the top of natural subgrade, which acts as foundation of the pavement structure. Therefore, the strength of subgrade is of utmost importance to make the road pavement durable. Hence for construction of new road, subgrade improvement has become a major issue in its design stage. The most popular method of strengthening of subgrade is to place suitable type of soil from borrow pit on the top of natural subgrade and to compact it with required target density and depth. The depth of compacted subgrade, thus prepared, primarily increases the durability of road against rutting and on the other hand the increased CBR of compacted subgrade reduces the requirement of pavement layer thickness, thereby reducing the project cost. In present paper a mechanistic-empirical approach has been used to determine the thickness of compacted subgrade on the top of natural subgrade.

2 Literature Review

Nataatmadja et al [1] proposed a methodology to obtain the effective design subgrade CBR using Odemark's [2] transformation method, both with and without a correction factor in a multi-layered elastic system. Biswas et al [3] formulated a methodology for determination of suitable thickness of compacted subgrade on the top of natural subgrade using mechanistic-empirical design approach with stress-based design criteria. The findings of the study correlate the compacted subgrade thickness corresponding to specified axle load repetitions on weak subgrade. Tarefder et al [4] studied a weak subgrade with a wide variation in strength and stiffness to evaluate its influence on pavement design and performance. Putri et al [5] presented model to determine the threshold stress on sub grade and thereby determined the thickness of pavement by limiting plastic deformation simultaneously. The design method is evaluated by observing the performance of an actual formation under repeated load applications. IRC:37-2018 [6], an Indian guideline for design of bituminous road pavement, recommends at least 500 mm thickness as compacted sub grade on the top of weak natural subgrade. But the guideline does not recommend any correlation with axle load repetition and thickness of the compacted sub grade. Reddy et al [7] examined the issue of selecting effective material properties, CBR or modulus value, for the combination of embankment soil and sub grade layer. The finding suggests equivalent CBR value for different types of embankment soil and the sub grade layer using layer elastic theory based on equal sub grade deflection. Ministry of Rural Development (MORD) [8] specification for rural roads has defined the subgrade as top 300mm portion of embankment just beneath the pavement crust without any variation of subgrade thickness with load repetitions.

3 Objective

The failure of natural subgrade is characterized by the vertical compressive strain on the top of the subgrade corresponding to standard axle load repetitions. Therefore, thickness of the compacted subgrade should be selected with such an approach so that it can protect the failure of natural subgrade under rutting from anticipated axle load repetitions on pavement. In this context, attempts are made in this paper to establish correlation between compacted layer thickness with strength of natural subgrade and anticipated axle load repetitions using mechanistic empirical approach.

4 Proposed Model

In the present analysis compacted subgrade with higher CBR and natural subgrade with lower CBR has been considered as a two layered as shown in Fig.1 The elastic modulus of both natural and compacted subgrade may be estimated from the relationship developed by Powell et al [9] as given in Equation 1 and 2.

$E = 10CBR$ in (MPa) if CBR ≤ 5 (1)

$E = 17.6\ CBR^{0.64}$ in (MPa) if CBR >5 (2)

In this paper, permissible stress (σ_f) on the top of compacted subgrade has been obtained using the CBR-depth correlation of flexible pavement developed by Yoder-Witczak [10] as shown in Equation 3.

$\sigma_f = 0.025\ CBR$ (3)

Where σ_f = permissible stress on subgrade in MPa

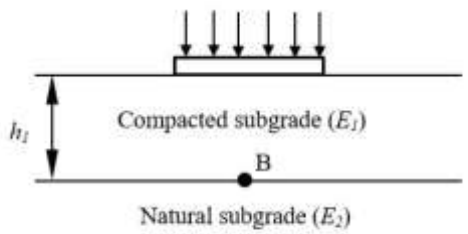

Fig. 1. Two layered system with natural and compacted subgrade.

The permissible stress thus obtained from Equation 3 has been assumed to act on the top of the compacted subgrade in the form of a circular flexible uniformly distributed load with same diameter as that of the loaded area at surface, for which the vertical compressive strain on the top of the natural subgrade has been determined using theory of elasticity as proposed by Boussinesq's [11] and shown in Equation 4. The strain thus calculated on the top of natural subgrade should be less or equal to the allowable vertical compressive strain to protect the pavement failure under rutting mode. Therefore, to limit the vertical strain on natural subgrade with comparatively lower elastic modulus (E_2), compacted subgrade would require appropriate thickness with higher elastic modulus (E_1) for required dissipation of stress up to layer interface, in a two layered system.

$$\epsilon_v = \frac{(1+v)q}{E}\left[\frac{\frac{z}{a}}{\left\{\sqrt{1+\left(\frac{z}{a}\right)^2}\right\}^3} - (1-2v)\left\{\frac{\frac{z}{a}}{\sqrt{1+\left(\frac{z}{a}\right)^2}} - 1\right\}\right] \quad (4)$$

However, the permissible vertical compressive strain on natural subgrade corresponding to specified standard axle load repetitions may be obtained from Equation 5, which may be used in Equation 4 to find the out the required depth of soil in a homogeneous system.

$$N = 1.41 * 10^{-8} * \left(\frac{1}{\epsilon_v}\right)^{4.5337} \quad (5)$$

After determination of the soil depth which is required in a homogeneous system to limit the vertical compressive strain on top of natural subgrade by solving Equation 4 transformation of such depth has been made in a two layered system by using Equation 7 based on Odemark's method.

4.1 Odemark's Method for Transformation of Layered System

The assumptions made by Odemark for transformation of a two-layer system to a homogeneous system include that the stress or strain below a layer depend on the stiffness of that layer only. If the thickness (h_1), Poisson's ratio (μ) and modulus of a layer (E) are changed but the stiffness remains unchanged, the stress, strain below the layer should also remain unchanged. According to Odemark, a two layered system can be transformed into an equivalent thickness of a homogenous layer as shown in Fig.2 and explained by Equation 6.Using the formulation of Odemark, the two layered system as shown in Fig.1 can be transformed into a homogeneous system with an elastic modulus (E_2) , where the equivalent thickness of the transformed section has been expressed by Equation 6.

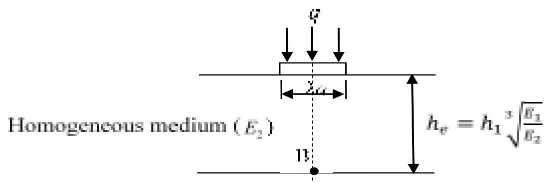

Fig. 2. Transformation of a layered system by Odemark's Approach.

Considering the Poisson's ratio of top and bottom layer as same in a two-layer system, equivalent thickness of the homogenous layer may be expressed as

$$h_e = f h_1 \sqrt[3]{\frac{E_1}{E_2}} \quad (6)$$

where, 'f' is the Odemark's correction factor for layer interface and depends on the characteristics of constituent layers. Its value usually ranges between 0.8 - 1.0. In present paper, the value of 'f' has been considered as 1.0 in numerical analysis as both the layers under consideration in a two-layer system is subgrade soil with different elastic modulus.

Therefore, in order to determine the transformed depth with compacted subgrade in a two layered system Equation 7 may be used.

$$h_1 = \left(z * \sqrt[3]{\frac{E_2}{E_1}}\right) \quad (7)$$

In the present analysis, the natural CBR of weak subgrade has been considered between 2% to 4.0%, whereas the compacted subgrade CBR has been considered from 8.0% to 15%.

5 Result and Discussion

The methodology proposed in this paper can be designated as an analytical approach of soil improvement technique. The thickness of compacted subgrade has been so designed that target CBR can be achieved on top of the weak natural subgrade and below the granular subbase layer. The range of CBR of compacted subgrade chosen in the present analysis between 8% to 15%.

The thickness of compacted subgrade thus obtained corresponding to different natural subgrade and for different axle load repetitions are presented in Table 1 to Table 3. It is relevant to note that, as the failure of natural subgrade in terms of vertical strain is related to axle load repetitions on pavement, similarly the stability of the compacted subgrade should also be related to the same axle load repetitions. In this context, analysis has been made in the present paper to establish correlation between thickness of compacted subgrade and axle load repetitions when placed over weak subgrade. The results obtained from analytical study show that the thickness of compacted subgrade reduces if the CBR of natural subgrade increases for a specific axle load repetition and vice versa. The reason of such result is obvious since the increased strength of natural CBR as foundation of the pavement would require less thickness of compacted subgrade for a specified axle load repetitions.

Moreover, the thickness of compacted subgrade was found to increase with the increase in axle load repetitions if the CBR of natural and compacted subgrade remain constant. It is relevant to note that the rate of change of thickness becomes significant up to a load repetition of 50 msa, beyond which the rate of change of compacted subgrade thickness becomes less. It is relevant to mention that the variation in compacted subgrade thickness due to change in load repetitions from 2 msa to 150 msa was found to vary between 65% to 70% for the natural subgrade with CBR ranging between 2% to 4%. Therefore, the effect of axle load repetitions on failure of compacted subgrade has to be understood in terms of failure of pavement under rutting. It is evident from the results obtained in this paper that for higher volume of axle load, the requirement of compacted subgrade thickness would be higher and vice versa. Ministry of Rural Development (MORD) specification for rural roads has defined the subgrade as top 300mm portion of embankment just beneath the pavement crust. Similarly, IRC:37-2018, the guidelines for the design of Flexible pavements in India recommends the thickness of compacted layer of subgrade as 500 mm immediately below the bottom of the pavement structure as a measure of subgrade improvement if the natural subgrade is weak in terms of its CBR. In this backdrop, the findings of the present study reveal that a constant thickness of compacted subgrade as recommended in IRC:37-2018 or in MORD specification either will be under designed or over designed, resulting unsafe or uneconomic pavement from rutting failure.

Moreover, the guideline also recommends a new concept to find out an effective CBR of subgrade when compacted subgrade with standard thickness is placed on the natural subgrade to design the pavement thickness based on effective CBR thus obtained. The findings of the present analysis reveal that adopting a fixed and standard thickness of compacted subgrade on the top of natural subgrade is not a scientific approach. Such selection of a fixed thickness of compacted subgrade may either lead to under designed or over designed section by changing the effective CBR of subgrade resulting unsafe or uneconomic pavement. The results obtained from present study show the required thickness of compacted subgrade as recommended in IRC:SP-72-2015 [12] is substantially less than the thickness obtained using present analytical approach, which in other way emphasizes the recommendation of guideline as unsafe in terms of compacted subgrade thickness. For future scope of work, the concept of effective CBR as recommended in IRC:37-2018 may be redefined with variation in compacted subgrade thickness with axle load repetitions and the CBR of natural subgrade.

Table 1. Compacted subgrade thickness on natural subgrade with 2% CBR for different axle load repetitions.

Natural Subgrade (2% CBR)				
Axle load (msa)	Compacted subgrade CBR			
	8%	10%	12%	15%
2	386	415	440	472
10	467	501	531	568
20	507	543	575	615
50	564	604	638	682
100	610	653	690	738
150	639	684	722	772

Table 2. Compacted subgrade thickness on natural subgrade with 3 % CBR for different axle load repetitions.

Axle load (msa)	Natural Subgrade (3% CBR) Compacted subgrade CBR			
	8%	10%	12%	15%
2	352	381	405	436
10	430	463	491	527
20	467	503	532	570
50	521	560	592	634
100	566	606	641	686
150	592	635	671	718

Table 3. Compacted subgrade thickness on natural subgrade with 4% CBR for different axle load repetitions.

Axle load (msa)	Natural Subgrade (4% CBR) Compacted subgrade CBR			
	8%	10%	12%	15%
2	326	356	380	411
10	402	436	463	498
20	439	474	502	540
50	491	528	560	600
100	533	573	607	651
150	560	601	636	682

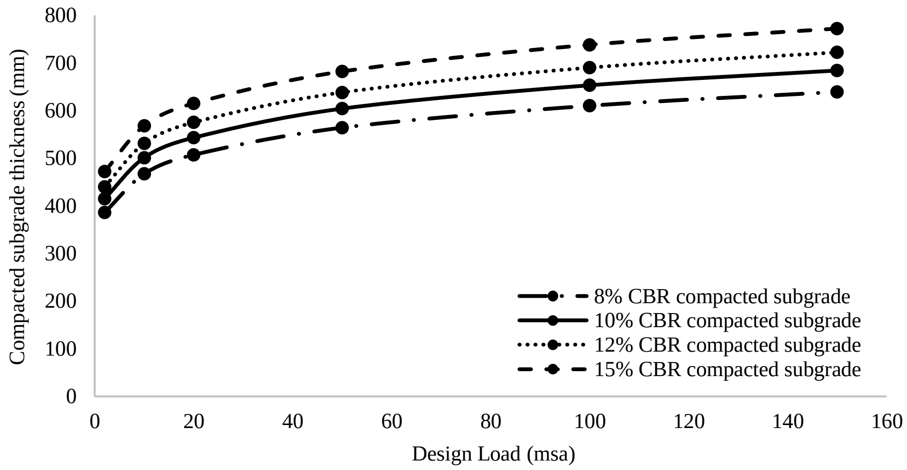

Fig. 3. Variation of compacted subgrade thickness with axle load repetition for 2% CBR of natural subgrade.

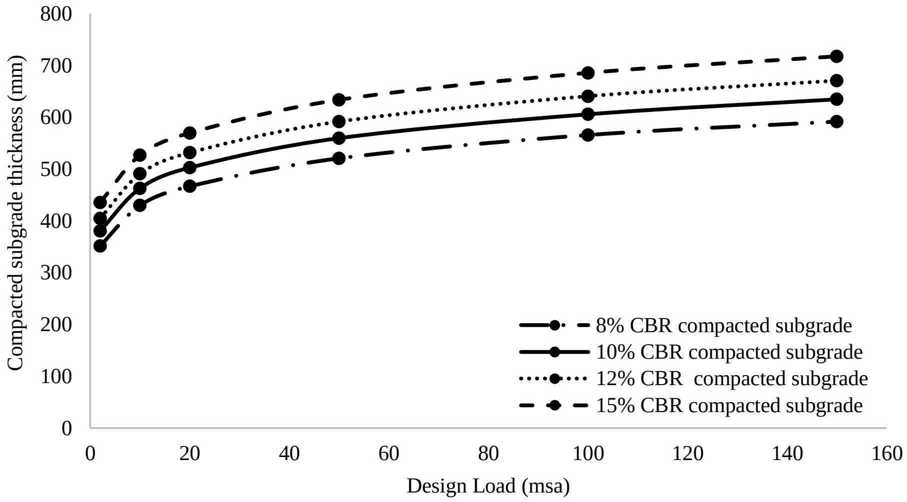

Fig. 4. Variation of compacted subgrade thickness with axle load repetition for 3% CBR of natural subgrade.

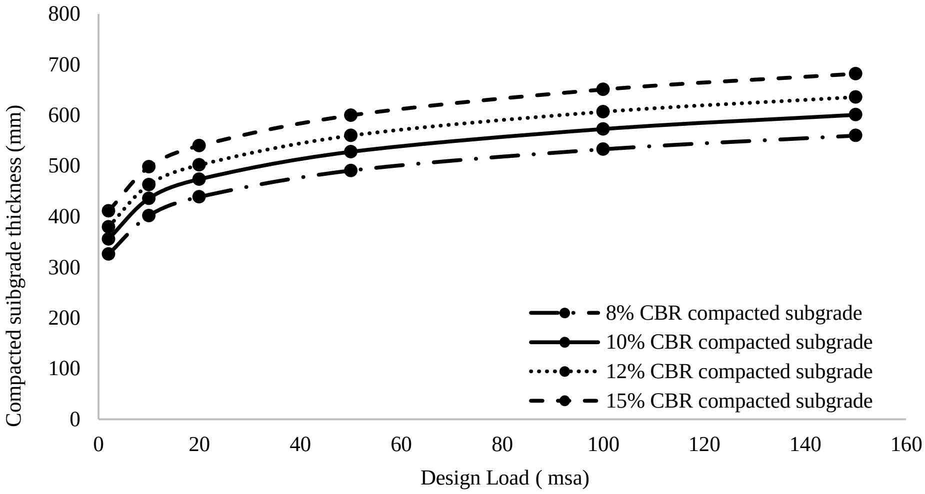

Fig. 5. Variation of compacted subgrade thickness with axle load repetition for 4% CBR of natural subgrade.

6 Conclusions

The mechanistic empirical approach used in present analytical study may be used to determine the compacted subgrades thickness on the top of a weak natural subgrade as a measure of ground improvement for specified axle load repetitions. It has been found that the requirement of compacted subgrade increases with the increase in axle load and decrease in strength of natural subgrade .It has been found in present study that the variation in compacted subgrade thickness due to change in load repetitions from 2 msa to 150 msa ranged between 65% to 70% corresponding to the natural subgrade with CBR between 2% to 4%. It has also been found that consideration of a constant thickness of compacted subgrade as recommended in IRC:37-2018 or in MORD specification will result either an under designed or over designed section, resulting unsafe or uneconomic pavement in terms of rutting failure. Present analytical approach may be used to find out the effective CBR of subgrade when natural subgrade has been strengthened by adding compacted subgrade in pavement section.

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