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Numerical Analysis of Road Embankment Stability and Settlement Using Variations of Bamboo Chips and Fly Ash Mixtures

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ABSTRACT

Soft soil is a major challenge in road embankment construction due to its low bearing capacity, low shear strength, and high compressibility, which can lead to excessive settlement and slope instability. Therefore, an effective ground improvement method is required to enhance the mechanical performance of the subgrade soil. This study aims to analyze the stability and deformation behavior of road embankments constructed on soft soil stabilized with *Fly Ash* and reinforced with *Bamboo Chips*. The analysis was carried out using the Finite Element Method (FEM) based on the Mohr–Coulomb constitutive model. The numerical model compared untreated and stabilised soil conditions at various percentages of Fly Ash and *Bamboo Chips*. Soil parameters were obtained from laboratory testing and incorporated into the numerical model. The analysis stages included embankment geometry modeling, load application, consolidation analysis, and safety factor analysis using the *phi/c reduction* method. The results indicate that the addition of *Fly Ash* and *Bamboo Chips* increased the embankment safety factor and reduced settlement compared to untreated soil conditions. Therefore, the combination of chemical stabilization using *Fly Ash* and reinforcement with *Bamboo Chips* has the potential to become an effective and sustainable alternative for soft soil improvement in road embankment construction in Indonesia.

Contribution to Sustainable Development Goals (SDGs):
SDG 9 : Industry, Innovation and Infrastructure
SDG 11 : Sustainable Cities and Communities
SDG 12 : Responsible Consumption and Production
SDG 13 : Climate Action
SDG 15 : Life on Land

1. INTRODUCTION

1.1. Research Background

Road infrastructure development in Indonesia frequently encounters problems with subgrade conditions, particularly in soft soils. Soft soils are generally characterized by low bearing capacity, low shear strength, and high compressibility, making them susceptible to deformation and settlement under embankment loads. These conditions may reduce embankment slope stability and increase the potential for pavement and structural failure.

The stability of structures constructed on soft soils requires ground improvement methods that enhance soil shear strength and bearing capacity. One of the commonly applied methods is stabilision using Fly Ash due to its pozzolanic properties, which can improve soil shear strength and bearing capacity [2]. In addition, bamboo-based materials have recently attracted attention as environmentally friendly stabilizing agents due to their ability to improve soil mechanical behaviour by increasing interlocking between soil particles [3]. Several studies have reported that the addition of Fly Ash and bamboo materials can improve unconfined compressive strength, shear strength, and California Bearing Ratio (CBR) values of soft soils.

The development of numerical approaches based on the Finite Element Method (FEM) has enabled more detailed analyses of soil stability and deformation behavior [4]. The Finite Element Method (FEM) is a numerical analysis approach widely applied in geotechnical engineering to simulate soil stress–strain behaviour and evaluate the safety factor and settlement of embankments constructed on soft soil 5].

1.2. *Literature Review*

Previous studies generally investigated the effects of Fly Ash and bamboo materials separately on soil mechanical properties. Therefore, this study aims to analyze the stability of road embankments on soft soil stabilized with a combination of Bamboo Chips and Fly Ash using Finite Element Method (FEM).

The improvement of soft soil has become an important topic in geotechnical engineering due to the low bearing capacity and high compressibility commonly found in soft ground conditions. Various stabilization methods have been developed to improve soil's mechanical properties and reduce the potential for excessive settlement under embankment loading. Among the materials that have recently attracted attention are bamboo-based materials and Fly Ash, both of which have shown potential in enhancing soil stability and strength. Therefore, this study reviews the use of Bamboo Chips and Fly Ash as alternative stabilization materials to improve the performance of soft soil embankments.

1.2.1. *Bamboo Chips*

The application of bamboo-based materials in soil improvement has gained increasing attention due to their environmentally friendly characteristics and their potential to enhance soil mechanical behavior. The inclusion of bamboo fibres and bamboo-derived materials has been reported to improve California Bearing Ratio (CBR), shear strength, and soil bearing capacity, thereby enhancing the stability of soft soils. Previous studies have shown that bamboo fiber and bamboo ash can improve both the physical and mechanical properties of clay soils with low stability [6]. These findings provide the basis for the present study, which evaluates bamboo-based materials as an alternative stabilisation method for soft soil embankments.

1.2.2. *Fly Ash*

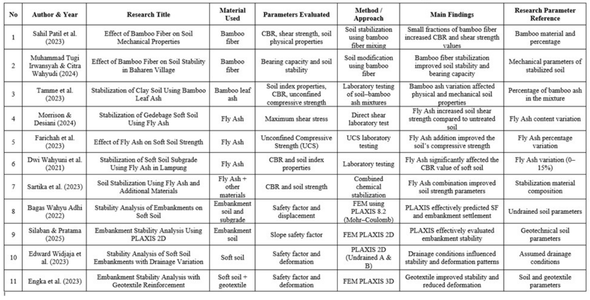
Soil stabilisation using Class F Fly Ash has been widely applied in soft soil improvement due to its pozzolanic properties, which enhance soil mechanical characteristics. Several studies have demonstrated that the addition of Fly Ash can increase shear strength, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) values of soft soils. [2]reported that Fly Ash mixtures increased the maximum shear stress of soft soil, while [7] observed improved resistance to compressive loading after stabilization treatment. In addition, [8] found that different percentages of Fly Ash significantly influenced the index and mechanical properties of soil. These results indicate that Fly Ash has strong potential as a stabilisation material to improve the stability of embankments constructed on soft soils.

1.2.3. *Finite Element Method (FEM)*

Embankment stability analysis is essential in road construction, especially on soft soils. The Finite Element Method (FEM) is widely used in geotechnical engineering to evaluate safety factors, settlement, and soil deformation, accounting for soil parameters and constitutive models such as the Mohr–Coulomb model. Previous studies have shown that FEM is effective for analyzing embankment behavior under various soil and loading conditions. [9] demonstrated that FEM could predict displacement and safety factor values on soft soils under undrained conditions. [10] also reported that FEM provided reliable evaluations of embankment slope stability.

In addition, [11] found that drainage conditions significantly affected embankment deformation and stability, while[12] showed that reinforcement materials could improve embankment performance and reduce deformation. These findings indicate that FEM is an effective numerical approach for predicting embankment stability and settlement in soft soils under various ground conditions and stabilization scenarios.

Table 1. 1 Previous Studies Related to Soft Soil Stabilization and Embankment Stability Analysis



No	Author & Year	Research Title	Material Used	Parameters Evaluated	Method / Approach	Main Findings	Research Parameter Reference
1	Sahil Patil et al. (2023)	Effect of Bamboo Fiber on Soil Mechanical Properties	Bamboo fiber	CBR, shear strength, soil physical properties	Soil stabilization using bamboo fiber mixing	Small fractions of bamboo fiber increased CBR and shear strength values	Bamboo material and percentage
2	Muhammad Tugi Irwansyah & Citra Wahyudi (2024)	Effect of Bamboo Fiber on Soil Stability in Baharen Village	Bamboo fiber	Bearing capacity and soil stability	Soil modification using bamboo fiber	Bamboo fiber stabilization improved soil stability and bearing capacity	Mechanical parameters of stabilized soil
3	Tamme et al. (2023)	Stabilization of Clay Soil Using Bamboo Leaf Ash	Bamboo leaf ash	Soil index properties, CBR, unconfined compressive strength	Laboratory testing of soil–bamboo ash mixtures	Bamboo ash variation affected physical and mechanical soil properties	Percentage of bamboo ash in the mixture
4	Morrison & Desiani (2024)	Stabilization of Gedebage Soft Soil Using Fly Ash	Fly Ash	Maximum shear stress	Direct shear laboratory test	Fly Ash increased soil shear strength compared to untreated soil	Fly Ash content variation
5	Farichah et al. (2023)	Effect of Fly Ash on Soft Soil Strength	Fly Ash	Unconfined Compressive Strength (UCS)	UCS laboratory testing	Fly Ash addition improved the soil's compressive strength	Fly Ash percentage variation
6	Dwi Wahyuni et al. (2021)	Stabilization of Soft Soil Subgrade Using Fly Ash in Lampung	Fly Ash	CBR and soil index properties	Laboratory testing	Fly Ash significantly affected the CBR value of soft soil	Fly Ash variation (0–15%)
7	Sartika et al. (2023)	Soil Stabilization Using Fly Ash and Additional Materials	Fly Ash + other materials	CBR and soil strength	Combined chemical stabilization	Fly Ash combination improved soil strength parameters	Stabilization material composition
8	Bagas Wahyu Adhi (2022)	Stability Analysis of Embankments on Soft Soil	Embankment soil and subgrade	Safety factor and displacement	FEM using PLAXIS 8.2 (Mohr–Coulomb)	PLAXIS effectively predicted SF and embankment settlement	Undrained soil parameters
9	Silaban & Pratama (2025)	Embankment Stability Analysis Using PLAXIS 2D	Embankment soil	Slope safety factor	FEM PLAXIS 2D	PLAXIS effectively evaluated embankment stability	Geotechnical soil parameters
10	Edward Widjaja et al. (2023)	Stability Analysis of Soft Soil Embankments with Drainage Variation	Soft soil	Safety factor and deformation	PLAXIS 2D (Undrained A & B)	Drainage conditions influenced stability and deformation patterns	Assumed drainage conditions
11	Engka et al. (2023)	Embankment Stability Analysis with Geotextile Reinforcement	Soft soil + geotextile	Safety factor and deformation	FEM PLAXIS 3D	Geotextile improved stability and reduced deformation	Soil and geotextile parameters

1.3. *Research Objective*

The objective of this study is to analyze the safety factor and settlement of road embankments constructed on soft soil without ground improvement based on the results of Finite Element Method (FEM) analysis. In addition, this research aims to evaluate the safety factor and settlement behaviour of embankments after stabilization of soft soil using Bamboo Chips and Fly Ash. Furthermore, the study compares the stability performance and settlement characteristics of embankments before and after soil stabilization to determine the effectiveness of Bamboo Chips and Fly Ash in improving the engineering properties of soft soil.

2. MATERIALS AND METHODS

A systematic research methodology is required to ensure that each stage of the study is conducted in a structured and organized manner. This methodology includes the research location, analysis methods, data collection procedures, and the parameters evaluated in the study. The overall research process is also illustrated using a flowchart to provide a clear description of the research stages.

The collected data were processed and analyzed through manual calculations and numerical analysis based on the Finite Element Method (FEM). The final results of the analysis consist of the safety factor and settlement values of the road embankment obtained from the stability evaluation.

2.1. *Research location*

The soft soil samples used in this research were obtained from the Bozem area of Universitas Pembangunan Nasional "Veteran"

Jawa Timur and used as subgrade data for embankment stability and settlement analysis. The location of the soil sampling point is presented in Figure 1.

Figure 1 Research Location Soil Sampling Point

2.2. Laboratory Testing

A one-dimensional consolidation test (Oedometer test) was conducted to obtain the consolidation parameters of soft soil required for the embankment settlement analysis. The parameters obtained from this test included the Compression Index (Cc), Swelling Index (Cs), and Coefficient of Consolidation (Cv). The test was carried out using an Oedometer apparatus under incremental vertical loading on saturated soil specimens, with specimen height monitored over time until primary consolidation was achieved.

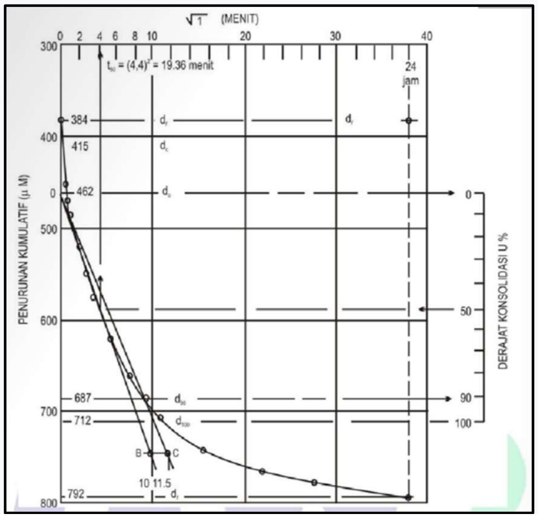


Figure 3. Graph Of The Relationship Between Root Time And Cumulative Decline.

Time Root Method:

$$c_v = \frac{0{,}112\times {H_r}^2}{t_{90}} \text{...(2.1)}$$

Logarithmic Method of Time :

$$c_v = \frac{0{,}026\times {H_r}^2}{t_{50}} \text{...(2.2)}$$

The Compression Index (Cc) was determined from the slope of the void ratio and effective vertical stress relationship (e-log \sigma').

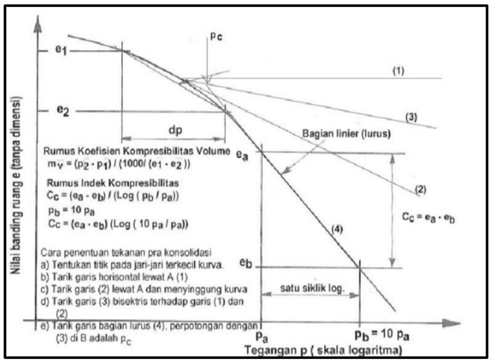


Figure 2 Cc Value Determination Graph

$$C_c = \frac{e_a - e_a}{\log(\frac{p_b}{p_a})} \text{...(2.3)}$$

2.3. Numerical Modeling

2.3.1. Geometry Data

The embankment design was developed based on the Detail Engineering Design (DED) of the planned road section. The embankment slope was designed with a 1V:2H ratio, and the hard soil depth was determined from bore log data at 30 m. The road embankment geometry is presented in Figure 4.

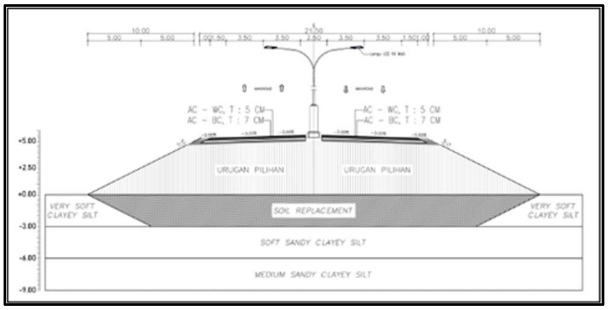
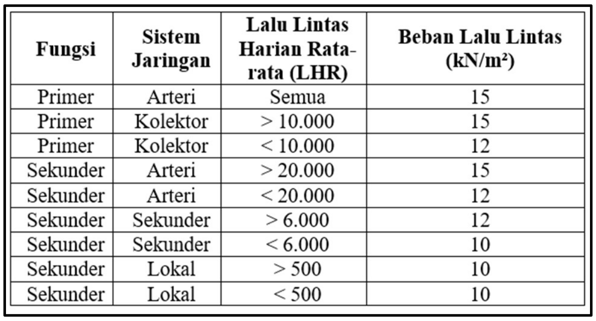


Figure 3 . Road Embankment Design

As shown in Figure 2.4, the upper soft soil layer from elevation 0.00 m to –3.00 m was excavated and replaced with stabilized soil material. The replacement layer consisted of soft soil mixed with Fly Ash and Bamboo Chips as stabilization materials. This soil replacement method was applied to improve the engineering properties of the subgrade, increase embankment stability, and reduce settlement under loading conditions.

2.3.2. Loading Data

The pavement and traffic loading used in this study were determined according to the guidelines provided in Kimpraswil Guideline No. Pt T-10-2002-B. The traffic load parameters applied in the analysis are shown in Figure 5.



Fungsi	Sistem Jaringan	Lalu Lintas Harian Rata-rata (LHR)	Beban Lalu Lintas (kN/m²)
Primer	Arteri	Semua	15
Primer	Kolektor	> 10.000	15
Primer	Kolektor	< 10.000	12
Sekunder	Arteri	> 20.000	15
Sekunder	Arteri	< 20.000	12
Sekunder	Sekunder	> 6.000	12
Sekunder	Sekunder	< 6.000	10
Sekunder	Lokal	> 500	10
Sekunder	Lokal	< 500	10

Figure 4. Traffic Load Parameters

2.3.3. FEM Analysis Procedure

The numerical analysis was performed using the Finite Element Method (FEM), modelling both untreated and stabilized soil conditions with Bamboo Chips and Fly Ash. The analysis stages included project setup, input of soil parameters, embankment geometry modeling, loading application, mesh generation, groundwater level definition, and boundary condition assignment. A staged construction method was then applied to simulate the embankment construction sequence until the final condition was reached.

The analysis results consisted of safety factor and settlement values obtained from the numerical output. These values were compared for each stabilization variation to evaluate the influence of Bamboo Chips and Fly Ash on the stability performance of road embankments constructed on soft soil

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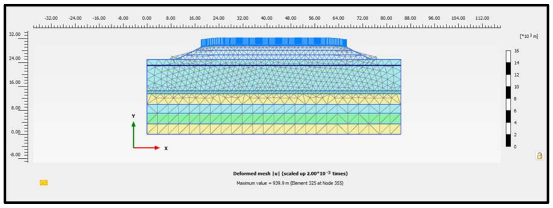


Figure 5 *Output* FEM

2.3.4. Research Flowchart

The overall research procedure is summarized in the flowchart presented in Figure .7.

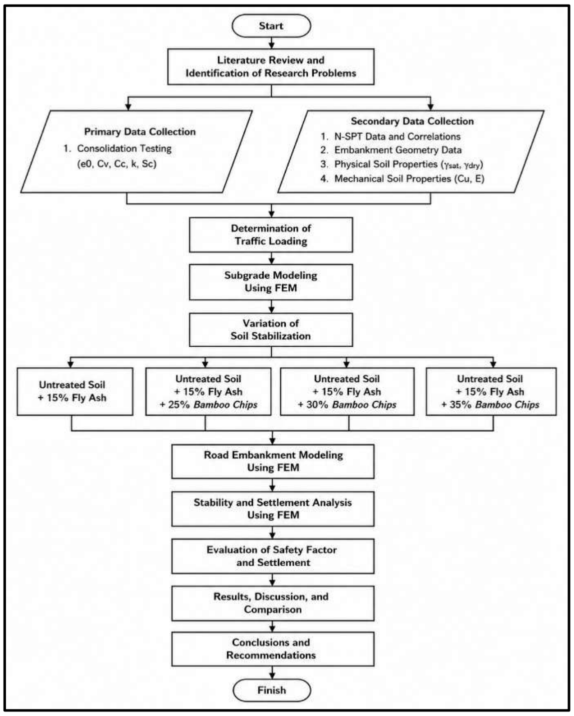
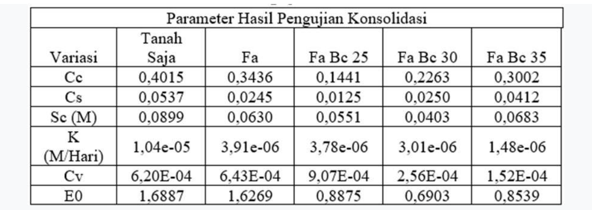


Figure 6 Research Flowchart

3. RESULT AND DISCUSSION

3.1. Consolidation Test Results (Oedometer Test)

The consolidation test was conducted on untreated soil and several mixtures of *Fly Ash* and *Bamboo Chips* to obtain the soft soil consolidation parameters used in the settlement analysis through the Finite Element Method (FEM). The evaluated parameters included the *Compression Index* (Cc), *Swelling Index* (Cs), coefficient of permeability (k), *Coefficient of Consolidation* (Cv), initial void ratio (e0), and consolidation settlement (Sc).



Parameter Hasil Pengujian Konsolidasi					
Variasi	Tanah Saja	Fa	Fa Bc 25	Fa Bc 30	Fa Bc 35
Cc	0,4015	0,3436	0,1441	0,2263	0,3002
Cs	0,0537	0,0245	0,0125	0,0250	0,0412
Sc (M)	0,0899	0,0630	0,0551	0,0403	0,0683
K (M/Hari)	1,04e-05	3,91e-06	3,78e-06	3,01e-06	1,48e-06
Cv	6,20E-04	6,43E-04	9,07E-04	2,56E-04	1,52E-04
E0	1,6887	1,6269	0,8875	0,6903	0,8539

Figure 8. Laboratory Test Results

The test results indicate that the addition of stabilization materials significantly influenced the consolidation characteristics of soft soil (Figure 8). . The Cc value of untreated soil was 0.4015 and decreased in all stabilization variations, with the lowest value of 0.1441 obtained from the mixture containing 15% *Fly Ash* and 25% *Bamboo Chips*. This reduction indicates lower soil compressibility and improved resistance to loading. Similarly, the Cs value decreased from 0.0537 in untreated soil to 0.0125 in the same variation, indicating reduced swelling potential.

https://doi.org/10.29165/ajarcde.v10i2.1052

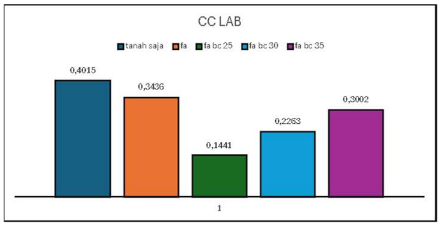


Figure 9 Relationship Between Cc Value and Stabilization Variation

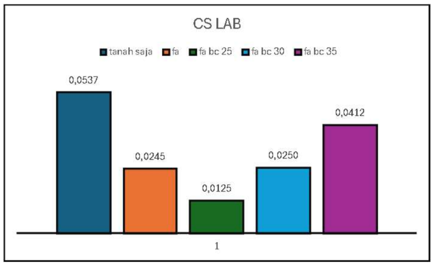


Figure 10. Relationship Between Cs Value and Stabilization Variation

For consolidation settlement (Sc), untreated soil produced the highest value of 0.0899 m, while the lowest value of 0.0403 m was obtained from the 15% Fly Ash + 30% Bamboo Chips mixture. This result shows that the stabilization materials were effective in reducing the potential for long-term settlement. In addition, the initial void ratio (e0) decreased from 1.6887 to 0.6903, indicating a denser soil structure after stabilization.

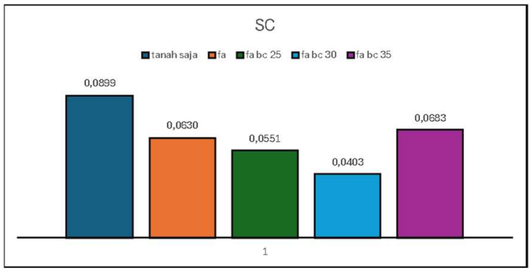


Figure 10. Relationship Between Sc Value and Stabilization Variation

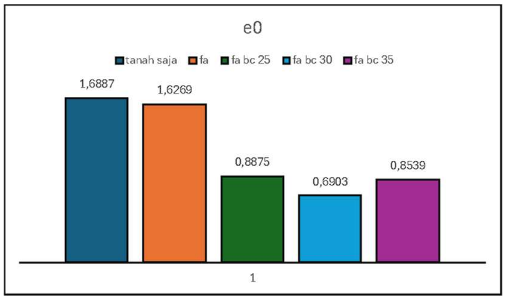


Figure 11. Relationship Between e0 Value and Stabilization Variation

The coefficient of consolidation (Cv) increased in the stabilized soil mixtures, with the highest value of 9.07×10^{-4} obtained from the 15% Fly Ash + 25% Bamboo Chips variation. Meanwhile, the permeability coefficient (k) generally decreased after stabilization due to the pozzolanic reaction of Fly Ash, which reduced soil voids and produced a denser soil structure. However, a slight increase in permeability was observed at higher Bamboo Chips contents. This behaviour is associated with the physical characteristics of bamboo particles, which have irregular shapes, rough, fibrous surfaces, and relatively larger dimensions than those of clay particles. Excessive bamboo content may create interconnected macro-pores and a non-uniform pore distribution within the clay matrix, resulting in preferential water-flow channels.

Consequently, the hydraulic conductivity of the stabilized soil tends to increase even as soil strength improves. Similar behaviour was reported by [13], who explained that the addition of bamboo fibres modifies soil structure by forming voids between soil particles and fibres, thereby affecting particle interactions and altering soil engineering properties.

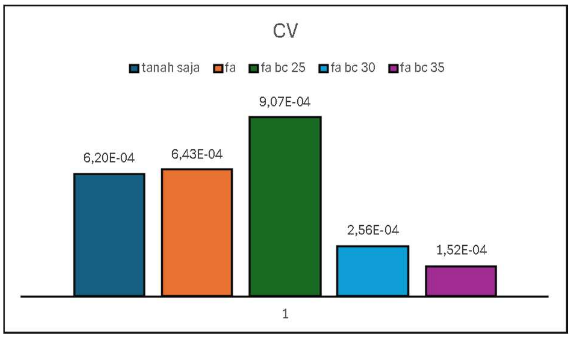


Figure 12. Relationship Between Cv Value and Stabilization Variation

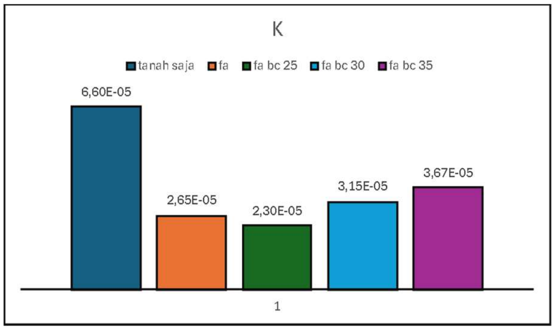


Figure 13. Relationship Between k Value and Stabilization Variation

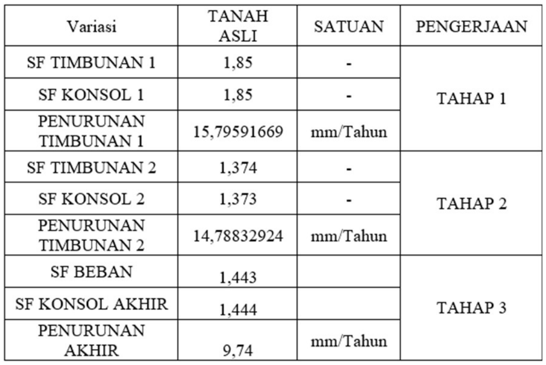
Overall, the results demonstrate that the combination of *Fly Ash* and *Bamboo Chips* improved the consolidation behavior of soft soil and reduced the settlement potential of road embankments.

3.2. Analysis of Safety Factor and Embankment Settlement on Untreated Soil

The embankment analysis under untreated soil conditions was carried out using the Finite Element Method (FEM) to evaluate stability and settlement behaviour without stabilization treatment. The analyzed parameters included the Safety Factor (SF) and consolidation settlement at each loading stage.

The analysis results indicate that during Embankment Stage 1, the SF value reached 1.85, indicating that the embankment condition was still stable and satisfied the minimum safety requirement (SF > 1.5). The settlement rate at this stage was 15.80 mm/year, with a total settlement of 263.9 mm. During Embankment Stage 2, the SF value decreased to 1.374, indicating the onset of instability under additional loading. The settlement rate at this stage reached 14.79 mm/year, while the total settlement increased to 494.7 mm.

Under the final loading condition, the SF value was 1.443, which remained below the required safety limit. Meanwhile, the final settlement rate was recorded at 9.74 mm/year, with a cumulative settlement of 596.7 mm.



Variasi	TANAH ASLI	SATUAN	PENGERJAAN
SF TIMBUNAN 1	1,85	-	TAHAP 1
SF KONSOL 1	1,85	-	
PENURUNAN TIMBUNAN 1	15,79591669	mm/Tahun	
SF TIMBUNAN 2	1,374	-	TAHAP 2
SF KONSOL 2	1,373	-	
PENURUNAN TIMBUNAN 2	14,78832924	mm/Tahun	
SF BEBAN	1,443		TAHAP 3
SF KONSOL AKHIR	1,444		
PENURUNAN AKHIR	9,74	mm/Tahun	

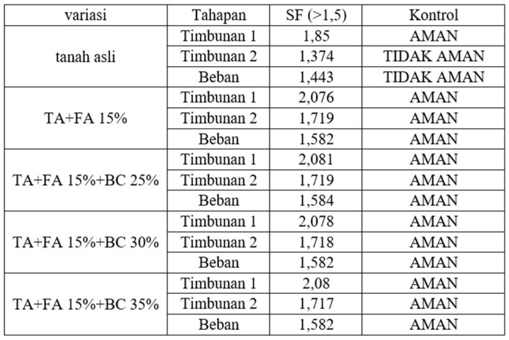
Figure 14. Recapitulation of FEM Analysis Results for Untreated Soil

Although the settlement values remained within the allowable limit for road embankments (<20 mm/year), the analysis shows that untreated soft soil exhibited relatively low stability under advanced loading conditions.

3.3. *Analysis of Safety Factor and Embankment Settlement with Stabilization Materials*

The FEM analysis results indicate that the addition of stabilization materials, in the form of Fly Ash and Bamboo Chips, significantly improved embankment stability and reduced settlement in soft soil.

Under untreated soil conditions, the Safety Factor (SF) values decreased during Embankment Stage 2 and the final loading stage to 1.374 and 1.443, respectively, indicating that the embankment did not satisfy the minimum safety requirement (SF > 1.5). After stabilization using 15% Fly Ash combined with Bamboo Chips, all variations produced SF values greater than 1.5 at each loading stage, indicating stable embankment performance. The highest SF value during Embankment Stage 1 was 2.081 for the variation containing 15% Fly Ash and 25% Bamboo Chips, while the final loading stage produced SF values ranging from 1.582 to 1.584 for all stabilization variations.

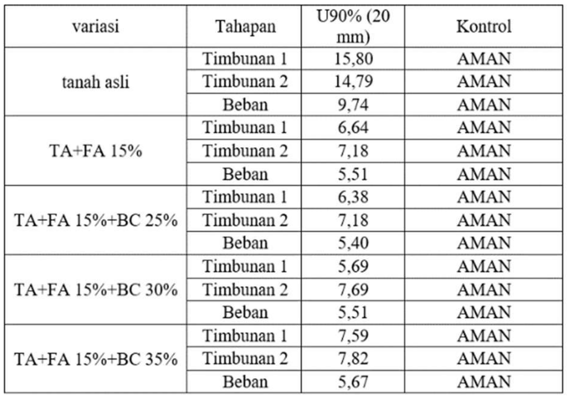


variasi	Tahapan	SF (>1,5)	Kontrol
tanah asli	Timbunan 1	1,85	AMAN
	Timbunan 2	1,374	TIDAK AMAN
	Beban	1,443	TIDAK AMAN
TA+FA 15%	Timbunan 1	2,076	AMAN
	Timbunan 2	1,719	AMAN
	Beban	1,582	AMAN
TA+FA 15%+BC 25%	Timbunan 1	2,081	AMAN
	Timbunan 2	1,719	AMAN
	Beban	1,584	AMAN
TA+FA 15%+BC 30%	Timbunan 1	2,078	AMAN
	Timbunan 2	1,718	AMAN
	Beban	1,582	AMAN
TA+FA 15%+BC 35%	Timbunan 1	2,08	AMAN
	Timbunan 2	1,717	AMAN
	Beban	1,582	AMAN

Figure 15. Recapitulation of SF Values for All Variations

These results demonstrate that the stabilization materials improved the bearing capacity and stability of the subgrade under embankment and traffic loading.

Based on the consolidation settlement analysis, all stabilized soil types showed lower settlement values than untreated soil. The highest settlement in untreated soil occurred during Embankment Stage 1 at 15.80 mm/year, whereas the stabilized soil showed settlement values ranging from 5.40 to 7.82 mm/year. The lowest final settlement value, 5.40 mm/year, was obtained from the 15% Fly Ash + 25% Bamboo Chips variation, while the 15% Fly Ash + 30% Bamboo Chips variation produced a settlement value of 5.51 mm/year.



variasi	Tahapan	U90% (20 mm)	Kontrol
tanah asli	Timbunan 1	15,80	AMAN
	Timbunan 2	14,79	AMAN
	Beban	9,74	AMAN
TA+FA 15%	Timbunan 1	6,64	AMAN
	Timbunan 2	7,18	AMAN
	Beban	5,51	AMAN
TA+FA 15%+BC 25%	Timbunan 1	6,38	AMAN
	Timbunan 2	7,18	AMAN
	Beban	5,40	AMAN
TA+FA 15%+BC 30%	Timbunan 1	5,69	AMAN
	Timbunan 2	7,69	AMAN
	Beban	5,51	AMAN
TA+FA 15%+BC 35%	Timbunan 1	7,59	AMAN
	Timbunan 2	7,82	AMAN
	Beban	5,67	AMAN

Figure 16. Recapitulation of Settlement Values for All Variations

All settlement values remained below the allowable limit for road embankments, which is less than 20 mm/year. Overall, the study demonstrates that the combination of Fly Ash and Bamboo Chips improved the engineering characteristics of soft soil, increased the safety factor, and reduced the settlement potential of road embankments.

Based on the analysis results, the variation containing 15% Fly Ash and 25% Bamboo Chips provided the most effective performance in enhancing embankment stability and minimizing soil settlement. Although the 15% Fly Ash + 30% Bamboo Chips variation showed better physical consolidation characteristics in laboratory testing, particularly lower consolidation settlement (Sc) and smaller initial void ratio (e0), the FEM analysis indicated that the 25% variation produced a more stable embankment response. This difference suggests that embankment performance in the numerical model was not solely controlled by consolidation parameters, but was also strongly influenced by the interaction between soil strength and stiffness parameters used in the FEM analysis.

The addition of Bamboo Chips at higher percentages may improve soil densification and reduce compressibility in laboratory-scale consolidation testing; however, excessive bamboo content can also create a more heterogeneous soil structure and reduce uniform particle interaction. As a result, the overall stiffness and stress distribution within the embankment model may become less effective under loading conditions. Consequently, although the 30% variation exhibited improved physical compaction characteristics, the 25% variation produced a more balanced combination of compressibility reduction, shear resistance, and deformation control in the numerical analysis. This indicates that the optimal stabilisation composition should not be evaluated solely on the basis of laboratory consolidation parameters, but also on the overall mechanical response obtained from FEM embankment analysis.

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4. CONCLUSION

The FEM analysis results indicate that untreated soft soil experienced a reduction in Safety Factor (SF) under advanced loading stages. During Embankment Stage 1, the SF value of 1.85 still satisfied the minimum safety requirement. However, the value decreased to 1.374 in Embankment Stage 2 and 1.443 under the final loading condition, indicating that the embankment condition became unstable. Despite this, the settlement rate of 9.74 mm/year remained within the allowable limit for road embankments.

The addition of stabilization materials, in the form of Fly Ash and Bamboo Chips, proved effective in improving embankment stability and reducing settlement in soft soil. All stabilization variations yielded SF values greater than 1.5 and settlement rates below 20 mm/year, indicating that the embankment met the required safety and serviceability criteria. The most effective result was achieved by the mixture containing 15% Fly Ash and 25% Bamboo Chips, which produced a final SF value of 1.584 and a settlement value of 5.40 mm/year.

In general, the use of Fly Ash and Bamboo Chips improved the engineering behaviour of soft soil under embankment loading. However, excessive addition of Bamboo Chips tended to increase settlement values again, indicating that higher bamboo content may reduce the effectiveness of soil stabilization.

Future studies are recommended to investigate a wider range of Fly Ash and Bamboo Chips mixtures to determine the optimal stabilization composition for improving embankment stability and minimizing settlement. The use of more advanced soil constitutive models, such as the Hardening Soil Model or Soft Soil Model, should also be considered to better represent field soil behaviour. This recommendation is important because the Mohr–Coulomb model assumes linear-elastic-perfectly plastic soil behaviour and cannot fully capture the stress-dependent stiffness, creep behaviour, and consolidation characteristics commonly observed in soft soils. In contrast, the Soft Soil Model is better suited to simulate highly compressible soils because it can more realistically represent nonlinear stress–strain relationships and time-dependent consolidation behaviour.

In addition, external factors, including groundwater fluctuations, dynamic traffic loading, and seismic effects, should be incorporated into future analyses to yield more comprehensive results. Further studies may also apply consolidation acceleration methods, such as Prefabricated Vertical Drains (PVDs) or sand drains, to shorten consolidation time. Long-term investigations into the durability of Bamboo Chips under environmental exposure and moisture variations are also necessary to evaluate their effectiveness as a sustainable soft-soil stabilization material.

In addition, future research is recommended to examine lower percentages of Bamboo Chips than those used in this study in order to evaluate the influence of reduced bamboo content on the Safety Factor and settlement values. This recommendation is important because the present results indicate that excessive Bamboo Chips content tends to increase soil settlement again. Therefore, further investigation is required to identify the optimal proportion of Bamboo Chips for soft soil stabilization.

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