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Geosynthetic Reinforced Unpaved Road: Literature Study and Design Example

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Abstract**—**This paper, in its first part, presents the state-of-the-art literature of design approaches for geosynthetic reinforced unpaved roads. The literature starting since 1970 and the critical appraisal of flexible pavement design by Giroud and Han (2004) and Jonathan Fannin (2006) is presented. The design example is illustrated for Indian conditions. The example emphasizes the results computed by Giroud and Han's (2004) design method with the Indian road congress guidelines by IRC SP 72 -2015. The input data considered are related to the subgrade soil condition of Maharashtra State in India. The unified soil classification of the subgrade soil is inorganic clay with high plasticity (CH), which is expansive with a California bearing ratio (CBR) of 2% to 3%. The example exhibits the unreinforced case and geotextile as reinforcement by varying the rut depth from 25 mm to 100 mm. The present result reveals the base thickness for the unreinforced case from the IRC design catalogs is in good agreement with Giroud and Han (2004) approach for a range of 75 mm to 100 mm rut depth. Since Giroud and Han (2004) method is applicable for both reinforced and unreinforced cases, for the same data with appropriate Nc factor, for the same rut depth, the base thickness for the reinforced case has arrived for the Indian condition. From this trial, for the CBR of 2%, the base thickness reduction due to geotextile inclusion is 35%. For the CBR range of 2% to 5% with different stiffness in geosynthetics, the reduction in base course thickness will be evaluated, and the validation will be executed by the full-scale accelerated pavement testing set up at the College of Engineering Pune (COE), India.

Keywords**—**Base thickness, design approach, equation, full scale accelerated pavement set up, Indian condition.

I. INTRODUCTION

THE fundamental idea of each pavement design approach is to capture the response of wheel loading on roads. The pavement design methods ascertain the overall cost reduction by reducing the layer thickness and prolonging its service life for specific design traffic. The early approaches in road design are empirical and semi-empirical methods. Nowadays, research focuses on developing a mechanistic-based design method for geosynthetic reinforcement [4], [5], [10]. Geosynthetic inclusion in road design develops reinforcement mechanisms that improve the base layer's load distribution angle and reduce vertical subgrade stress.

Geosynthetic reinforcement mechanism is escalated in a particular condition when the road layers laid over weak subgrade, where the degradation spotted by the reduction in the capability of the base layer to spread the stress due to wheel load to a broader area, lowering the base layer thickness, and when the intensity of vertical stress transferred to the subgrade is more. Reference [9] states that geogrids and woven geotextiles are mostly considered to improve weak subgrade layer with CBR less than 3. The reinforcement benefits of geotextile get mobilized in deep rutting. The tensioned geotextile partially absorbs the stress due to wheel load and improves the weak subgrade's bearing capacity. Geosynthetic reinforcement in road layers improves road performance and subgrade bearing capacity by its failure pattern.

The design parameters involved in road design are traffic, wheel load, tire contact area, stress distribution, layer modulus, CBR, and the influence of reinforcement in road layers [3]-[5]. The road's performance is estimated in terms of rut depth, rate of the rut, and heave outside the loaded area. Rut depth is vertical deformation measured at the wheel path from the original surface and is one of the predominant serviceability criteria for analyzing the pavement performance.

Unpaved roads, commonly known as water-bound macadam roads, are constructed as local, low volume roads. References [7], [6], [23] described low volume roads as rural roads usually designed to carry standard axle load for less than 100,000 passes, where the gravel base is always recommended.

II. LITERATURE SURVEY

A. Early Survey

In the early period, [1] experimented with 43 test sections of unreinforced unpaved test section by changing the layer thickness and traffic. Layer thickness equation developed with the rut depth of 75 mm as design criteria. Reference [2] was the first researcher to illustrate reinforcement benefits and have seen fabric strain in the design approach. The allowable subgrade stress in reinforced conditions quantified as the function of subgrade cohesion. References [2] and [3] proposed different empirical equations in the determination of aggregate thickness for the unreinforced condition. Reference [3] used the experimental data of [1] for validating his equation.

Reference [3] showed the increase in bearing capacity factor of geotextile reinforcement in road layers from elastic to ultimate capacity in the design approach. The investigation also highlights the importance of mobilizing the reinforcement mechanism and anchorage in geotextile at the interface until the road's shoulder prevents slippage.

Researchers in their respective investigation noticed tensioned membrane effect when subgrade deforms deeply

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under traffic load. The relation between Cu and CBR is derived. Reference [8] derived an equation for overall geotextile strain when subjected to load in road layers.

Reference [11] conducted a study on design parameters involved in the existing design procedures provided for geotextile-reinforced unpaved roads. The test sections considered the variation in aggregate layer thickness as a dependent parameter of wheel load, cohesion value of weak subgrade, count of load cycles, and geotextile tensile modulus. The survey indicates that even though design methods' results are approximate with the study in some instances, as the basic assumptions are varied, the inconsistency is observed in some other instances.

Reference [13] studied three design methods: [3], [12], and the European method for unpaved roads. The sensitivity analysis is implemented to compare the design parameters involved in those three methods. The design methods are based on quasi-static analysis for repeated traffic load. The design method considered shows that the same equation of unreinforced condition is utilized for the reinforced condition. In such formulations, there is no direct integration for the reinforced layer and the monotonic load.

Reference [14] observed the instrumented unpaved road's vehicle response on soft ground for geotextile and geogrid reinforcement. The strained geosynthetic as the layer deforms limits the outward shear stress and restricts deformation in the subgrade surface. At deep ruts, the field observation matches well with the analytical results. The field data interpretation for clayey subgrade of 40 kPa by changing base course thickness from 0.25 m to 0.5 m yields significant improvement in the thinner base course layer.

Critical studies on design methods using geosynthetic reinforcement in unpaved roads include [12], [4], [5]. The investigation shows shear stress carried by reinforcement when placed at the interface [12], [15].

References [4], [5] semi-empirical design approach considered CBR of the base layer compared to the empirical [3] method. Reference [5] developed a comprehensive design equation for the geogrid reinforced unpaved road. The design equation does not consider a particular dual wheel load, but the methodology is flexible for different wheel load configurations. The dual tire contact area is circular for subgrade failure analysis. The design equation's validity is for the rut depth ranging between 50 mm to 100 mm, maximum modulus ratio (R_E) as 5, and CBR of the subgrade less than 5. This equation involves parametric design groups. The design equation is used for geotextile by appropriately changing the bearing capacity factor (N_c) and geogrid aperture value (J) relevant to geotextile.

Studies reveal limited field test data to calibrate and validate the design equation parameters and charts. The research need of an experimental database to calibrate the existing analytical approaches of pavement design method is in high demand. Table I summarizes the design equation developed by the researchers for geosynthetic reinforcement in roads. The formula by [4], [5] is presented in flexible pavement design.

TABLE I
DESIGN EQUATIONS DEVELOPED IN THE EARLIER DESIGN METHOD

Researcher	Remarks	Design equation	Description of the parameter involved in the design equation
[1]	Unpaved road Rut depth: 75 mm	${h_0}^1 = (0.0236 \log N + 0.0161)\sqrt{\frac{P}{CBR}} - 17.8A$	ho^I: Design thickness (m) A: Tire contact area (m^2) P: Equivalent single wheel load (kN) N: Traffic
[3]	Equation 1 and 2 for N or Ns less than 10,000; Quasi-Static analysis for N less than 20 Design curves available	${h_0}^1 = \frac{0.19 \log N_5}{(CBR)^{0.63}}$ ${h_0}^1 = (1.6193 \log N + 6.3964 \log P - 3.7892r - 11.8887)$	ho^I: Design thickness (m) Ns: Number of axle passes of standard load 80 kN N: Number of axle passes of any configuration P: Wheel load (kN) r: Rut depth (m) Cu: Undrained cohesion (kPa)
[8]	Data incomplete	$\epsilon = 0.5\left[\sqrt{1+\beta^2} + \beta^{-1} \ln\left(\beta + \sqrt{1+\beta^2}\right)\right] - 1$	ϵ: Overall geotextile strain $\beta = 4D/B^I$ D: Maximum vertical downward deflection B^I: Distance measured to the inflection point of strained geotextile
[24], [25]	Method for membrane effect in geotextile	$S_0\left(\frac{d^2w}{dx^2}\right) = -(q_0 - q_1) - \gamma H$	S: Geotextile tensile stress So: S in a horizontal direction x: Horizontal distance to the truck's center
	Derived maximum tensile stress in geotextile	$S = S_0\sqrt{\left[\left(\frac{dw}{dx}\right)^2 + 1\right]}$	w: Geotextile movement in vertical axes H: Base layer thickness ϒ: Unit weight of the aggregate

B. Recent Survey

Reference [16] compared two semi-empirical design methods with common base theory but differing in input groups' parametrization. The (s/fs) in the Han equation yields three constants that need calibration. These constants are ξ, ω, and n, challenging to calibrate. Reference [16] further expresses the need to replace these three constants with the independent variable to improve accuracy.

Reference [10] outlines the design of planar geosynthetics with the methodology generally applied in the United States. The geosynthetics functions are discussed in detail for both unpaved and paved roads. The advantage of geosynthetic in the design methods of unpaved roads results in the decreased base thickness and the roadway's extended life.

Reference [17] deals with the parametric study of the currently available design methods in unpaved roads with variation in soil and geogrid properties, rut depth, and traffic. The results reflected the dependency of the required aggregate layer on rut depth and geogrid aperture stability modulus. The design approach's need for calibration is suggested by design parameters like the size of the geogrid opening, base particle size, interlocking effect, rib thickness, and profile.

Reference [18] predicted the road performance by taking rut depth as the core design parameter. The research involves 12 test sections with geosynthetics and control sections to evaluate the subgrade layer's strength and aggregate layer height. The results update the design methodology with a design equation calibrated for the design parameters. The new approach details the geogrid benefits in roads by swapping the aperture stability modulus with junction stiffness in the cross-machine direction.

Reference [19] aims to reduce the thickness of the base layer required in the field. The performance of geogrid reinforced unpaved sections at increased stresses by repeated plate load tests is investigated. The observed optimum depth at 50 mm of geogrid located in the base layer achieves a maximum reduction in rut depth by 40%. The study on geogrid reinforced test sections demonstrates the strain reduction on the subgrade top surface. Resilient modulus is predicted from resilient deformation data. Experiments on reinforced sections confirm the reduction in permanent deformation by at least 50% for different base course thicknesses.

Reference [20] highlighted the geotextile strain as a design parameter affecting the required aggregate base thickness. The mathematical framework is developed in spreadsheets with embedded subroutines for the iterative solution of the governing equations. The tool compared the worldwide acceptable design methodologies for the optimum design of geotextile reinforced unpaved roads. The methodologies' comparative parametric analysis showed similarities and differences between them, with parameters like undrained shear strength, CBR, vehicle passes, the rut depth, geotextile tensile modulus, and the geotextile strain.

The elastic layer theory is discussed by [21] to derive solutions for a particular three-layer geosynthetic reinforced flexible pavement. The permanent deformation inspected in layers is the indicator of quantifying the lateral restraint and tensioned membrane effect of geosynthetics. The derived results were used in the mechanistic-empirical approach to calculate pavement rutting of geosynthetic reinforcement in flexible systems.

Reference [22] conducted a field performance study on test sections of geotextile and geogrid unpaved road models. The sections display soil-geosynthetic interaction. A more significant shear stress improvement was observed in the reinforced soil sample, wherein the friction angle of soil ranges from 20° to 25°.

C. Indian Road Congress Guidelines

The Indian codes approach [6], [23], as a first step, estimates the design traffic for new roads. The traffic is designed based on the available information on the existing roads with a similar condition. At least three subgrade soil samples must be tested in the lab. Based on agriculture and industrial development, the expected traffic is estimated. The subgrade strength is assessed with the samples tested in the laboratory for IS classification test, compaction test, and CBR. Determination of pavement thickness and composition aims to maximize the use of locally available material in layer construction from the material survey and lab test result for the representative sample. From design catalogs, pavement thickness and composition are determined after knowing the design traffic and subgrade strength. From the total thickness requirement, the thickness of different layers is arrived at by keeping in mind to maximize the use of locally available material in layer construction.

III. Flexible Pavement Design

A. Unreinforced Condition

We consider 'P' as the single wheel load on the road surface for a two-layer road system. The wheel load creates uniform stress 'ρ' on the base layer. The formulation of the basic equation is established with the loading pattern as depicted in Fig. 1 where h: base thickness, R: wheel contact radius, R^l: effective radius of subgrade surface stress distribution, β: Stress distribution angle. The assumptions for the layer system are: 1. For a wheel load (P), the tire contact area is circular on the base layer surface, 2. The tire inflation pressure is equal to the uniform stress applied on the base surface (ρ).

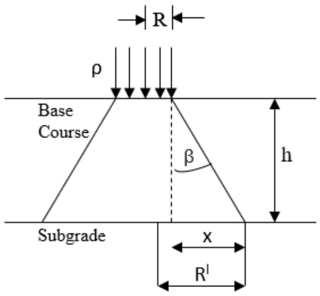

Fig. 1 Schematic representation of the load pattern for road [16]

Researchers arrived at the fundamental equation (1) with design parameters in the analytical methodology. References [4], [5] modified (1) to develop a comprehensive equation for compacted base thickness involving design parametric group of geosynthetic reinforcement.

$$h = \frac{R}{\tan\beta}\left[\sqrt{\frac{P}{N_c s_u}} - 1\right] \quad (1)$$

where, N_c: bearing capacity factor, S_u: undrained shear strength of the subgrade.

The basic concept behind achieving (1) depends on the stress on the base surface and stress field on the road layer's subgrade surface, as shown in Fig. 1. The relation between R and R^l is derived by base thickness (h) and stress distribution angle (β). The resulting equation derived gives the relation between R and R^l as represented in (3):

$$R^I = R + x \tag{2}$$

$$R^I = R + h\tan\beta \tag{3}$$

Wheel load (P) and the tire contact area ($A = \pi R^2$) decide the stress on the surface of the road base layer. The allowable stress field acting on the subgrade layer (ρ^1) depends on its undrained shear strength (S_u) and bearing capacity factor (N_c). The area of the stress on the subgrade surface ($A = \pi[\mathrm{R} + \mathrm{h}\tan\beta]^2$) depends on the effective radius (R^l) as given in (3).

$$\rho\,(\pi R^2) = \mathrm{NcSu}(\pi[\mathrm{R} + \mathrm{h}\tan\beta]^2) \tag{4}$$

Equating the wheel load on the base surface to the subgrade surface load as in (4) yields to basic equation (1) for estimating base thickness in unreinforced road design, which is later modified by [4] for the geosynthetic reinforced condition in unpaved roads.

B. Geosynthetic Reinforced Condition

The design approach proposed by [4], [5] can be applied for unreinforced and geotextile or geogrid reinforced unpaved roads with allowable rut depth of 50 mm to 100 mm. Reference [4] related the geogrid aperture modulus with the deterioration rate for two geogrid products in unpaved roads. Formula (5) for calculating the needed base thickness developed by [4] and [5] is as follows:

$$h = \frac{0.868+\left(0.661-1.006J^2\right)\left(\frac{r}{h}\right)^{1.5} logN}{1+0.204[R_E-1]}\left[\sqrt{\frac{\frac{P}{\pi r^2}}{\left(\frac{s}{f_S}\right)\left[1-0.9e^{-\left(\frac{r}{h}\right)^2}\right]N_c f_C CBR_{sg}}} - 1\right] r \quad (5)$$

where h: required base course thickness (m), P: wheel load (kN), N: number of passes of an axle, J: geogrid aperture stability modulus, (J as 0 for geotextile reinforced and unreinforced state) r: radius of equivalent tire contact area, R_E: limited modulus ratio for base and subgrade layer, s: allowable rut depth (mm), f_S: factor equal to 75 mm, N_c: bearing capacity factor, f_C: factor equal to 30 kPa, CBR_{sg}: subgrade CBR.

IV. DESIGN EXAMPLE

The soil in India is primarily suitable for agriculture. In India, most of the rural roads with local soil are subjected to heavy-laden vehicles. The challenging aspect is the need for good roads, which is not possible without reinforcement. The acceptable rut depth for unpaved roads is 50-100 mm. However, 150 mm rut depth may be allowed in some cases. The typical choice for design standards is a rut depth of 75 mm for both reinforced and unreinforced conditions.

In the design example, Maharashtra State's soil is accounted for subgrade layer for which CBR and other engineering properties are tested in the laboratory. The black cotton soil's lab test values of CBR 2% are considered in the base thickness layer's computation process. In the present computation, the rut depths varied from 25 mm to 100 mm for design traffic of 60,000 to 1 lakh (100,000).

A. Input Values

The basic design parameters involved as the primary input for base thickness design are stress distribution angle (β), wheel load (P), the radius of the wheel contact area (R), stress on the base layer (ρ), bearing capacity factor (N_c) and undrained shear strength of the subgrade (S_u). References [4] and [5] validated the analysis with the input data from [14]. The input values used in the present work are laboratory result values tested on the four representative soil samples collected from Maharashtra State in India. Reference [6] recommends the pavement design catalogs for the required total base thickness as per the Indian condition. The proposed data of [6] are plotted along with the design results obtained from Giroud and Han approach. Table II summarizes the present design example's input values with the data of [5].

TABLE II
INPUT VALUES

Input	Definition	Design Example input Indian Condition (Geotextile reinforcement)	[5] (Geogrid reinforcement)
R_E	E_{bc}/E_{sg} Limited modulus ratio	5	5
P	Wheel load	40 kN	40 kN
Nc	Bearing capacity factor	3.14 (unreinforced) 5.14 (Geotextile reinforcement)	5.71
ρ	Pressure on the tire contact area	566.17 kPa	620 kPa
R	The radius of the tire contact area	0.15 m	0.143 m
s	Limiting rut depth	0.025 m to 0.100 m	0.075 m
fs	Factor equal to 75 mm rut depth	0.075 m	0.075 m
ξ	Constant	0.9	0.9
ω	Constant	1	1
n	Constant	2	2

B. Indian Road Congress [6]

Performance-based design by [6] focuses on providing serviceability, not below the acceptable level during service life. The design catalogs are available for Indian conditions at CBR, ranging from 2% to 15% (S1 to S5) with seven different traffic categories below 2 msa (T1 to T7). Rural roads are designed for a maximum of 100,000 equivalent single axle loads (ESAL). The design example subgrade CBR falls in the very poor quality. Hence the pavement composition shown in Fig. 2 is considered for the traffic category of 60,000 to 100,000.

C. Computed by Giroud and Han Design Equation

The method [5] is applicable for both reinforced and unreinforced cases. Hence the base thickness is computed for the unreinforced case and geotextile reinforced condition with the input in Table II by using the appropriate Nc factor for the same rut depth as the function of axle passes from 60,000 to

100,000. The excel sheets are prepared for multiple iterations. The computed base thicknesses by [5] are displayed in Fig. 3 for unreinforced condition and in Fig. 4 for geotextile reinforced condition.

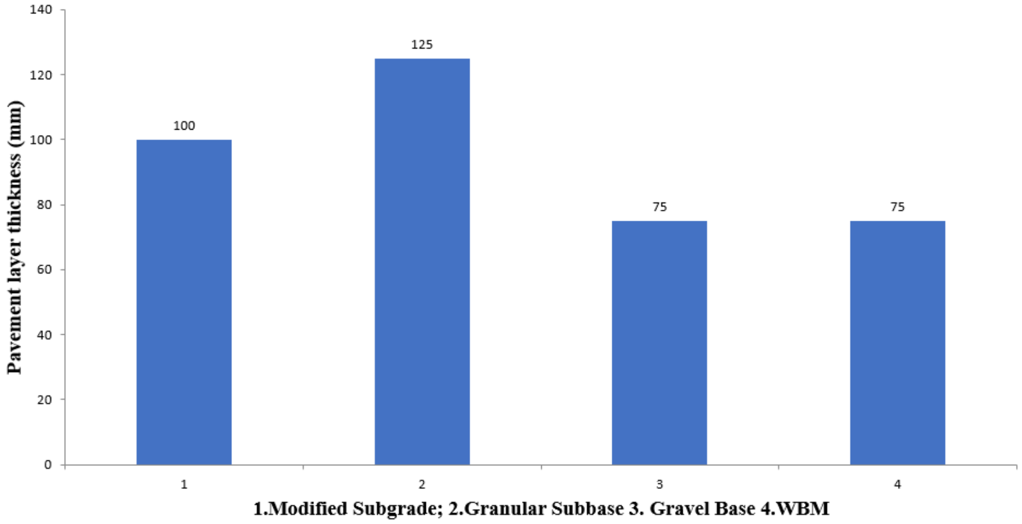

Fig. 2 Pavement Design Catalogues [6] for Subgrade CBR 2%

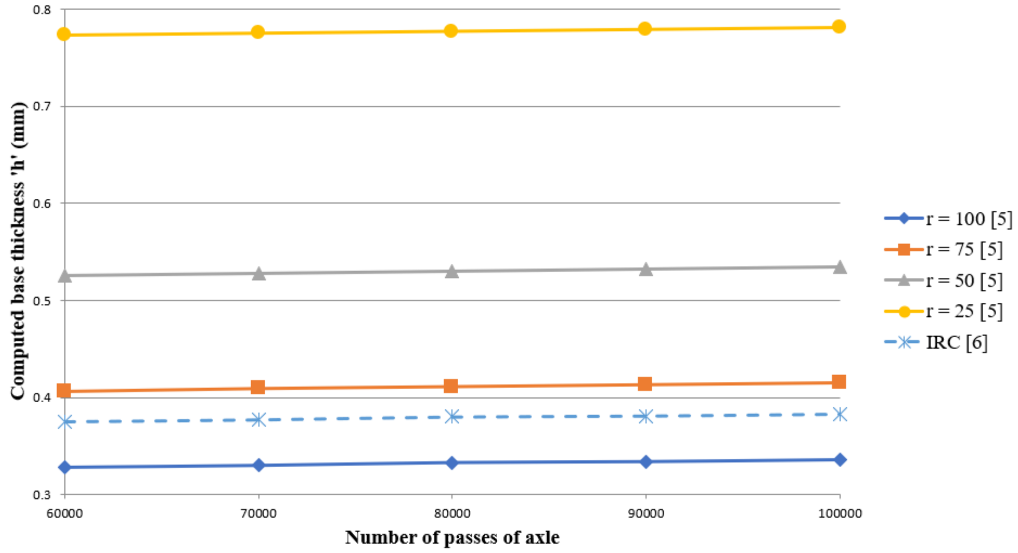

Fig. 3 Computed Base thickness by [5] for the unreinforced condition [2% Subgrade CBR; rut depth: 25 mm to 100 mm]

From Figs. 3 and 4, it is observed that the computed base thickness for the rut depth of 25 mm is significantly higher than that of other rut depths. The reason may be [5] is applicable only for a rut range of 50 mm to 100 mm.

The total pavement composition thickness of [6] is plotted in the unreinforced curves of Fig. 3 computed from [5]. The result reveals that the expected rut depth for the unreinforced condition is between 75 mm to 100 mm. The predicted rut depth range is superimposed with [6] in geotextile reinforced condition, as plotted in Fig. 4. The analysis of the variation shown from [6] in Figs. 3 and 4 proves a reduction in base thickness by 35% upon reinforcing the road layer with geotextile. The catalogs for the reinforced condition can be recommended to IRC by varying the CBR range from 2% to 5% by different geosynthetic stiffness.

V. CONCLUSION

- Design parameters like traffic, subgrade strength, wheel load, and tire contact area are considered standard parameters in the developed known approaches. The parameters like geotextile stiffness/tensile strength, expansive soil swelling and shrinking behavior, and anchorage effect are not considered for with the design approaches.
- References [4] and [5] considered 'J' aperture stability modulus as a design parameter for geogrid and referred to 'J' as zero for geotextile reinforcement. But 'J' may be replaced by geotextile tensile strength to verify its impact on the road layer design.
- The design example results reveal that for the subgrade

soil of 2% CBR, the base layer thickness reduction is by 35% for geotextile reinforced roads.

- The design curves for the geosynthetic reinforced condition to be recommended to IRC for a range of CBR. It can be validated using full-scale accelerated pavement testing set up [26] on a full-scale road model.

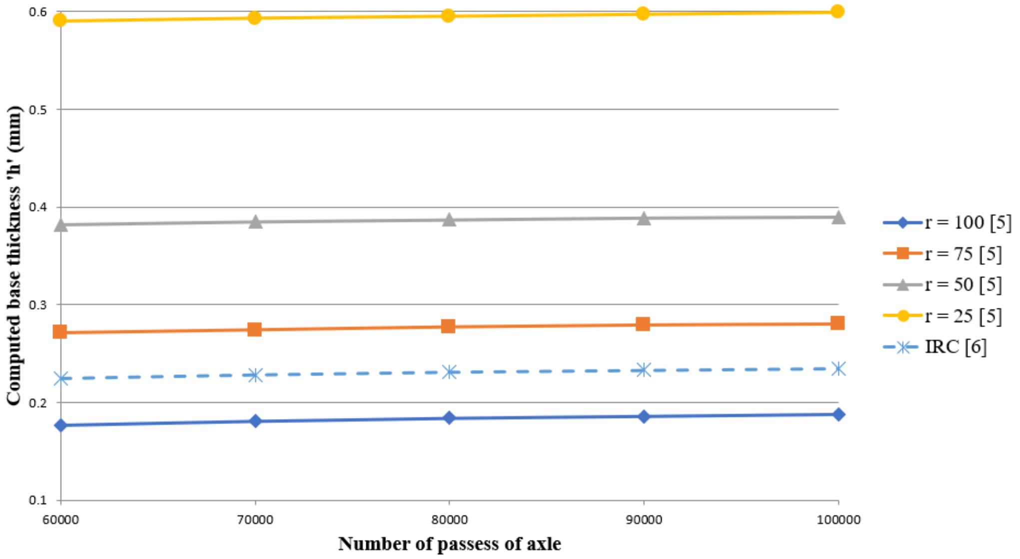

Fig. 4 Computed Base thickness by [5] for Geotextile reinforced condition [2% Subgrade CBR; rut depth: 25 mm to 100 mm]

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