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GEOSYNTHETIC-REINFORCED SUBGRADE IMPROVEMENT UNDER CYCLIC LOADING: A GIROUD–HAN METHOD ANALYSIS

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ABSTRACT: Pavement damage is a common problem resulting from the combined effects of environmental factors and repeated traffic loads. One of the primary contributors is subgrade saturation caused by heavy rainfall, which weakens the soil structure and reduces bearing capacity. When this condition is followed by repeated loading from vehicle wheels, the degradation of subgrade strength becomes more severe. This study aims to analyze the influence of cyclic loading on the soaked California Bearing Ratio of subgrade soil and to determine the required thickness of the subgrade improvement layer using the Giroud–Han method. Samples soil from the Gumitir, East Java, were evaluated under saturated conditions with cyclic load variations of 345, 690, and 1035 kPa. The results showed that the soaked CBR decreased exponentially with increasing load cycles, with a decay constant k = 0.034. Initial CBR values of 5.3% and 5% declined to 1.4% and 2.7%, respectively, after repeated loading, confirming that cyclic loading significantly reduces bearing capacity. The comparison indicates that the conventional design produces a subgrade improvement layer approximately 34% thinner than the layer required when cyclic loading is considered, even with geosynthetic reinforcement. Moreover, when cyclic loading is analyzed without reinforcement, the required thickness becomes nearly 70% greater than the conventional design. Further analysis using the Giroud–Han method shows that geotextiles can reduce required layer thickness by up to 38%, while geogrids can reduce it by up to 52%, demonstrating their effectiveness in improving subgrade performance and overall pavement reliability.

Keywords: Cyclic Load, Soaked CBR, Geosynthetic, Threshold

1. INTRODUCTION

Road pavement failures frequently occur due to several design factors that are not fully considered during the planning and evaluation stages. One of the most critical issues is the accurate estimation of subgrade strength, as the required thickness of subgrade reinforce layers depends heavily on the reliability of the CBR value used in design [1]. However, conventional CBR evaluation often overlooks actual field conditions, including high rainfall typical of tropical regions, which causes prolonged saturation, reduces effective stress, and accelerates subgrade strength loss [2], [3]. Under these conditions, saturated subgrades exposed to repeated traffic loading may still undergo progressive plastic deformation, indicating that conventional design parameters are insufficient and that a more comprehensive analytical approach is required to accurately evaluate long-term deformation behavior under cyclic and saturated conditions [4].

Cyclic loading plays a critical role in determining the long-term performance of saturated subgrade soils, as repeated traffic loads progressively accumulate plastic deformation, the soil's bearing capacity decreases, and the road structure becomes more susceptible to permanent deformation under traffic loads [5], [6]. Cyclic load is a load applied repeatedly to soil or pavement materials to simulate the effects of repeated vehicle traffic in the field. The application of cyclic loads for 50 repetitions with a given load results in permanent deformation, whereas 50 repetitions with the same load result in elastic deformation [7]. Laboratory studies have demonstrated that repeated loading can reduce soaked CBR values by 40–60%, indicating substantial strength loss under saturated and cyclic conditions[8]. These results highlight the importance of incorporating cyclic behavior into the evaluation of subgrade reinforcement strategies, as conventional static CBR measurements may not adequately capture strength degradation under real traffic loading conditions.

Geosynthetic reinforcement has been shown to significantly enhance the mechanical behavior of weak subgrades subjected to repeated loading, primarily through soil–geosynthetic interlocking, improved confinement, and tensile membrane effects. Recent studies confirm that the shear resistance at the soil–geogrid interface can increase by 25–40% depending on soil gradation and geogrid type when subjected to cyclic shearing [9], [10]. In numerical models of flexible pavements, placing geotextile at the base–subgrade interface resulted in rutting reductions of up to 25.2% under repeated traffic loads[11].

Soaked conditions represent the most critical state for evaluating subgrade behavior in tropical environments, as prolonged water infiltration weakens particle bonding, reduces effective stress, and accelerates strength loss. Laboratory studies have shown that repeated loading under saturated conditions leads to progressive reductions in soaked CBR values, indicating that moisture amplifies the deterioration of subgrade stiffness and bearing capacity [8]. In addition, cyclic loading promotes the development of excess pore-water pressure within the subgrade, which further contributes to permanent deformation and reduced structural stability [12]. Cyclic shear investigations also report that the interaction between soil and reinforcement elements weakens more rapidly under saturation, emphasizing that moisture plays a key role in interface degradation and long-term deformation behavior [10]. These findings reinforce the importance of evaluating subgrade performance using soaked cyclic parameters rather than relying solely on conventional static CBR tests.

Given the limitations of conventional strength measurements in capturing long-term degradation under saturated cyclic conditions, an analytical framework that incorporates both soil behavior and reinforcement mechanisms is required. The Giroud–Han method provides such a framework by integrating subgrade strength parameters, geosynthetic properties, and traffic loading to estimate the required thickness of reinforced layers[13]. This method has been widely adopted in the design of mechanically stabilized pavements, as it accounts for the improved load distribution and confinement provided by geosynthetics, while also considering subgrade deformation criteria [14], [15].

While many studies have examined geosynthetic-reinforced subgrades and the effects of cyclic loading and saturation, few directly incorporate soaked cyclic CBR results into analytical design methods like the Giroud–Han approach. Previous research often treats cyclic behavior, moisture weakening, or reinforcement separately. Since subgrade improvement thickness depends on CBR, reductions under saturated cyclic conditions can increase required thickness. This study integrates soaked cyclic CBR parameters into the Giroud–Han method, providing a more realistic basis for pavement design in tropical regions and improving long term deformation predictions.

2. RESEARCH SIGNIFICANCE

This study offers an innovative contribution by integrating soaked cyclic CBR parameters directly into the Giroud–Han analytical method, thereby enabling a more accurate representation of reinforced subgrade behaviour under saturated, repeatedly loaded conditions. Previous research has typically examined moisture effects, cyclic degradation, and geosynthetic reinforcement independently, resulting in design approaches that do not fully capture their combined influence on long-term pavement performance or the corresponding requirements for subgrade improvement thickness.

By unifying these critical components into a single analytical framework, this study provides a more comprehensive basis for evaluating subgrade response in tropical environments characterised by high rainfall and persistent saturation. The proposed integration improves the precision of deformation predictions and thickness determination for reinforced subgrade layers, thereby increasing the overall reliability of pavement design. This innovative approach strengthens the methodological foundation for assessing long-term structural performance by linking laboratory-derived soaked cyclic CBR results with a widely recognised analytical model.

3. LABORATORY TEST

3.1 The Soil Tested

Following the subgrade conditions described earlier, the laboratory investigation focused on soil samples from the Gumitir. Gumitir is a national road corridor connecting Jember and Banyuwangi, East Java experiences high traffic volumes throughout the year. Climatically, the area is characterized by high rainfall intensity, ranging from 1500 to 3000 mm/years, often resulting in elevated subgrade moisture levels [16]. Two undisturbed soil samples were collected from the road shoulder near distressed pavement sections, spaced about 100 m apart, following standard subgrade investigation practices. Samples were taken from 0.50 m depth to avoid upper layers affected by pavement materials and construction activities. Undisturbed samples were used to determine index properties, while cyclic CBR specimens were remolded to ensure uniformity, repeatability, and comparability of the tests.

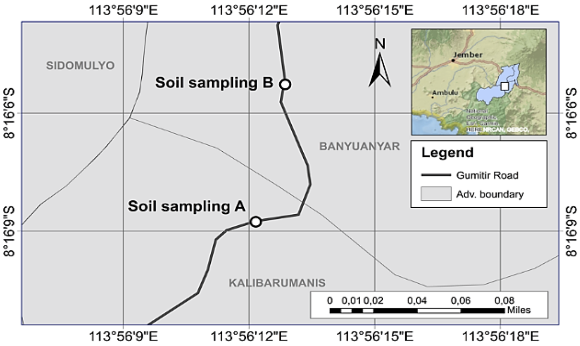
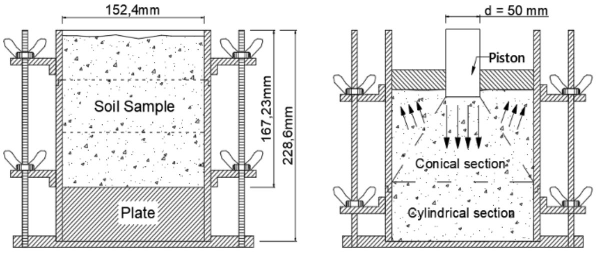


Fig. 1 Soil sampling location

3.2 Experimental Equipment

There are several cyclic CBR analysis processes based on the procedures of SNI 1742:2008 and SNI

1744:2012, applicable in Indonesia, and in accordance with ASTM D1883. The first sequence is the California Bearing Ratio, the sample was compacted in 3 layers, gradually, using a hammer, according to the testing procedure of SNI 1744:2012. After compaction, penetration testing was conducted to determine the CBR value, before being subjected to cyclic loads. The cyclic loading was applied through a circular loading plate with a diameter of 50 mm, the contact area of 0.001964 m^2 and calibrated by verifying the applied pressure against a standard laboratory pressure measuring device.



(a) (b)

Fig. 4 (a) CBR design specimen, and (b) cyclic CBR specimen

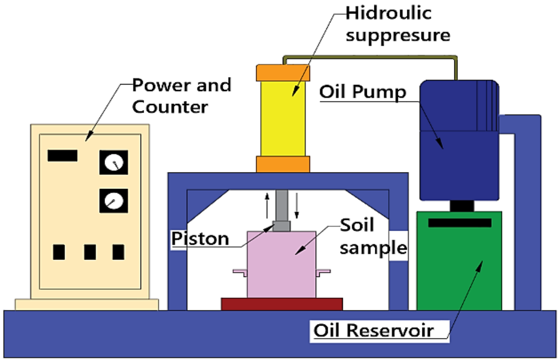


Fig. 5 Cyclic CBR tester

3.3 Test Method

This research was carried out in two main stages, stage 1, sample preparation, and stage 2, cyclic loading and CBR testing. The purpose of this test is to determine the effect of repeated loading on the CBR value of the subgrade soil under saturated conditions.

Step 1, Sample preparation. Grain-size distribution and plasticity index were analyzed to characterize the soil samples. Based on SNI 03-1968:1990 and SNI 1966:2008, soil samples A and B were classified as silty sand, with 200-mesh sieve passing percentages of 20% and 30% and PI values of 10.8–13.6. The maximum dry density (MDD) and optimum moisture content (OMC) were determined in accordance with SNI 1742:2008 and used for CBR specimen preparation. Seven specimens for each soil type were compacted at the OMC and soaked for 96 hours to achieve near saturated conditions, followed by a 1-hour stabilization period. Cyclic loading was applied at a constant frequency to isolate the effect of stress magnitude, while pore-water pressure effects were indirectly reflected through cyclic CBR degradation.

Step 2 cyclic loading and CBR testing. Repeated loading was applied at three pressure levels 345 kPa, 690 kPa, and 1035 kPa, representing light vehicles, medium vehicles, and heavily loaded trucks, respectively. These pressure levels were selected to reflect increasing traffic loading severity. For each pressure level, specimens were subjected to 50 loading cycles followed by an additional 100 cycles [7]. To minimize boundary effects, cyclic loading was applied at the center of the specimen, while CBR penetration tests were conducted at an edge region not previously subjected to cyclic loading. The cyclic loading location is illustrated in Figure 6.

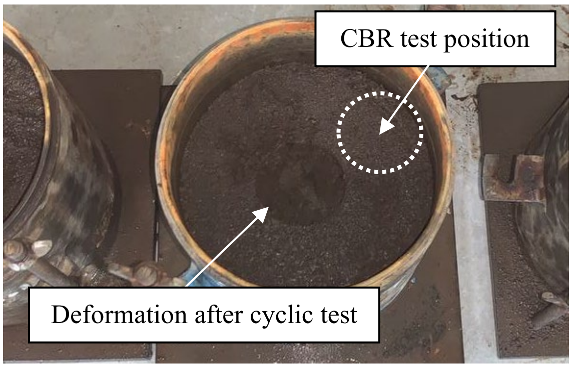


Fig. 6 Condition of the soil specimen after cyclic

Each CBR test was performed on a separate specimen to avoid cumulative damage. Seven tests were conducted per soil point, one non cyclic and six under cyclic loading. Testing followed SNI 1744:2012 and ASTM D1883 using a Cyclic CBR Tester, with load penetration data recorded for each cycle. The specimen layout is shown schematically in Figure 7.

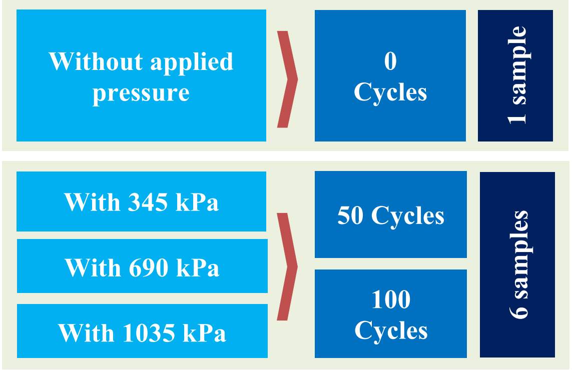


Fig. 7 Sequence of cyclic loading and CBR testing for each soil sampling point

4. EMPIRICAL APPROACH

4.1 Giroud and Han Approach 2004

The Giroud–Han (2004) method was developed to design pavement layers laid on subgrade that can be reinforced with geosynthetics [14], [15]. The consideration for its use in this study is that the method of reinforced layer matches the reinforced subgrade in Indonesia, which convert the rut depth to the allowable settlement limits specified, and by materials with a CBR ≥ 30%. Parameters from Giroud–Han (2004) are shown in Table 1 :

Table 1. Giroud-Han's Parameters

Parameter	Equation
Tire contact pressure (***r***)	$r = \sqrt{\frac{P}{\pi p}}$
Limited Modulus ratio ($\boldsymbol{R_E}$)	$R_E = Min\left(\frac{3.48CBR_{bc}^{0,3}}{CBR_{sg}}\right)$
Ratio factor ($\boldsymbol{f_E}$)	$f_E = 1 + 0.204(R_E - 1)$
Bearing capacity mobilization factor (m)	$m = \left(\frac{s}{f_s}\right)\left\{1 - 0.9exp\left[-\left(\frac{r}{h}\right)^2\right]\right\}$
Bearing capacity factor(Nc)	Nc = 3.14 for unreinforced, Nc = 5.14 for geotextile, Nc = 5.71 for geogrid.

In this study, the Giroud-Han's Equation is used to determine the thickness of the subgrade improvement layer. The formula used is in Eq. (1) :

$$h = \frac{0.868+\left(0.661-1.006J^2\right)\left(\frac{r}{h}\right)^{1.5}\log N}{1+0.204(R_E-1)} \times \sqrt{\frac{\frac{P}{\pi r^2}}{\left(\frac{s}{fs}\right)\left\{1-0.9exp\left[-\left(\frac{r}{h}\right)^2\right]\right\}N_C f_C CBR_{sg}}} \quad (1)$$

Table 2. Description Giroud-Han's Equations

Symbols	Description
$\boldsymbol{h}$	Thickness of the aggregate layer (m)
$\boldsymbol{s}$	The allowable rut depth (mm)
$\boldsymbol{J}$	Represents the geogrid aperture stability modulus ($Nm/°$)
$\boldsymbol{r}$	The radius of the tire contact (m)
$\boldsymbol{CBR_{sg}}$	The subgrade CBR value (%)
$\boldsymbol{CBR_{bc}}$	Subgrade improvement CBR value (%)
$\boldsymbol{f_s}$	Is the 75 mm correction factor

In this study, the applied laboratory pressures of 345, 690, and 1035 kPa represent the wheel contact pressure (p) in the Giroud Han method. For calculation, a contact pressure of 1035 kPa was used to ensure a reliable design, with a single wheel load (P) of 45 kN representing typical heavy truck axle loads in Indonesia. The bearing capacity factor (Nc) is 3.14 for unreinforced, 5.14 for geotextile-reinforced, and 5.71 for geogrid-reinforced layers, with the geogrid aperture stiffness (J) assumed as 0.3 Nm/deg [14], [15] .

4.2 Empirical Model of Cyclic CBR Reduction on Subgrade Soil

Cyclic CBR reduction is the relative decrease in subgrade CBR due to repeated cyclic loading under near-saturated conditions, reflecting subgrade strength degradation over time [17]. In this study, the empirical approach was developed to describe the cyclic degradation of subgrade strength through the variation of the California Bearing Ratio (CBR) value under repeated loading. The relationship between the CBR value and the number of loading cycles (N) can be expressed by the following empirical model :

$$CBR(N) = CBR_{min} + (CBR_0 - CBR_{\text{min}})e^{-k_{ref}N} \quad (5)$$

This empirical equation represents the gradual reduction in the CBR value from its initial condition (CBR_0) to a residual minimum value (CBR_{min}) as the soil approaches a stable state due to repeated loads[18]. The coefficient, denotes the rate of CBR reduction, which reflects how quickly the soil loses its bearing capacity under cyclic loading conditions [19]. In this study, the value of k_{ref} was determined using the logarithmic relationship :

$$k_{ref} = \frac{1}{N} Ln\left(\frac{CBR_0-CBR_{min}{}^{2/3}}{CBR_{min}-CBR_{min}{}^{2/3}}\right) \quad (6)$$

The value of the degradation constant k was obtained from two soil samples tested under cyclic loading conditions. Each sample was analyzed using the empirical equation shown in Eq. (7) :

$$k = \frac{k_{ref}A + k_{ref}B}{2} \quad (7)$$

4.3 Framework of Calculation Method Using Giroud–Han Analysis

The calculation procedure adopted in this study integrates key design parameters for subgrade improvement using the Giroud–Han analytical method. As shown in Figure 8, the input parameters include cyclic CBR reduction, allowable settlement limits, selected geosynthetic reinforcement, and bearing capacity factors for reinforced conditions adopted from established literature to maintain consistency with the Giroud–Han framework [13]. Soil-specific behavior is represented by laboratory-derived cyclic CBR results, while the bearing capacity factors are treated as standardized parameters governed by reinforcement–soil interaction mechanisms. These inputs are used to determine the required thickness of the subgrade improvement layer, ensuring compliance with both performance and deformation criteria.

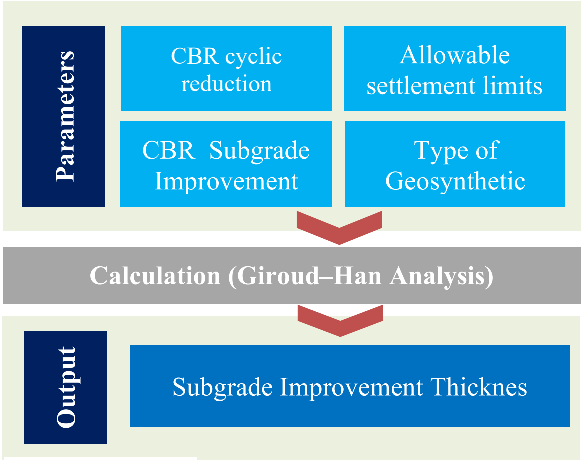


Fig. 8 Framework of Calculation

5. RESULTS AND DISCUSSIONS

5.1 Subgrade Strength Degradation due to Cyclic Loading

The initial CBR values of 5.3% and 5.0% progressively reduced to 1.4% and 2.7%, respectively, after cyclic loading under soaked conditions. The pronounced reduction observed during the first 10 cycles indicates rapid loss of subgrade shear strength during early cycles is attributed to structural collapse, involving particle rearrangement, interparticle bond breakdown after soaking, and possible fines migration. This pattern confirms that fine-grained soils in the Gumitir area are highly susceptible to traffic-induced weakening.

Other research found that repeated loading under wet conditions significantly reduces the apparent cohesion and stiffness of weak subgrades for 50-70%, leading to early-stage rutting failure [20]. The cyclic test results illustrated Figure 9 (a) and Figure 9 (b) demonstrate an exponential decrease in CBR value with increasing number of load repetitions for both sampling points A and B.

The influence of applied pressure is reflected in the absolute reduction of CBR at each pressure level, with higher pressures causing more pronounced decreases. Meanwhile, the effect of the number of cycles is observed in the rate of degradation over repeated loading, showing that early cycles induce the most significant strength loss. The degradation rate constant (k) was determined from two soil samples using the empirical relationship presented in Eq. (7) yielding value of $k = 0.034$. k is consistent with values reported in previous studies, where the degradation rate of subgrade CBR under cyclic loading typically ranges between 0.02 and 0.05 [18],[21],[22]. The degradation constant presented in this study is based on two sampling locations and is used only within the scope of this research. The value is intended as a preliminary estimate for mechanistic analysis.

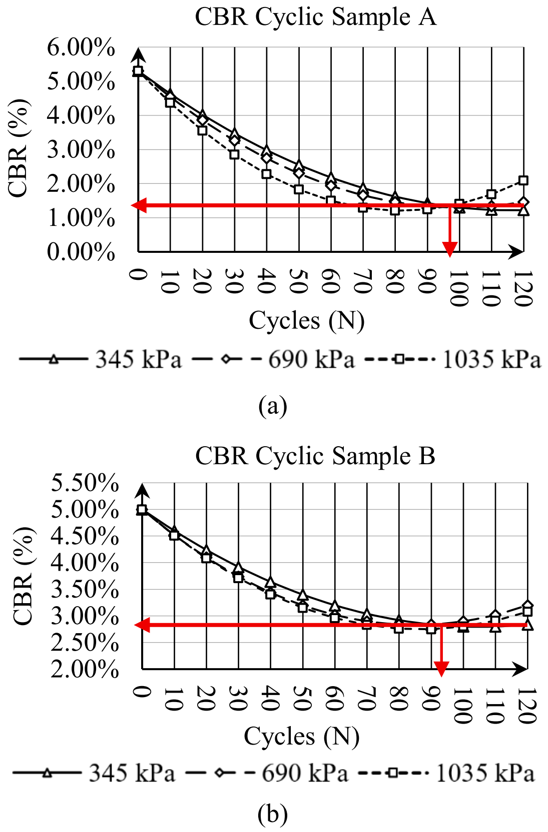


Fig 9. (a) Relationship between CBR value and loading repetitions at Point A, and (b) at Point B, under different applied pressures.

The mechanisms underlying the enhanced CBR values and reduced required soil layer thickness are associated with improved compaction characteristics, enhanced particle interlocking, and stronger soil fabric, which collectively increase load bearing capacity and stiffness

5.2 Giroud–Han Design Approach for Reinforced Subgrade Layers

The calculation results based on Eq. (1) are shown in the Table below. Subgrade strength and reinforcement type significantly affect pavement thickness, geotextiles reduced it by 38%, while geogrids achieved 52% reduction due to superior load distribution and aggregate interlocking. Similar results were reported by other research, that geotextile reinforced decreased base thickness on weak subgrades by 25–35% [11], [23]. The curve shows the relationship between the CBR value and the thickness of the subgrade improvement layer $(H_{improvement})$ resulting from calculations using the Giroud–Han method. Based on Figure 9, the number of cycles range 92-98. For comparison of pavement thickness according to cycles, refer to Figure 10-12 . For subsequent design, a value of 98 cycles was adopted. Geosynthetic reinforced is placed below the subgrade improvement layer, as shown in Figure 14.

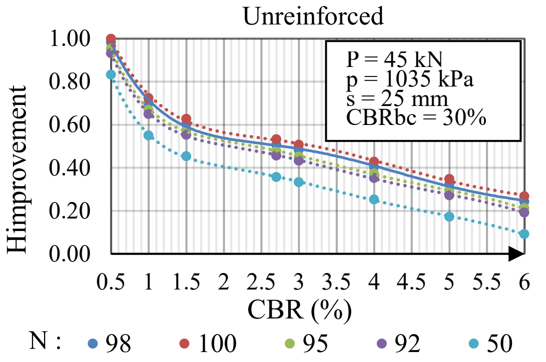


Fig. 10 Loading-cycle effect on subgrade thickness unreinforced.

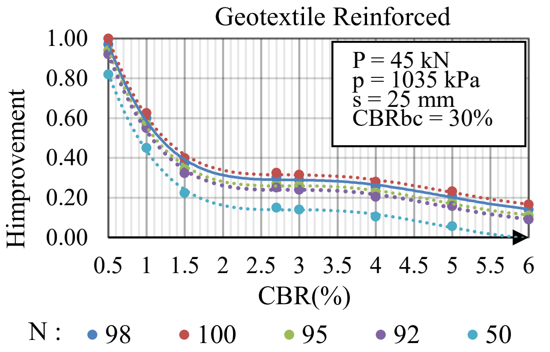


Fig. 11 Loading-cycle effect on subgrade thickness Geotextile Reinforced.

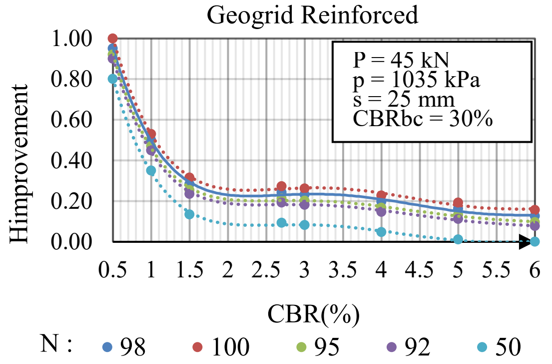


Fig. 12 Loading-cycle effect on subgrade thickness Geogrid Reinforced.

Table 3. presents the pavement thicknesses design, The results highlight the effect of cycling loading on layer thickness and provide a basis for comparison with alternative design.

Table 3. Height of subgrade improvement design.

CBR 1.4%	Himprov(m)	Improvement
Unreinforced	0.603	0.00%
Geotextile	0.373	38.19%
Geogrid	0.284	52.84%
CBR 2.7%	Himprov(m)	Improvement
Unreinforced	0.507	0.00%
Geotextile	0.316	37.67%
Geogrid	0.242	52.19%

Note: The rut depth was adjusted according to the allowable settlement limits specified in the applicable standards.

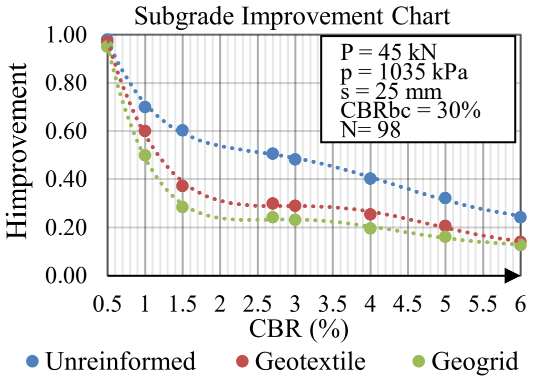


Fig 13. Subgrade improvement chart based on CBR value for different reinforced types

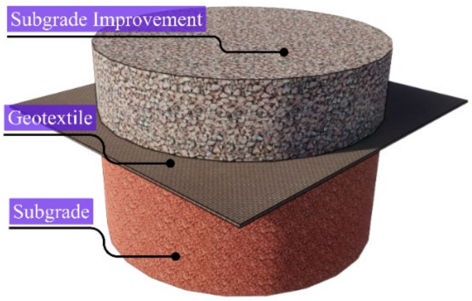


Fig. 14 Illustration of subgrade improvement system using geotextile.

5.4 Comparison of Subgrade Design under Cyclic Loading Conditions

In this study, pavement design followed the MDPJ 2024 method applicable in Indonesia, using conventional CBR. Traffic data were obtained from a one-week survey, yielding a CESA of 8 million according to MDPJ 2024 calculations. Analysis using the Giroud–Han method indicates that cyclic loading significantly affects pavement thickness and reinforcement efficiency. Figures 15–17 illustrate these conditions, cyclic CBR with reinforcement in Figure 15, cyclic loading without reinforcement in Figure 16, and conventional design ignoring cyclic effects in Figure 17. Subgrade improvement under cyclic loading with geosynthetics is 166 mm thicker than without loading, while without reinforcement it is 344 mm thicker than required, highlighting the reduction in residual CBR and the need for increased pavement thickness compared to conventional design.

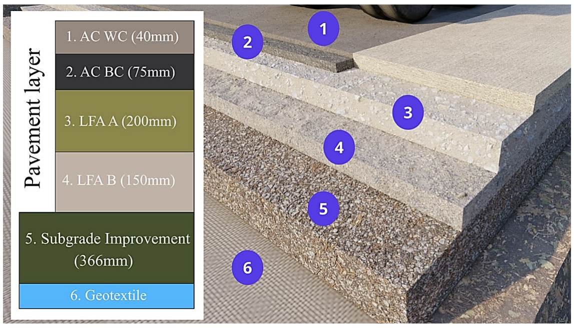


Fig 15. Subgrade design with cyclic loading and geotextile-reinforced subgrade.

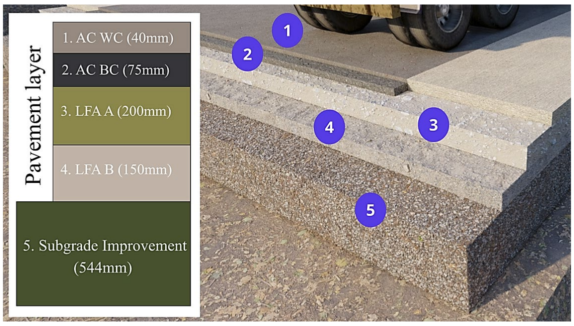


Fig 16. Subgrade design under cyclic loading without reinforced.

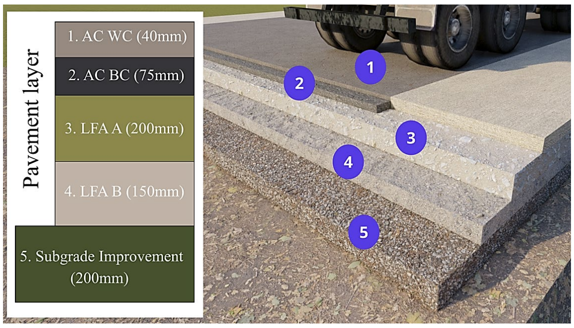


Fig 17. Subgrade design without cyclic loading and without reinforced.

6. CONCLUSION

This study shows that soaked CBR values of silty sand subgrades decrease markedly under cyclic loading. At Point A, CBR dropped from 5.3% to 1.4%, and at Point B from 5.0% to 2.7%, corresponding to reductions of 46–71% for loads between 345 and 1035 kPa. Incorporating geosynthetics enhanced subgrade performance, with geotextiles and geogrids reducing the required improvement thickness by 38% and 52%, respectively. For cyclic loads within 345–1035 kPa, assuming a rut depth limit of 25 mm and minimum subgrade improvement CBR of 30%, the decay constant k was 0.034. Soils not exposed to cyclic loading initially required no improvement however, MDPJ 2024 analysis indicates that cyclic loading necessitates increased pavement thickness. Conventional design underestimates subgrade thickness by about 34% even with reinforcement, and without reinforcement, the required thickness is nearly 70% greater.

7. ACKNOWLEDGMENTS

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