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Original Article

Determination of Compacted Subgrade Thickness to Achieve An Effective CBR Based on Subgrade Deflection Using Odemark's Method

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Abstract *- Improvement of the natural subgrade often involves reinforcing weak underlying ground by adding a compacted subgrade layer. The resulting combined structure, where the compacted subgrade overlays the natural subgrade, determines its strength through the effective CBR (California Bearing Ratio). This paper estimates the effective CBR of the soil subgrade in a two-layered system by employing Odemark's theory for transforming layers and Boussinesq's method to calculate deflection in distinct layers. Assuming a uniform medium with an elastic modulus to represent the two-layered system, such that it yields an equivalent deflection across both subgrade layers, the transformed homogeneous section's modulus is utilized to estimate the effective CBR. The outcomes obtained using this approach are compared with results from the ELAYER program. The close alignment between the findings from both methods validates the credibility and acceptance of the proposed technique.*

Keywords *- Boussinesq's, Odemark's, Compacted subgrade, CBR, Subgrade deflection.*

1. Introduction

The approach to pavement design is conceptually dynamic and is changing with the advancement of knowledge in construction material, methodology, and equipment. The empirical approach of pavement design has been adjusted in association with the mechanical approach to evolve the Mechanistic–Empirical approach, which is now widely practiced worldwide. The basic mechanism of thickness design is based on limiting the stress, strain, and deflection of constituent paving layers. Such layers are arranged in order of decreasing magnitude of elastic modulus from top to bottom. The subgrade is the foundation of the pavement structure. Therefore, the stability of the pavement structure largely depends on the foundation's performance on which it is supposed to transfer the load to the soil.

Improvement of the subgrade is qualitatively different from improving the strength of other paving layers. The paving layers include a granular base and sub-base, binder base, and wearing course, frequently strengthened by adding additional overlay thickness. However, once the pavement is laid on the subgrade, supporting it during its service life becomes challenging.

The most frequent type of failure in bituminous pavement failure is rutting caused by failure of soft subgrade. However, rutting may also be caused by the failure of the binder base due to higher axle load with increased tyre pressure. The repair to prevent rutting by rut-resistant bituminous layer is done, but that is expensive in terms of pavement life cycle cost. Therefore, it is essential to study the type and strength of the natural subgrade and to decide upon the strengthening measures at the initial stage of construction.

The most widely used method in this context is to put compacted subgrade with adequate thickness to achieve a better strength of composite subgrade with a stiffer layer on top, followed by the soft natural subgrade. The strength of the subgrade needs to be increased to withstand excessive deflection of the granular sub-base to cause pavement deterioration under static and dynamic stresses generated by traffic.

The better the strength of the subgrade, the greater the requirement for pavement crust, which results in savings in the cost of construction. Keeping this in mind, the engineers have already explored the improvement of natural subgrade by various techniques including soil stabilization by adding different additives, admixtures and fibers, geotextiles, use of sand drains, etc., and frequently used in highway construction. The guidelines for designing flexible pavements in India have also recommended using a compacted subgrade layer on top of a weak natural subgrade to increase subgrade strength and reduce pavement thickness.

2. Study Objectives

The objective of the present paper is to formulate a mechanistic-empirical approach for estimating compacted subgrade thickness on the top of the natural subgrade to improve subgrade strength to resist pavement failure under rutting. A two-layered system has been considered with a compacted subgrade made with borrowed soil on top followed by the natural subgrade at the bottom to fulfill the objective. The design thickness of compacted subgrade in such a layered system has been estimated based on the deflection of two layers determined using Boussinesq's approach after the transformation of the layered system by Odemark's method.

3. Methodology

This paper has considered a two-layered system to determine the compacted subgrade thickness based on layer deflection, as shown in Figure 1. The top layer in such a system consists of a compacted subgrade made with better-quality soil collected from a borrow pit, which rests on the natural subgrade. The present methodology of bituminous pavement design advocates using effective CBR of subgrade when compacted subgrade is used for strength improvement of natural subgrade.

Thus, the effective CBR to be used to estimate pavement thickness needs to be determined suitably, which characterizes the strength of two different layers of subgrade in a multi-layered pavement system. Against this backdrop, this paper has proposed estimating the deflection of compacted and natural subgrade for a standard wheel load. However, to determine the deflection of compacted and natural subgrade using (Boussinesq's 1885) equation, it is necessary to transform the two-layered system into a homogeneous layer using Odemark's (N. Odemark,1949; Valle, P. D et al. 2018., Subagio, B.2005; El-Badawy et al 2011) method, which has been illustrated below.

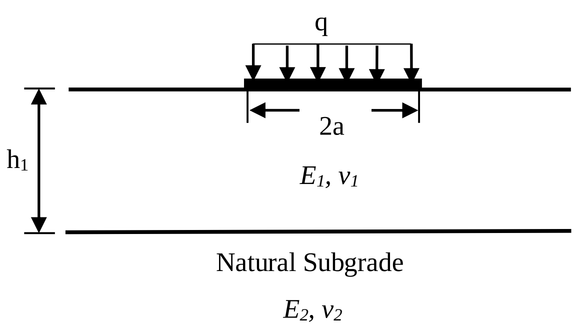

Fig. 1 Two-layer system with compacted subgrade over the natural subgrade

4. Odemark's Method

This approach involves converting a two-layered system comprising a top layer with a modulus (E_1) and thickness (h_1) and Poisson's ratio (ν_1), resting upon a bottom layer with a modulus (E_2) and Poisson ratio (ν_2), can be represented by an equivalent thickness (h_e) as depicted in Equation 1.

$$h_e = fh_1 \sqrt[3]{\frac{E_1(1-\upsilon_2{}^2)}{E_2(1-\upsilon_1{}^2)}} \quad (1)$$

Where, f is the Odemark's correction factor, which depends on the type of layer interface and varies between 0.8-1.0. However, in the present analysis, the value of Odemark's correction factor has been considered as 0.9. If the Poison's ratios of the layers are assumed to be approximately the same for the two layers under consideration, the equivalent thickness corresponding to the two-layered system may be expressed as,

$$h_e = 0.9 * h_1 \sqrt[3]{\frac{E_1}{E_2}} \quad (2)$$

5. Model for Estimation of Effective Subgrade CBR

The paper explores estimating the thickness of compacted subgrade by employing a two-layered model for mathematical representation. This model consists of a top layer representing the compacted subgrade with a higher resilient modulus, followed by a lower resilient modulus layer representing the natural subgrade. It is crucial to note that the combined modulus of this dual-layered system significantly relies on the individual moduli of each layer within the system and the thickness of the compacted subgrade.

The study assumes that the deflection experienced by both the natural and compacted subgrade layers under a wheel load represents the total subgrade deflection in this two-layered system. To determine the modulus of this composite system, the authors derived an equivalent modulus through the transformation of the two-layered system. This equal modulus corresponds to a homogeneous system that generates subgrade deflection identical to the original layered system.

The deflection at a depth (z) for a circular load of radius: 'a', load intensity 'q', modulus 'E' and Poisson's ratio 'ν' in a homogeneous section may be expressed as shown in Equation 3 (Boussinesq. V.J, 1885; Ullidtz, P., 1998).

This analysis defines the concept of equivalent modulus, termed effective CBR, used for estimating the thickness of the compacted subgrade. To compute the deflection of the compacted subgrade (δ_l), Equation 3 requires the following input parameters.

$$\delta_Z = \frac{(1+\nu)*q*a}{E}\left[2*(1-\nu)-\left(\left(\frac{1}{\sqrt{1+\left(z/a\right)^2}}\right)+(1-2*\nu)*\left(\sqrt{1+\left(z/a\right)^2}-\frac{z}{a}\right)\right)\right] \quad (3)$$

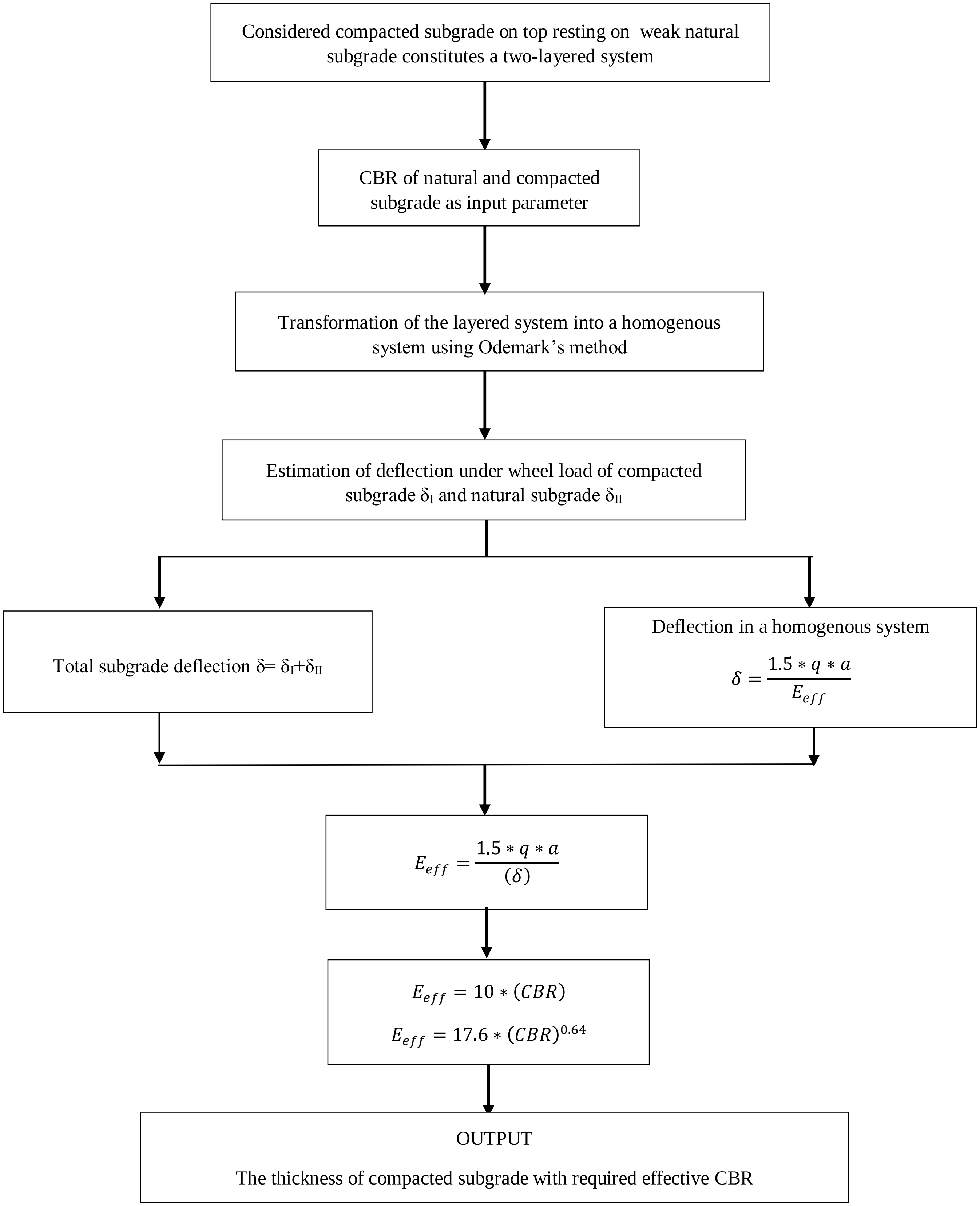

Fig. 2 Flow diagram of deflection-based effective subgrade CBR and compacted subgrade thickness determination

$z = h_{cs}, E = E_{cs}, \nu = 0.40$, a = 150.8 mm for a wheel load of 40 kN with tyre pressure 0.56 Mpa.

Similarly, for estimation of the deflection of natural subgrade (δ_{II}) in a two-layer system, the following input parameters have been used in Equation 3.

$z = h_{eq} = 0.9 * h_{cs} \sqrt[3]{\frac{E_{cs}}{E_{ns}}}$, $E = E_{ns}, \nu = 0.40$, a =150.8 mm for a wheel load of 40 kN with tyre pressure 0.56 Mpa.

The total deflection on the subgrade may be considered a summation of deflection in the compacted and natural subgrade. So total deflection in subgrade may be shown in Equation 4.

$$(\delta) = \delta_I + \delta_{II} \quad (4)$$

It has been considered that the top layer with compacted subgrade with higher CBR with required thickness rests on the natural subgrade, which is semi-infinite with comparatively lower CBR. In such two-layered systems, the equivalent modulus may be obtained from Equation 5. (Burmister, D. M, 1943;)

$$E_{eq} = \frac{2*(1-\nu^2)*q*a}{\delta_I + \delta_{II}} \quad (5)$$

This paper's Effective CBR has been considered the equivalent CBR of two different subgrade layers in a flexible pavement. This paper estimates the effective CBR of subgrade from the equal modulus (E_{eq}) by back calculation using the empirical correlations shown in Equations 6 and 7 (IRC:37-2018).

$$E_{eq} = 17.6*(CBR_{eff})^{0.64} \quad (6)$$

$$E_{eq} = 10*(CBR_{eff}) \quad (7)$$

Where, CBReq = effective CBR of subgrade

The present paper considers the effective CBR as an input parameter for estimating compacted subgrade layer thickness. The other input parameters used in the design are the CBR of compacted and natural subgrade. Therefore, using the present methodology, if the natural CBR of the subgrade is known, the thickness of the compacted subgrade may be estimated, corresponding to a required effective CBR for the pavement design. The flow diagram of the adopted methodology has been shown in Figure 2.

6. Result and Discussion

The effective CBR is an essential parameter for the subgrade characterization when subgrade improvement is made by placing compacted borrowed soil over natural subgrade from the borrow pit. An increase in effective CBR significantly improves the service life of flexible pavement against rutting. Therefore, it is important to study the influence of the factors that may affect the effective CBR as a design parameter.

Moreover, it is also essential to identify the most sensitive factor out of various other factors that may influence a layered subgrade's effective CBR. In the present chapter, the depth of compacted subgrade has been determined using natural subgrade CBR and compacted subgrade CBR as input variables to achieve an effective CBR of compacted subgrade to be made using borrowed soil. The natural subgrade CBR between 2-7% has been considered in the present analysis, whereas the borrowed soil CBR for compacted subgrade has been considered between 7-50%.

In this study, natural subgrade CBR values have been considered in the lower range, which characterizes the strength of comparatively weak subgrade But, the strength of borrowed soil CBR for compacted subgrade has been considered relatively in a higher range, which is needed for strength improvement of weak subgrade. In this context, it is relevant to mention that if the in-situ subgrade CBR is less than 5%, IRC-37-2018 recommends subgrade improvement by placing borrowed soil on top of the weak natural subgrade. In the present analysis, the effective CBR of subgrade has been considered from 5- 15 %.

It is to be noted that the thickness design of bituminous road pavement is now based on the effective CBR of the subgrade when the natural subgrade requires to be strengthened by a compacted subgrade. Variation of the thickness of compacted subgrade with effective CBR obtained from the present analysis using the proposed model has been presented in this paper from Figure 3 to Figure 18. It has been observed that the thickness of compacted subgrade decreases sharply with an increase in the CBR of borrowed soil. However, such rate of change of compacted subgrade thickness varies with the variation in effective CBR, the CBR of borrowed soil, and natural subgrade.

Moreover, such a change in the thickness of the compacted bed becomes significant when the requirement for effective CBR is higher. In this study, effective CBR between 5-10% has been characterized as a lower range, and CBR between 10-15% has been considered a higher range of effective CBR. It has been observed in the present analysis that the rate of change of thickness of compacted subgrade is significant, up to 20% CBR of borrowed materials when effective CBR lies in the lower range. The thickness change of compacted subgrade becomes less significant beyond the threshold of 20% CBR of borrowed materials. However, the same was found to vary significantly up to a CBR of 30%, when effective CBR lies in the higher range.

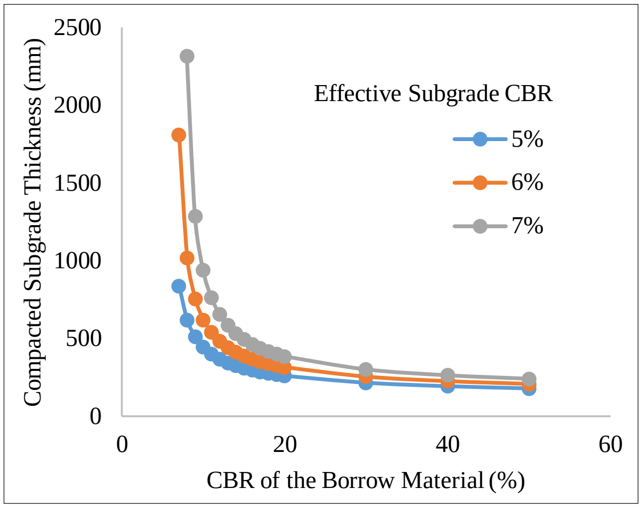

Fig. 3 Variation of the depth of borrow material with different CBR placed on natural subgrade with 2% CBR

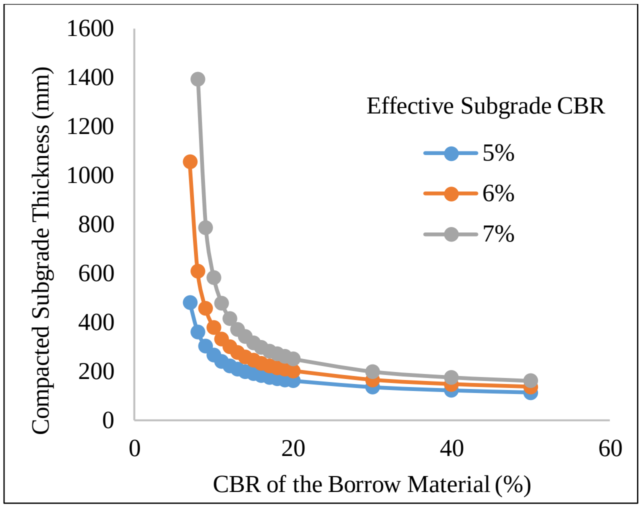

Fig. 6 Variation of the depth of borrow material with different CBR placed on natural subgrade with 3% CBR

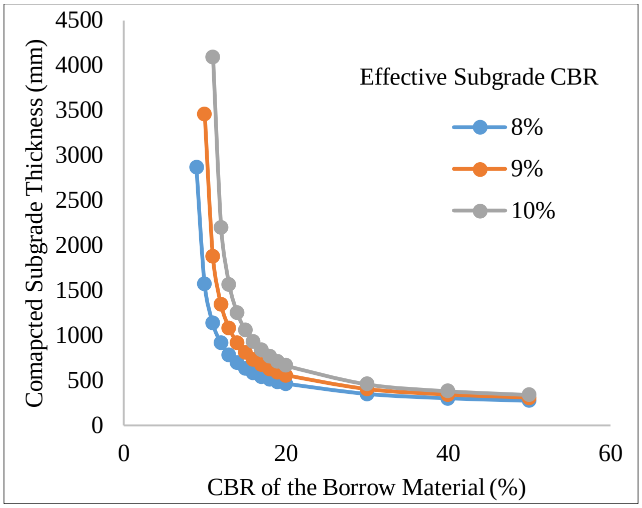

Fig. 4 Variation of the depth of borrow material with different CBR placed on natural subgrade with 2% CBR

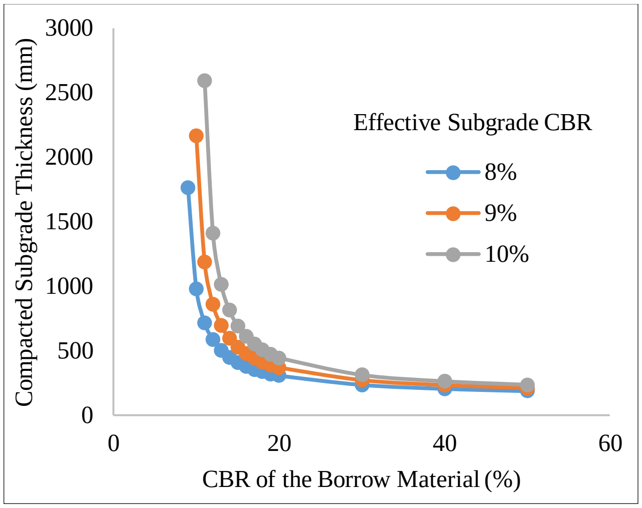

Fig. 7 Variation of the depth of borrow material with different CBR placed on natural subgrade with 3% CBR

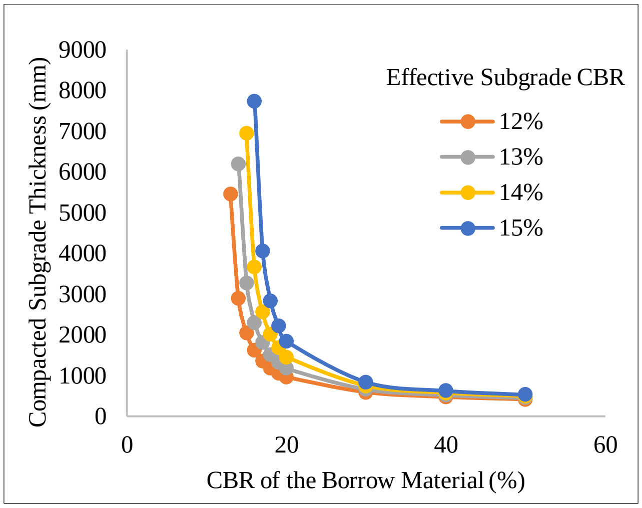

Fig. 5 Variation of the depth of borrow material with different CBR placed on natural subgrade with 2% CBR

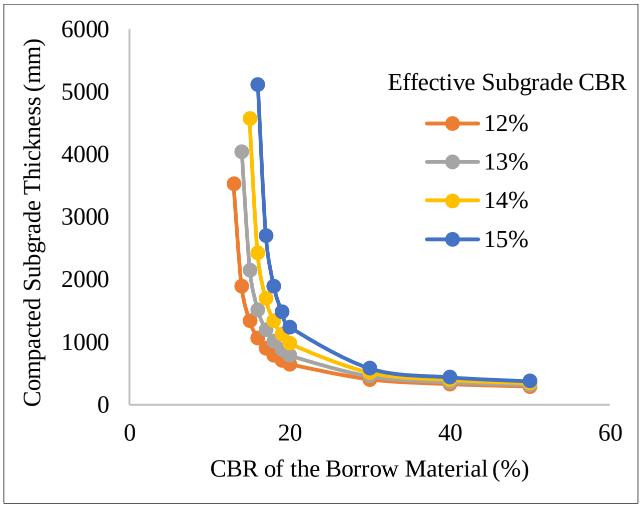

Fig. 8 Variation of the depth of borrow material with different CBR placed on natural subgrade with 3% CBR

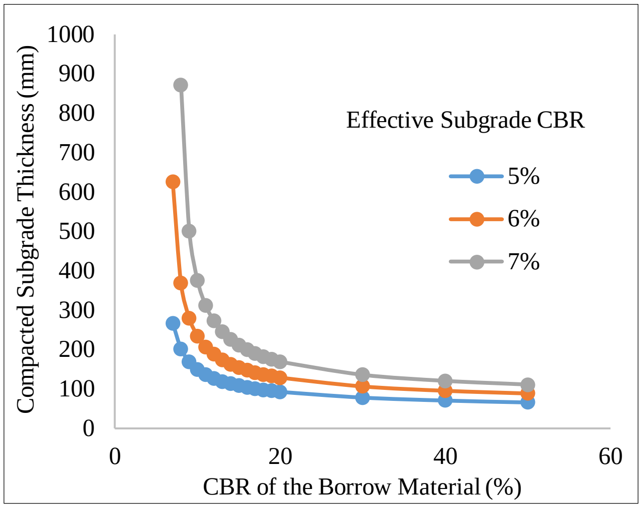

Fig. 9 Variation of the depth of borrow material with different CBR placed on natural subgrade with 4% CBR

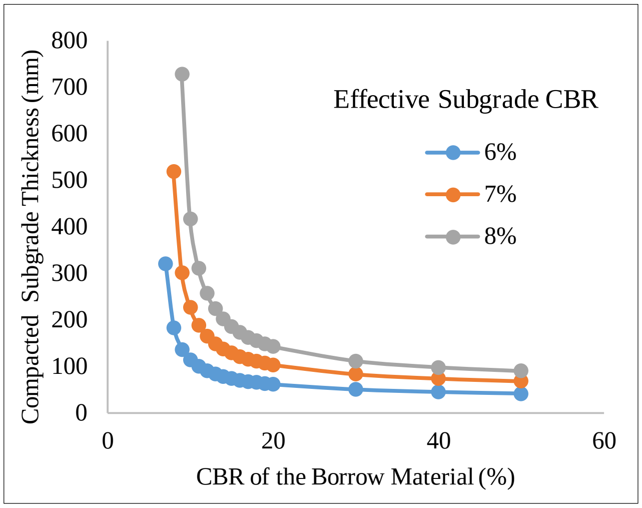

Fig. 12 Variation of the depth of borrow material with different CBR placed on natural subgrade with 5% CBR

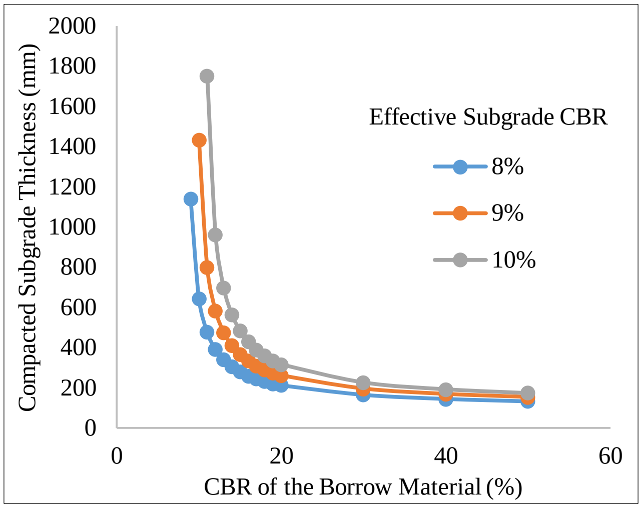

Fig. 10 Variation of the depth of borrow material with different CBR placed on natural subgrade with 4% CBR

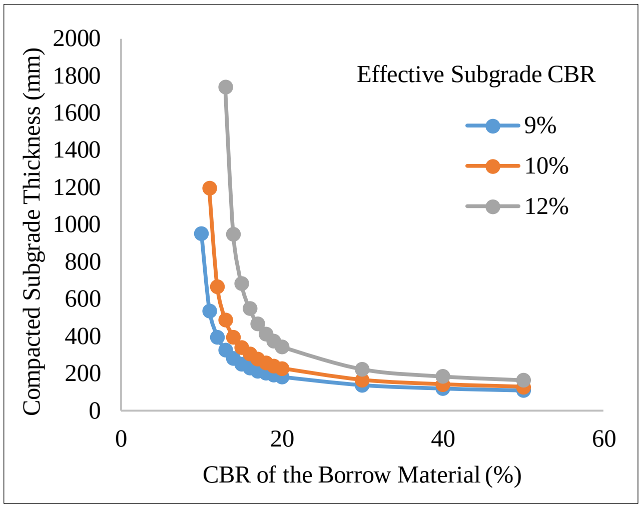

Fig. 13 Variation of the depth of borrow material with different CBR placed on natural subgrade with 5% CBR

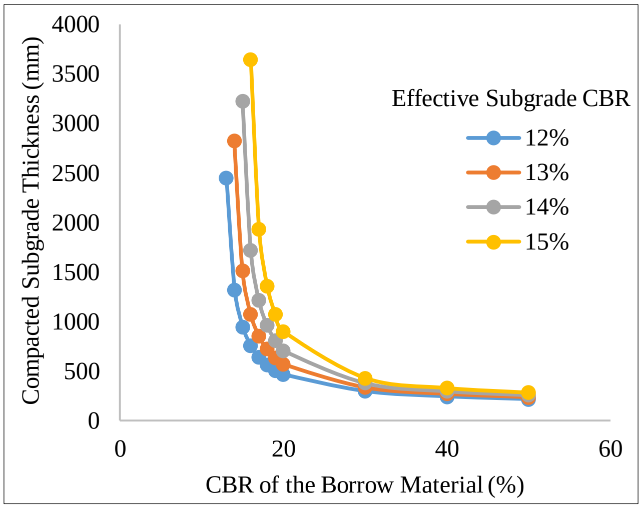

Fig. 11 Variation of the depth of borrow material with different CBR placed on natural subgrade with 4% CBR

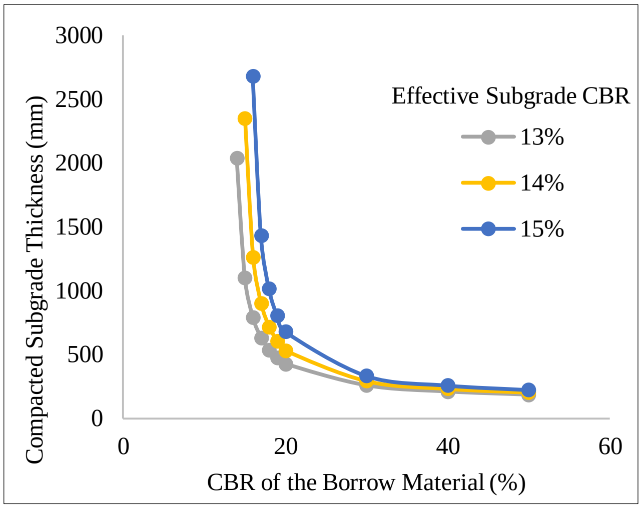

Fig. 14 Variation of the depth of borrow material with different CBR placed on natural subgrade with 5% CBR

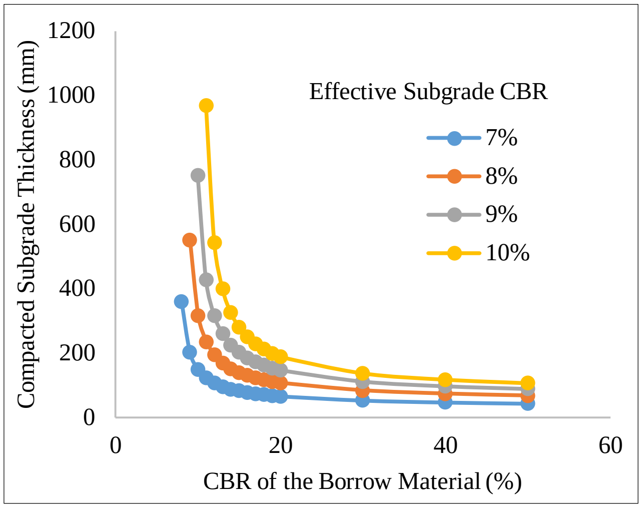

Fig. 15 Variation of the depth of borrow material with different CBR placed on natural subgrade with 6% CBR

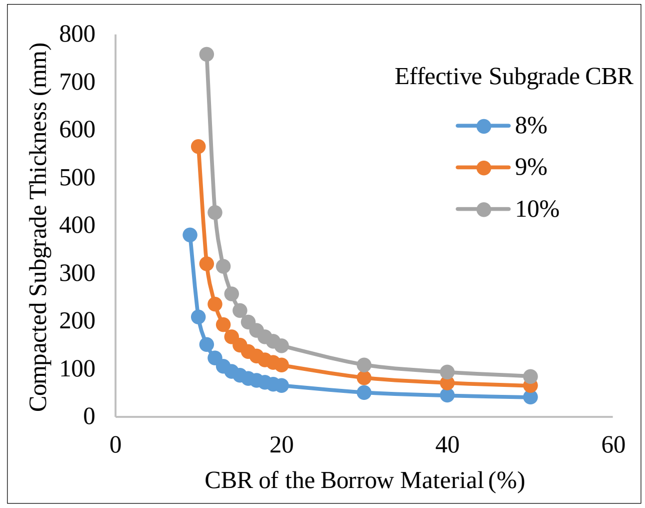

Fig. 17 Variation of the depth of borrow material with different CBR placed on natural subgrade with 7% CBR

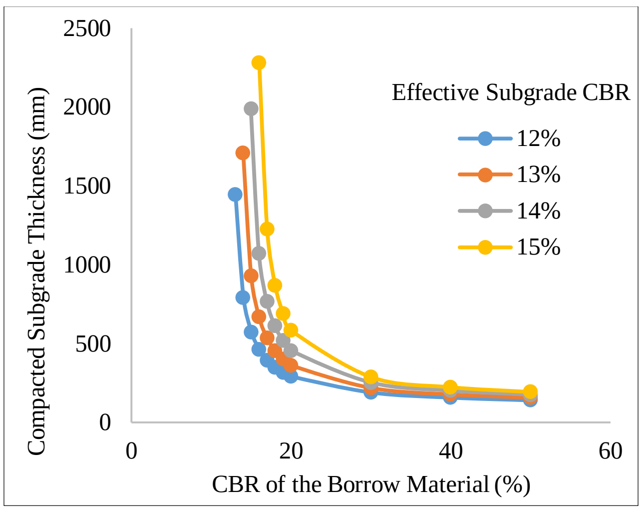

Fig. 16 Variation of the depth of borrow material with different CBR placed on natural subgrade with 6% CBR

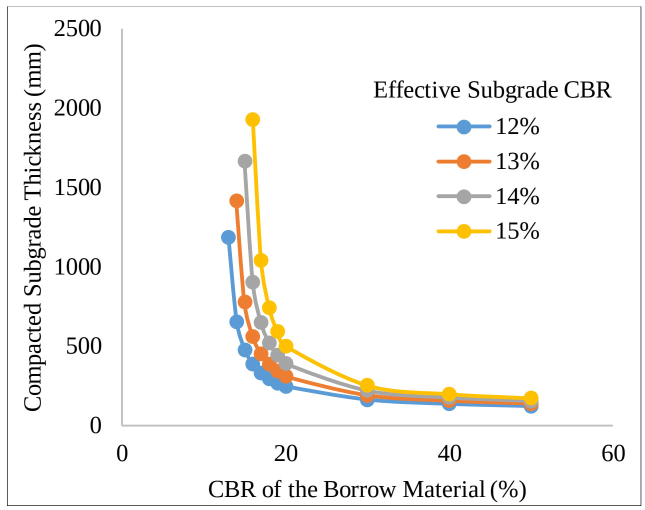

Fig. 18 Variation of the depth of borrow material with different CBR placed on natural subgrade with 7% CBR

The requirement of compacted subgrade thickness becomes more elevated when a borrowed material of comparatively lower CBR is used. But when the borrow material strength is higher with a higher CBR value, the thickness of the compacted subgrade becomes less.

Moreover, the variation of compacted subgrade thickness was also found to vary with natural subgrade strength. However, the effect of variation of natural subgrade CBR on compacted subgrade thickness is less sensitive than the variation of CBR of borrowed material.

6.1. Validation of the Proposed Model

For validation of test results, the analysis presented in IRC-37-2012 has been considered in the present study. The natural CBR of soil in the IRC-37-2012 ranges between 1.5% to 7%, whereas the CBR of borrowed soil has been considered from 5% to 50%. The effective CBR recommended in IRC: 37-2012 has been estimated for a thickness of 500 mm of the compacted subgrade. The effective CBR of subgrade in a two-layered system was obtained using the present method with similar variables of IRC: 37-2012 corresponding to natural CBR between 1.5% to 7%, and it has been presented in Figures 19 to 20.

It has been found that the adequate CBR data obtained using the present method matches closely with IRC-37-2012 data. However, it is relevant to mention that the results obtained from IRC-37-2012 are based on the output of the ELAYER (Reddy et al., 1993) computer program used by the researchers in IIT Kharagpur.

The program is based on Burmister's (Burmister, D. M., 1943) analysis with a layered system having a rough interface. However, the present study is based on a linear elastic theory using the method of equivalent thickness.

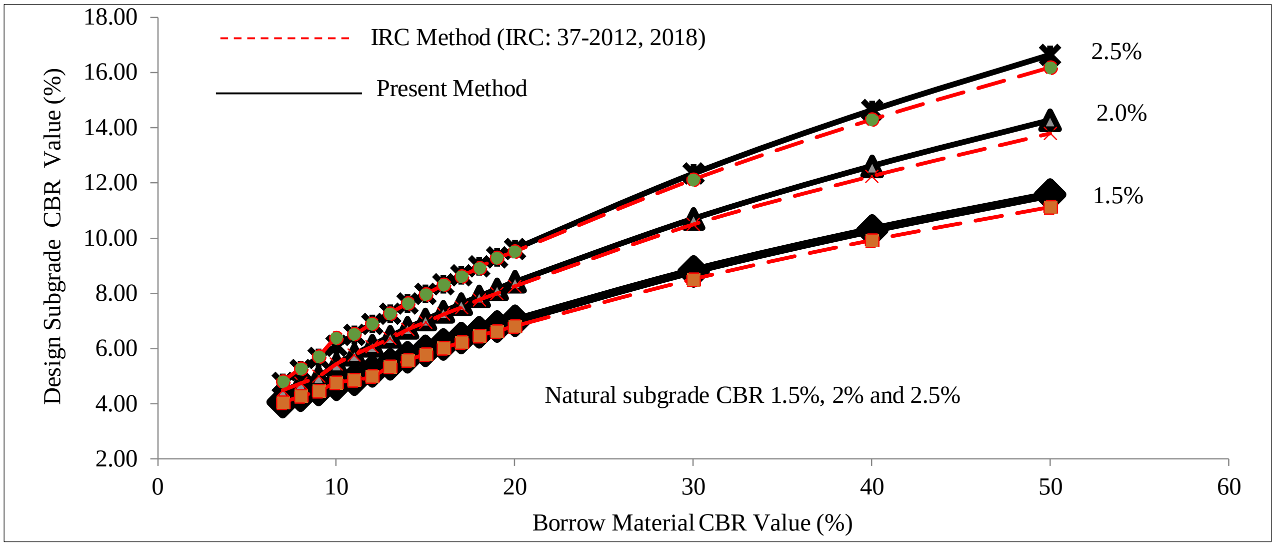

Fig. 19 Variation of effective subgrade CBR values for 500 mm compacted thickness of borrow material with different CBR for natural subgrade CBR (1.5%, 2.0%, and 2.5%)

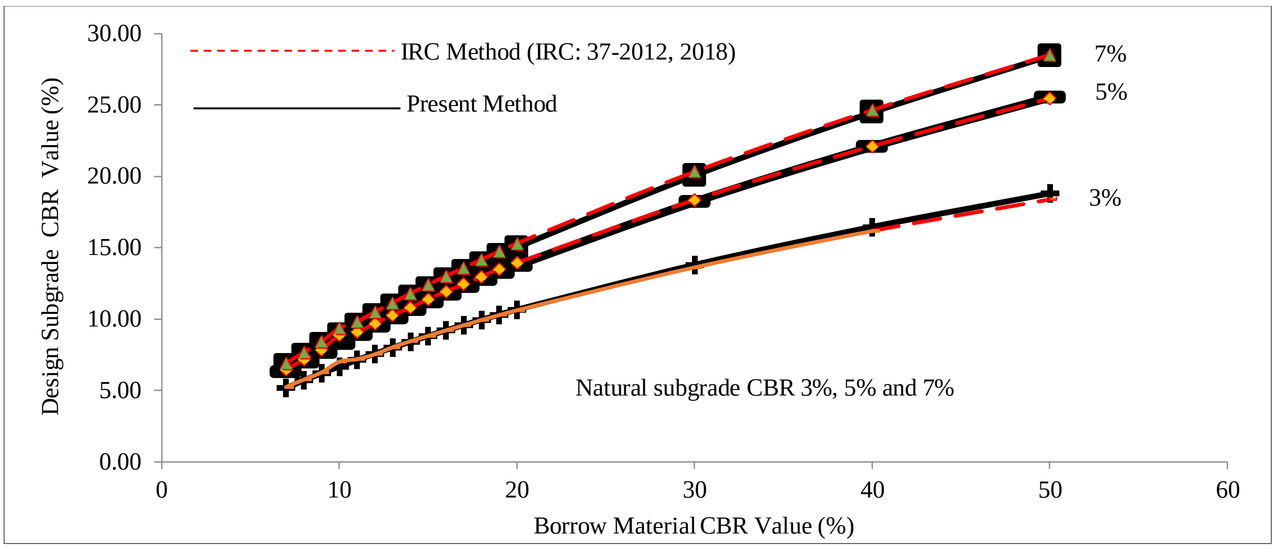

Fig. 20 Variation of effective subgrade CBR values for 500 mm compacted thickness of borrow material with different CBR for natural subgrade CBR (3%, 5%, and 7%)

Convergence of output data regarding effective CBR justifies the acceptability of the proposed methodology presented in this chapter. However, in the future, the effective CBR (compacted subgrade CBR) value may be estimated using a strain and stress-based approach where the vertical compressive strain and stress on top of the subgrade may be the design parameter. In such cases, the strain and stress-based method may include the number of standard axle load repetitions that the improved subgrade can withstand before it fails under rutting.

7. Conclusion

Effective CBR can be estimated based on the fixed thickness of compacted borrow materials placed on the natural subgrade. However, the present method for estimating compacted subgrade thickness may be used to achieve a targeted effective CBR of subgrade for the design of flexible road pavement. This method uses natural subgrade CBR, compacted soil subgrade CBR, and effective CBR as input variables, while the compacted subgrade thickness becomes output. It is relevant to mention that when the natural subgrade CBR is less than 5%, the subgrade improvement becomes essential to make the pavement durable with a higher service life against rutting. It has been found from the present study that the thickness of compacted subgrade largely varies up to the CBR of borrowed soil of 20%, beyond which the variations are not significant. In the future, efforts are needed to estimate the effective subgrade CBR considering the pavement's service life.

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