

Putu SARI ✉ 

Mohamad ANSORI 

Noor Endah MOCHTAR 

Laode VIZENTHE

Amanda ANNIDA

Anggoro ATMOJO

Institute Teknologi Sepuluh Nopember, Department of Civil Engineering, Indonesia

Evaluating the effectiveness of foam mortar as a lightweight fill for reducing foundation settlement on soft soils: a case study of Indonesian toll road projects

Keywords: foam mortar, lightweight fill, settlement reduction, slope stability, soft soil, ground improvement

Introduction

The issue of subsoil consolidation beneath road embankments is a primary constraint in the development of toll road infrastructure in Indonesia. The completion of consolidation is necessary before the road becomes operational to prevent premature damage to the overlying pavement structure. However, the natural consolidation process requires significant time, which often conflicts with tight project completion schedules. The need to operationalize toll roads rapidly is urgent,

driven by the focus on enhancing connectivity and economic considerations for investors. Consequently, several methods to accelerate soil consolidation continue to be developed. Conventional methods such as prefabricated vertical drains (PVD), sand drains, and stabilization using piles have been the cornerstone solutions. However, the application often faces the major constraint of high cost, specifically because toll road sections can extend for thousands of kilometers.

The need for a more economical alternative has led to the widespread adoption of a strategy to minimize compression magnitude by reducing embankment load. This strategy requires replacing conventional fill material with a unit weight above $18 \text{ kN}\cdot\text{m}^{-3}$ using lightweight fill. The significantly lower unit weight of the material can substantially reduce the vertical pressure on the subsoil and shorten both the duration and magnitude of settlement.

Previous studies have reported on the effectiveness of different lightweight materials. For example, Zaika et al. (2023) used expanded polystyrene (EPS) beads mixed with cement (geo-beads) – a product with a very low bulk density ($10.08 \text{ kg}\cdot\text{m}^{-3}$). The application of finite element method analysis showed that the material reduced settlement by 1.8–1.9 m in clayey silt soil. Abbasi et al. (2024) also evaluated several ground improvement methods and found that lightweight foamed concrete (LWFC) was the most effective, reducing settlement by 35% due to its low density ($6 \text{ kN}\cdot\text{m}^{-3}$) and high stiffness. Similar results were reported by several other studies (Marradi et al., 2012; Hao et al., 2024; Dou et al., 2025).

Innovation has led to the use of recycled materials, such as the compaction of waste tires into bales or cuboidal blocks of compressed whole tires to produce embankment material (Duda & Siwowski, 2022). The material offers advantages such as very low density (about $5 \text{ kN}\cdot\text{m}^{-3}$), high permeability, and sustainability. The results also showed that the tire bales reduced settlement by 28–33% compared to sand-filled embankments and improved slope stability in silty clay. Similarly, Ratha et al. (2018) investigated lightweight technologies and the so-called masonry arch bridge concept to reduce settlement in soft soils and to assess their environmental impact.

Several recent studies further strengthened the evidence, as observed in the report of Buathong et al. (2025), that the settlement in a conventional embankment was approximately 13.1 times greater than in a lightweight embankment on soft Bangkok clay. Ali et al. (2025) also showed that EPS particles predominantly govern the deformation process in silt-EPS mixtures by accounting for 55% to 80%. Moreover, Brouwer and Laerhoven (2024) proposed using foam glass as a lightweight fill for soft soil conditions, and initial field and laboratory results showed promising potential.

Most of these studies focus on new materials and laboratory-scale modelling, while field applications remain limited. In Indonesia, the Ministry of Public Works and Housing (PUPR) has issued a special specification for foam mortar material with a maximum dry density of $8 \text{ kN} \cdot \text{m}^{-3}$ as an embankment replacement. This is necessary to provide a regulatory foundation for the application in national road projects. This research on the use of lightweight materials was conducted not only to address settlement issues but also to consider slope stability, given that landslides have occurred in several sections of toll roads in Indonesia, both on embankments (Sari & Mochtar, 2023) and in cutting slopes (Sari et al., 2022).

Specifications are available in Indonesia, but the understanding of the performance of this material in relation to the diverse geotechnical conditions of the country requires in-depth investigation. Lastiasih and Mochtar (2022) provided initial insight by modeling two toll road sections and showed that the combination of 75% foam mortar and 25% granular soil could reduce settlement by a factor of 0.6 and increase the slope safety factor (*SF*) by 1.46 compared to a conventional embankment. However, the study was limited to soft soil at a depth of 12 m. A similar study on the use of foam mortar to analyze subsoil compression with several variations was also conducted by Efendi (2023), Jusi et al. (2024), and Jusi et al. (2025). However, that study also had certain limitations specific to its respective case study condition.

Field conditions, such as those on the Java, are highly variable in reality, both in terms of soft soil depth and embankment height. The impact of secondary consolidation settlement has also often not been adequately considered in existing studies. Therefore, this study aims to analyze the effectiveness of using foam mortar to reduce both primary and secondary settlement and enhance slope stability across three scenarios with variations in embankment height and soft soil depth in order to fill the identified gap. Another aim is to provide numerically simulated design recommendations for the application of foam mortar under specific geotechnical conditions in Indonesia for three study locations. These include Semarang–Demak 1A Sta 8+314–Sta 8+494, 1B Sta 2+850–Sta 3+010, Kediri–Kertosono (Sta 18+600–Sta 20+300), and Probolinggo–Banyuwangi Sta 45+300–Sta 46+000 sections.

The construction of toll roads on soft soil in Indonesia is associated with significant geotechnical challenges, which primarily focus on excessive and long-lasting settlement. Therefore, this study aims to evaluate the effectiveness of foam mortar as a lightweight fill to mitigate these issues across three distinct toll road projects, including Probolinggo–Banyuwangi, Kediri–Kertosono, and Semarang–Demak. The method used was comprehensive numerical analysis

with a focus on assessing the magnitude and rate of subsoil compression as well as slope stability under different scenarios of varying embankment heights, soft soil depths, and soil improvement strategies, including PVD and replacement. The results consistently showed that incorporating foam mortar significantly reduced settlement. An increase in foam mortar percentage in the embankment also led to a substantial decrease in compression magnitude. The optimal performance was observed at a mix of 75% foam mortar and 25% soil for high embankments. Furthermore, this study provided customized, efficient design solutions for each site. The trend shows that foam mortar is a viable and cost-effective alternative to conventional methods. This is because the application enhances slope stability and ensures compliance with stringent settlement rate criteria to offer a practical solution for infrastructure development on compressible soils.

Material and methods

This study analyzes the effect of lightweight fill on subsoil compression by accounting for both primary and secondary consolidation. Analyzing secondary settlement is crucial in this study, considering that several previous studies have demonstrated its influence on the stability of overlying road embankments (Chow et al., 2019; Aryandi et al., 2025). The research methodology is outlined in the accompanying flowchart (Fig. 1).

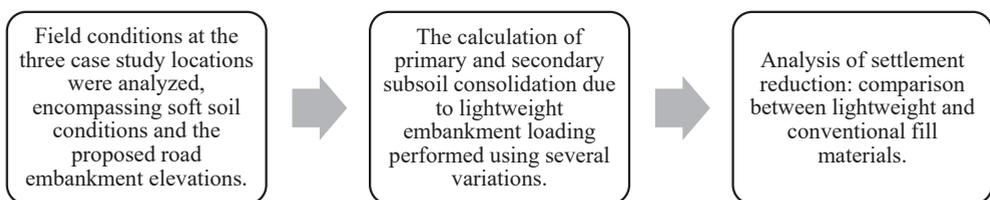


FIGURE 1. Research method

Source: own work.

The magnitude of secondary consolidation was determined and calculated using the method developed by Dhianty and Mochtar (2018). The occurrence of secondary consolidation over a relatively long period motivated Dhianty and Mochtar (2018) to recommend preloading before the operational period. This is required to eliminate the secondary consolidation (S_s) by applying a surcharge load (Δq). The magnitude of the surcharge is designed to induce an amount of settlement

equivalent to the expected secondary consolidation in addition to the primary consolidation (S_c).

The surcharge can be removed at the completion of the primary consolidation period. The completion of soil improvement through preloading stops further settlement from either primary or secondary consolidation. The determination of the magnitude of Δq and the initial embankment height (H_{init}) required to account for both S_c and S_s , presented as $H_{init(p+s)}$, requires calculating S_c , S_s , and S_c plus S_s for several iterations of load (q). The H_{init} needed to eliminate only primary consolidation is subsequently determined for all load iterations. The calculations can be used to generate the curves of H_{init} versus q_{fin} and H_{fin} versus H_{init} .

The extra surcharge load (Δq) required to eliminate S_s is further determined as follows. The Δq is removed after the soil improvement process is complete. The $H_{init(p+s)}$ represents the required initial embankment height to eliminate both primary and secondary consolidation. Therefore, it can be plotted on the curve to determine the corresponding final embankment height after settlement from both consolidation types has occurred, presented as $H_{fin(p+s)}$.

The removal of Δq from the embankment upon completion of preloading ensures the actual final embankment height in the field is less than $H_{fin(p+s)}$. The repetition of the process for all load (q) iterations leads to the generation of $H_{fin(p+s)}$ versus final embankment height ($H_{fin-field}$) and $H_{init(p+s)}$ versus $H_{fin-field}$ curves to determine $H_{init(p+s)}$ needed to eliminate both primary and secondary consolidation for any specified $H_{fin-field}$.

Several technical specifications are required for producing foam mortar, particularly regarding the cement, sand, foaming agent, and water. The parameters of common borrow material for embankment, foam mortar material, and subgrade soil are shown in Table 1.

TABLE 1. The parameters of common borrow material for embankment, foam mortar, and subgrade soil

Parameter	Common borrow material	Foam mortar	Soil subgrade
Bulk unit weight (γ) [$\text{kN}\cdot\text{m}^{-3}$]	18	8	It varies in consistency from very soft to soft clay at depth, depending on the study location.
Undrained shear strength (C_u) [$\text{kN}\cdot\text{m}^{-2}$]	0	0	
Internal friction angle (Φ) [$^\circ$]	30	40	

Source: own work.

The lightweight embankment material was specifically designed to replace conventional soil embankments with the primary purpose of reducing the load on the supporting subsoil. This is particularly beneficial for construction on soft soil, where excessive settlement is a concern. Several key parameters lead to reduced settlement at very low density, with a maximum planned dry density of $8 \text{ kN}\cdot\text{m}^{-3}$. This is significantly lighter than traditional compacted soil fills and drastically reduces the vertical stress, or overburden pressure, imposed on weak, compressible subsoils, thereby minimizing settlement. The second is the specified compressive strength (*UCS*) because the material provides structural integrity to the embankment. The two strength grades are specified as $UCS \geq 800 \text{ kPa}$ ($800 \text{ kN}\cdot\text{m}^{-2}$) for lower foundation layers or general embankment fill, and $UCS \geq 2,000 \text{ kPa}$ ($2,000 \text{ kN}\cdot\text{m}^{-2}$) for the main foundation layer. This ensures the embankment is stable and can distribute loads effectively without excessive internal deformation.

Case study area

The case study for geofoam application was conducted at three locations with different ground and site conditions. These locations include the Probolinggo–Banyuwangi Freeway Section Sta 45+300–Sta 46+000 (Fig. 2), the Kediri–Kertosono Freeway Section Sta 18+600–Sta 20+300 (Fig. 3), and the Semarang–Demak Freeway (Fig. 4), which comprises Section 1A (Sta 8+314–Sta 8+494) and Section 1B (Sta 2+850–Sta 3+010). The locations have different subsoil conditions and designed embankment heights, which result in the application of varying geofoam treatment methods. The focus on applying lightweight material across the three locations and conditions is based on a unified objective: reducing the impact of soil compression and enhancing the stability of the high embankments. Indonesian regulations stipulate that the rate of settlement in subsoils cannot exceed 2 cm per year. This requirement is in place to prevent cracking in the road pavement, which can pose dangers to freeway users.

The Kediri–Kertosono Toll Road, represents the second analyzed location. While this toll road is essential, it also poses a challenge for the Kediri watersheds, which are affected by its construction (Ansori et al., 2025). The section between



FIGURE 2. Probolinggo–Banyuwangi Toll Road project location – Section Sta 45+300– Sta 46+000
Source: own work based on Google Earth orthophoto.



FIGURE 3. Studied the location of Kediri–Kertosono Toll Road
Source: project report.

Sta 16+900 and Sta 20+300 traverses low-lying ground and is consequently planned to be constructed on an embankment with fill height varying from 4 m to 10 m. The subsoil condition consists of soft soil with an N -value of the standard penetration test of less than 10, and the thickness varies from 5 m to 9 m. The description shows that the design planned in this study requires embankment construction using two methods, including the replacement of subsoil material combined with preloading, as well as the use of conventional fill soil with foam mortar. The subsoil conditions with a soft soil thickness of up to 5 m, as observed in Sta 16+900–Sta 18+600, require subsoil replacement with preloading and without PVD. The replacement depth is expected to range from 2 m to 3 m. Meanwhile, a soft soil thickness of up to 9 m, as observed in Sta 18+600–Sta 20+300, requires a combination of conventional fill soil and foam mortar.



FIGURE 4. Studied the location of Semarang–Demak Toll Road
Source: project report.

The Semarang–Demak Toll Road, represents the third analyzed location. Section 1A, with a total length of 2.08 km, was constructed over swamps and ponds, while Section 1B extends for 6.4 km and is located over the Java Sea. The primary challenge in the construction process is that the embankment must be placed on deep, soft subsoil extending to 25 m. The research at this location is specifically focused on locations above very high embankments, namely 10.3 m, using 100% foam mortar as a substitute for ordinary embankment materials.

Results and discussion

The focus on using lightweight material in the form of foam mortar in the Probolinggo–Banyuwangi Toll Road project represents the first location analyzed in this study, addressing three main aspects. These included the magnitude of subsoil compression, the rate of subsoil compression, and slope stability under different embankment conditions. The magnitude of subsoil compression results showed that subsoil compression increased proportionally with the thickness of the compressible soil layer. For example, the compression occurring in an eight-meter-thick soil layer using the PVD method was greater than in a six-meter-thick layer. An identical trend was observed for the replacement method, where compression under a six-meter thickness was greater than under a four-meter thickness. This comparison was conducted using an identical percentage of foam mortar. A total of five variations of foam mortar percentage were used. The results showed that an increase in the foam mortar percentage in the embankment material significantly reduced the magnitude of compression. This trend occurred consistently across all tested variations for both PVD and replacement methods, as well as all thicknesses of the soft soil layer. The comparison of the two methods with the same foam mortar percentage showed that the compression from PVD was generally greater than the replacement (Fig. 5). This direct comparison was particularly evident in the six-meter-thick soil layer.

The subsoil compression rate results showed that the planned rate of embankment compression using both PVD and replacement methods (Fig. 6) generally met the specifications set by the Directorate General of Highways. An exception was found for the embankment over a six-meter-thick soft soil layer, where the rate failed from the second year to the third year, and the deficiency continued up to the twelfth year despite implementing a three-meter-thick replacement. This showed that the replacement method was recommended for the six-meter-thick soil layer due to the failure to satisfy the required compression rate criteria.

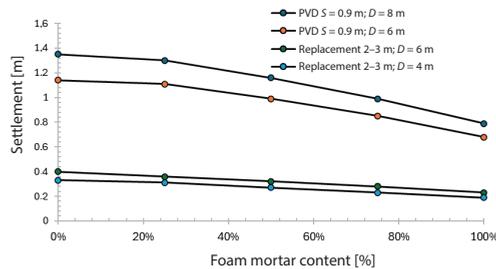


FIGURE 5. Comparison of the effect of foam mortar percentage on settlement for two improvement methods

Source: own work.

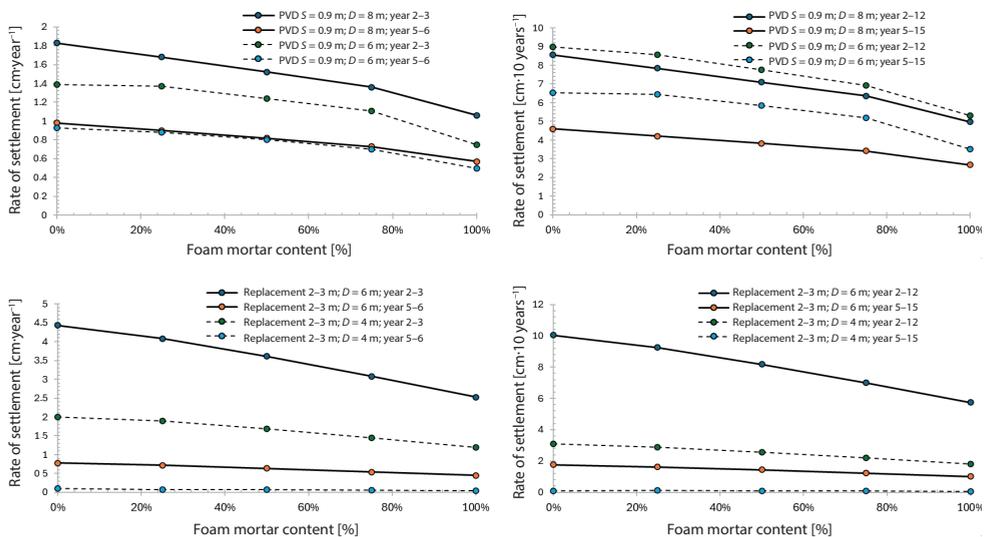


FIGURE 6. Effect of foam mortar percentage on rate of settlement for each ground improvement method for the Probolinggo–Banyuwangi Toll Road

Source: own work.

Slope stability results showed that several embankment conditions had *SF* values below 1.5. Although slope failures manifest in three dimensions, a two-dimensional analysis was employed for this study. This decision is supported by the work of Sari et al. (2020) and Sari et al. (2022), in which the amount of reinforcement required shows little variation between 2D and 3D analyses, even though the latter is substantially more labor-intensive. This reflected that the embankment did not meet safety standards and required reinforcement. The conditions were identified based on several scenarios, including embankments composed of 100% soil, 25% and 50% foam mortar mixtures, placed over six- and eight-meter-thick soft soil

layers, and a 100% soil embankment constructed using the replacement method on a four-meter-thick soft soil layer. The low SF values obtained under these conditions indicate the need to implement soil reinforcement methods to ensure embankment stability, as illustrated in Figure 7.

The significant compression observed at Section Sta 18+600–Sta 20+300 of the Kediri–Kertosono Toll Road represents the second location analyzed in this study, where the design of a composite embankment using soil and a lightweight material, in the form of foam mortar, was required. Two mix variations were considered, consisting of 50% embankment soil plus 50% foam mortar and 25% embankment soil plus 75% foam mortar. The recapitulation of the primary and secondary subsoil compression magnitudes for the different foam mortar percentages and varying embankment heights is presented in Figure 8.

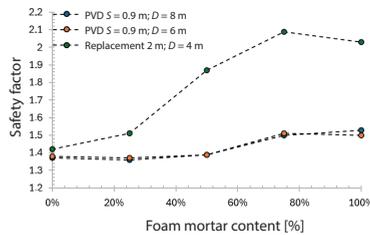


FIGURE 7. Safety factor of slope for two improvement methods with varying foam mortar percentage for the Kediri–Kertosono Toll Road

Source: own work.

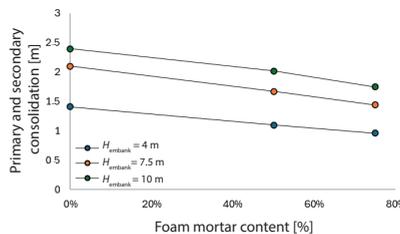


FIGURE 8. Primary and secondary consolidation of soil with various percentages of foam mortar and embankment heights (H_{embank}) for the Kediri–Kertosono Toll Road

Source: own work.

The analysis of subsoil compression beneath the embankment considered the rate of consolidation for both the untreated subsoil and that improved with PVD. The rate of settlement (RoS) was calculated by considering the compression per annum measured at periods of 2–3 years and 5–6 years after construction. Additional calculations were performed for decadal settlement covering the periods

of 2–12 years and 5–15 years post-construction. The recapitulation of *RoS* for different scenarios is presented in Figure 9 without PVD and Figure 10 with PVD.

The initial design of soil-foam mortar composite embankment failed to meet the requirements of the geotechnical guideline Pt T-8-2002-B (Departemen Perhubungan dan Prasarana Wilayah, 2002). Consequently, a subsoil improvement method was adopted through PVD. The most efficient embankment design for all height variations at Section Sta 16+900–Sta 18+600 was determined to be a standard soil without any subsoil replacement. For Section Sta 18+600–Sta 20+300. The most efficient design varied according to the embankment height. For an embankment height of 4 m, the most effective solution was a soil embankment preloaded and improved with PVD. When the height increased to 7.5 m, the most efficient configuration changed to a composite embankment consisting of 50% soil and 50% foam mortar. At a height of 10.5 m, the optimal design shifted again, favoring a composite embankment with 75% foam mortar and 25% soil, which performed best under higher loads.

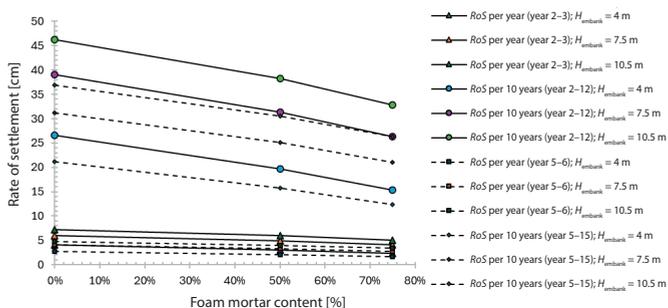


FIGURE 9. Effect of foam mortar content on settlement rate under different embankment loads (pre-PVD condition) for the Semarang–Demak Toll Road

Source: own work.

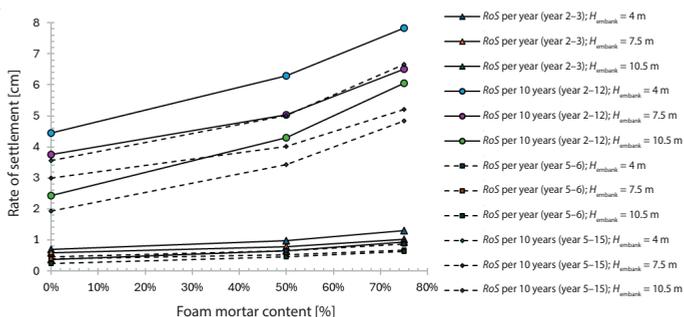


FIGURE 10. Effect of foam mortar content on settlement rate under different embankment loads (post-PVD condition) for the Semarang–Demak Toll Road

Source: own work.

The analysis and calculations yielded several inferences regarding the alternative design of the foam mortar light embankment for Section 1A (Sta 8+314–Sta 8+494) of the Semarang–Demak Toll Road, the third location analyzed in this study. The same was also observed for the evaluation of existing soil improvement and reinforcement designs and its steeper slope alternative for Section 1B (Sta 2+850–Sta 3+010). The light embankment foam mortar designed in Section 1A had an initial height of 12.2 m of which 1.5 m was uncompacted selected borrow material placed at the bottommost layer, 10.3 m was foam mortar in the middle, and 0.4 m was the height of the extra load placed at the top composed of compacted borrow material. Therefore, the H_{fin} of 10.3 m was maintained and composed of 100% of foam mortar after settlement and removal of the extra load at the completion of preloading. A total of 13 $\phi 400$ concrete micropiles with a length (L) of 14 m were used per side as reinforcements for the foam mortar light embankment. The assumption of the existing design that S_c was equal to 30% H_{fin} was found to be inaccurate and smaller by roughly 0.88 m than the calculated settlement for Zone J. It was also observed that the existing PVD design with a rectangular pattern and 1 m spacing in Section 1B could not reach consolidation of 95% at the completion of the effective age of 6 months. The situation led to improvements and corrections in the preloading and PVD design. Moreover, the existing 16 clusters of bamboo pile reinforcements for Section 1B could not assist in achieving the required slope stability at SF of 1.50, which led to the design of additional geotextile reinforcement and an embankment with a slope of 1 : 2 using uniaxial UW-30HL in both cases.

Conclusions

In conclusion, this study showed that using foam mortar as a lightweight embankment fill was highly effective for addressing the challenges of constructing toll roads on soft, compressible soils in Indonesia. The key results from the three case studies led to the following consolidated inferences:

- Significant settlement reduction: The incorporation of foam mortar directly and substantially reduced both the magnitude and rate of subsoil compression. The reduction in embankment load due to the low density of foam mortar was the primary mechanism, with higher foam mortar percentages producing greater settlement control.

- Enhanced slope stability: foam mortar embankments with a specific focus on those at higher mix ratios, such as 75%, improved slope stability with higher *SF* compared with conventional soil embankments by reducing the need for extensive reinforcement in several scenarios.
- Site-specific design optimization: The most efficient design was highly dependent on local conditions with a specific focus on embankment height and soft soil thickness. This was observed in several cases, including the Kediri–Kertosono route, where the optimal design transitioned from a soil embankment with PVD for a four-meter height to a 50/50 soil–foam mortar mix for 7.5 m and a 75% foam mortar mix for 10.5 m. In the Probolinggo–Banyuwangi section, the replacement method was considered unsuitable for six-meter-thick soft clay, whereas combinations of PVD and foam mortar proved effective. For the Semarang–Demak project, a 100% foam mortar embankment with micropile reinforcement was designed as a viable alternative to address construction difficulties in extremely soft soil conditions.
- Practical and economic viability: Foam mortar presented a practical and often more cost-efficient alternative to conventional ground improvement methods such as deep PVD installation or extensive soil replacement. It offered a sustainable solution by reducing embankment load at the source, thereby accelerating consolidation and minimizing long-term maintenance.

Foam mortar was a proven, versatile, and efficient material for embankment construction on soft soils. The results provided a strong technical foundation and specific design recommendations for its application in future Indonesian infrastructure projects, ensuring both structural performance and economic efficiency. Future research is critically needed to conduct real-time monitoring of foam mortar embankments under actual operational conditions. This would validate numerical predictions and assess long-term durability, settlement behavior, and environmental impacts.

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Summary

Evaluating the effectiveness of foam mortar as a lightweight fill for reducing foundation settlement on soft soils: a case study of Indonesian toll road projects. Evaluating the effectiveness of foam mortar as a lightweight fill for reducing foundation settlement on soft soils: a case study of an Indonesian toll road. The construction of toll

roads on soft soil in Indonesia is associated with significant geotechnical challenges, primarily excessive and long-lasting settlement. Therefore, this study aims to evaluate the effectiveness of foam mortar as a lightweight fill to mitigate issues across three distinct toll road projects: Probolinggo–Banyuwangi, Kediri–Kertosono, and Semarang–Demak. The method used was comprehensive numerical analysis, focusing on assessing the magnitude and rate of subsoil compression and slope stability under different scenarios of varying embankment heights, soft soil depths, and soil improvement strategies, including prefabricated vertical drains and replacement. The results consistently showed that incorporating foam mortar significantly reduced settlement. An increase in foam mortar percentage in the embankment also led to a substantial decrease in compression magnitude. Optimal performance was observed with a mix of 75% foam mortar and 25% soil for high embankments. Furthermore, this study provided customized, efficient design solutions for each site. The trend indicates that foam mortar is a viable, cost-effective alternative to conventional methods. This is because the application enhances slope stability and ensures compliance with stringent settlement-rate criteria, offering a practical solution for infrastructure development on compressible soils.