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Field assessment of enzyme-based stabilization for Sustainable Forest Roads in Sweden

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ABSTRACT

Sweden's climate goals require innovative strategies for maintaining forest road infrastructure. Increasing the gross weight of timber transport trucks can significantly cut CO_2 emissions but also places added stress on gravel roads, demanding improved stabilization techniques. This study assesses the effectiveness of enzyme-based stabilization methods in enhancing the load-bearing capacity and durability of forest roads. Two test sections were constructed on a pilot road in Trosa, Sweden: one treated with Road Stabilizr (RS) and Dust Blokr-Sugar Blend (DB-SB), and another with TerraZyme (TZ). Field assessments, including lightweight deflectometer (LWD) testing, surface profiling, and visual inspections, were conducted before and after exposure to weather conditions and simulated traffic. Laboratory analysis confirmed that Trosa's fine-grained material was suitable for enzyme-based stabilization. The results indicated that both stabilization methods improved the road's structural strength, with LWD tests showing a 17 % increase in the dynamic deformation modulus (Evd) for the RS/DB-SB section and an 11.4 % increase for the TZ section after stabilization. Additionally, dust suppression benefits were observed in the RS/DB-SB section, contributing to reduced environmental impact and enhanced road longevity. This study highlights the potential of enzyme-based stabilization as a sustainable solution to improve forest road performance and minimize maintenance needs.

1. Introduction

Sweden has set ambitious climate targets, aiming to reduce greenhouse gas emissions by 70 % by 2030 compared to 2010 levels, and to achieve carbon neutrality by 2045 (Ministry of the Environment, 2020).

The transport sector, particularly timber transport, plays a crucial role in achieving these goals. Two-thirds of the forest industry's domestic transport is done by truck and one-third by rail. The average transport distance by truck is about 100 km and by rail about 320 km (Roberge et al., 2020).

The increasing weight of vehicles has a positive impact on reducing CO2 emissions. A 30-meter-long logging truck with a maximum gross combination weight (GCW) of 90 tons was tested for over three years in northern Sweden. During two round trips, this truck carried a volume of roundwood equivalent to that hauled by three conventional Swedish 60-ton trucks. The results indicate that the truck reduces both costs and CO2 emissions by 20 % (Löfroth et al., 2012). From an environmental standpoint, the adoption of High-Capacity Vehicles (HCVs) offers significant benefits. According to Cederstav et al. (2022), HCVs could lead to a 40 % reduction in CO_2 emissions and a 50 % decrease in the number of truck trips.

Forest roads are the most costly structures in forestry and play a crucial role in managing forest resources (Teramoto et al., 2015; Babapour et al., 2017; Jeong et al., 2021; Kolkos et al., 2023). Their effective construction and maintenance are essential, as road deterioration is often caused by vehicle traffic, challenging climate conditions, inadequate maintenance, low-quality construction materials, and poor road surface drainage (Heidari et al., 2022). Sweden's extensive network of private forest roads is increasingly vulnerable to climate-induced challenges. These roads are subjected to frequent rainfall, freeze-thaw cycles, and heightened traffic due to a growing demand for forest products.

In Sweden, the recent increase in permissible truck gross weight from 64 tons to 74 tons has further exacerbated the stress on these roads. Studies have demonstrated that the performance of gravel roads is significantly affected by heavy traffic and climate factors. Research by Kuttah (2016) and Kuttah and Arvidsson (2017) highlighted the susceptibility of these roads to erosion and deformation under high loads.

To address these challenges, initiatives are underway to enhance the

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load-bearing capacity of forest roads through improved construction methods. Such efforts are essential to ensure that Sweden meets its ambitious CO_2 reduction objectives while maintaining the efficiency of its forestry sector.

In most geotechnical projects, it is not possible to obtain a construction site that will meet the design requirements without ground modification (Makusa, 2013; Sánchez-Garrido et al., 2022; and Khan et al., 2024). Soil improvement techniques are widely employed to address settlement and stability issues in soft soils by modifying their properties to enhance engineering performance (Heidari et al., 2020). These methods aim to increase soil strength, reduce compressibility, and improve overall stability (Chen, 2000; Petry and Little, 2002; Razouki et al., 2011; Puppala, 2016; Firoozi et al., 2017; Pooni, and Estabragh et al., 2022, 2024).

Soil properties that influence the effectiveness of stabilization include the type and amount of cementitious materials, as well as the soil's characteristics such as particle size distribution (PSD or gradation), chemical composition, mineralogy, plasticity, organic matter content, salt content (mainly sulfate), cation exchange capacity (CEC), pH, and specific surface area. Additionally, factors like the type and duration of curing conditions, along with the method and quality of construction (e.g., compaction effort), can impact the properties of stabilized soils (Behnood, 2018). Engineers must carefully evaluate these factors to determine the most suitable approach for a given project.

Stabilizing forest roads with low environmental impact additives is an innovative approach aimed at improving road sustainability while reducing ecological impact. These additives, often made from natural or biodegradable materials, work by enhancing the structural integrity of the soil, reducing erosion, and increasing resistance to weathering. By incorporating such additives in road construction and maintenance, the lifespan of forest roads can be extended and maintenance costs reduced. This method not only supports the efficient transport of forest resources but also contributes to sustainability goals by protecting surrounding ecosystems from harmful runoff and soil degradation.

In line with this, two different low environmental impact stabilization additives were selected for evaluation and testing in this project. One mixture consists of Road Stabilizr (RS) and Dust Blokr-Sugar Blend (DB-SB), while another section was treated with TerraZyme (TZ).

Generally, enzyme-based stabilization requires specific conditions to be met, such as the material to be stabilized containing fine-grained material passing sieve #200 (0.075 mm), with a proportion ideally between 15 % and 65 %. This fine fraction helps create a well-graded, high-density mixture when combined with available granular materials. The desired plasticity index (PI) of the material should be between 5 % and 15 %.

This project focuses on a scalable method for enhancing forest roads through Enzyme-based stabilizers. By incorporating this approach into forest road construction and maintenance, roads can be better equipped to withstand evolving challenges and increasing demands.

2. Methods for field assessment of road conditions

Accurate field assessments are essential for evaluating the structural integrity and performance of gravel roads. This section outlines the key methods used in this study to assess road conditions, including bearing capacity assessment based on Light weight Deflectometer (LWD) tests, moister content measurements, surface profiling, and visual inspections. The combination of these tests provides a holistic approach to road condition assessment.

2.1. Bearing capacity assessment using lightweight deflectometer (LWD)

The lightweight deflectometer (LWD) is an effective tool for evaluating the stiffness and load-bearing capacity of unbound granular materials used in road construction (Kuttah, 2023). By applying a dynamic load to the surface and measuring the resulting deformation, the LWD provides critical information about how well a road can withstand traffic without excessive settlement, see Fig. 1. This method is particularly advantageous due to its efficiency and non-destructive nature, allowing engineers to conduct rapid assessments without interrupting traffic flow.

LWD testing plays a crucial role in road evaluation by offering a reliable measure of the dynamic deformation modulus (Evd), a key parameter for assessing material strength. The calculation of Evd employs the elastic half-space theory for a one-layer system based on Boussinesq (1885), as shown in Eq. (1).:

$$\mathrm{Evd} = 2\mathrm{k}(1 - \mathrm{v})2/\mathrm{Aro} \quad (1)$$

where k represents soil stiffness (calculated as the ratio of peak load to peak deformation), r_0 is the radius of the loading plate, A is the stress distribution factor, and v is Poisson's ratio. By continuously monitoring road surface deformations under load, LWD testing provides valuable insights into road stability and structural performance under real traffic conditions. The deformation data recorded during testing is processed through the LWD device's built-in computational system, offering a clear assessment of the road's capacity to sustain traffic loads.

2.2. Surface profile measurements using rotating laser level (RLL)

A well-maintained road profile is essential for ensuring driving comfort, proper drainage, and uniform load distribution. In this study, a Rotating Laser Level (RLL) was used to measure the cross-sectional profiles of gravel roads, capturing variations in height, slope, and material distribution. These measurements help identify surface irregularities, such as rutting, washboarding (corrugations), and uneven settlements, which often develop due to repeated traffic loads and environmental conditions.

Surface profiling is particularly useful for detecting early signs of deterioration and determining whether additional material is needed in specific areas. The collected data also provides a basis for optimizing maintenance interventions, ensuring that road grading and material distribution are adjusted effectively.

Fig. 1. The lightweight deflectometer used in the project. *Photo: Dina Kuttah, VTI.*

2.3. Visual Inspection of Road Surface and Surrounding Terrain

While technical measurements provide quantitative data, visual inspections remain a crucial component of road assessment, allowing engineers to identify surface defects and evaluate the surrounding terrain. The inspection process focuses on identifying common issues such as ruts, potholes, loose gravel, and corrugations, all of which affect road stability and driving comfort. Additionally, evaluating drainage efficiency is a key aspect of visual inspections, as poor water runoff can lead to erosion and structural weakening. Signs of water accumulation, insufficient drainage ditches, or blocked culverts are carefully observed to determine necessary corrective actions.

3. Laboratory analysis of the tested road sections

As previously mentioned, enzyme-based stabilization requires specific conditions, including that the material to be stabilized contains fine-grained material passing sieve #200 (0.075 mm), with an ideal proportion between 15 % and 65 %. Additionally, the material must have a plasticity index (PI) between 5 % and 15 % to ensure effective stabilization. Therefore, it was essential to identify a pilot forest road that met these material requirements. In line with this, two material groups (one from Trosa and one from Sveg in Sweden) underwent extensive laboratory testing, including grain size distribution, Atterberg limits, moisture-density relationship and grain density tests.

The grain size distribution of the materials from Trosa and Sveg, according to SS-EN 933, 1 (2012), reveals that the material from Trosa contains, on average, about 40 % fine-grained material passing sieve #200 (0.075 mm), while the material from Sveg contains approximately 16 % fine-grained material passing the same sieve. The grain density for the materials from Trosa and Sveg was determined to be 2.63 g/cm^3 and 2.65 g/cm^3 , respectively, in accordance with SS-EN (1097)–6 (2013).

Compaction properties were determined according to SS-EN (1328) 6–2 (2010) to establish the optimum water content and maximum dry density for the tested materials. Figs. 2 and 3 display the moisture content-dry density curves for TZ-stabilized materials from Trosa and Sveg respectively. These figures show that the material from Trosa reached a maximum dry density of 1.86 g/cm^3 at an optimum water content of 13.5 %, while the material from Sveg exhibited a higher dry density of 2.12 g/cm^3 at an optimum moisture content of 8 %.

Consistency limits tests showed that the Trosa material had a liquid limit (LL) of 37 % and a plastic limit (PL) of 21.6 %, based on SS (0271) 20 (1990) and SS (0271)21 (1990), resulting in a plasticity index (PI) of 15.4 %. Similarly, the material from Sveg had a liquid limit (LL) of 21 % and a plastic limit (PL) of 18 %, giving it a plasticity index (PI) of 3 %.

As the desired plasticity index (PI) for enzyme-based stabilization should be between 5 % and 15 %, the Trosa material, with a PI of 15.4 %, is at the upper limit of the acceptable range for enzyme-based stabilization. On the other hand, the Sveg material, with a PI of 3 %, is below the minimum threshold for enzyme-based stabilization.

Given the material requirements for enzyme-based stabilization, Trosa material was chosen as the more suitable option due to its appropriate fine-grained content and plasticity index (PI) within the desired range of 5 % to 15 %.

4. Construction process for the road sections

The forestry company Holmen constructed its pilot sections along an existing forest road in Trosa (Södermanland County). The pilot road was divided into three main test sections: Section 1 was stabilized using a mixture of Road Stabilizr and Dust Blokr, Section 2 was left unstabilized, and Section 2.2 was stabilized with TerraZyme. Each of these sections measured approximately 350 m in length. In this study, the focus will be on the two stabilized sections, 1 and 3, to determine the effect of each stabilization material on road performance before and after stabilization.

The construction process of the pilot road project in Trosa carried out by Holmen's forestry company started with careful planning and the use of special equipment. The construction process was developed in a series of methodical steps. First, the grader removed the top 10–15 cm of material from the road and kept it in place. Next, the liquid product concentrates were diluted with water and sprayed onto the loose material in several passes. After applying the liquid, the grader mixed the material on the surface to ensure an even distribution of the product concentration. These steps were repeated until the entire road surface was treated. The grader blade was used to evenly spread the wet material and form the side area or side strip of the road. The surface was then compacted and once compaction was complete, the surface seal was applied. The road surface was allowed to dry for one day before use.

For the stabilized sections, the grader proved to be a crucial machine, necessary to remove material from the road surface to mix in the stabilizing fluids. However, challenges arose when trying to deepen the penetration of the blade, as the grader lacked sufficient weight. The project required the stabilizing fluids to be applied to a depth of at least 20 cm, but the actual depth of the compacted material was around 15 cm. This limitation made it difficult to remove enough road material

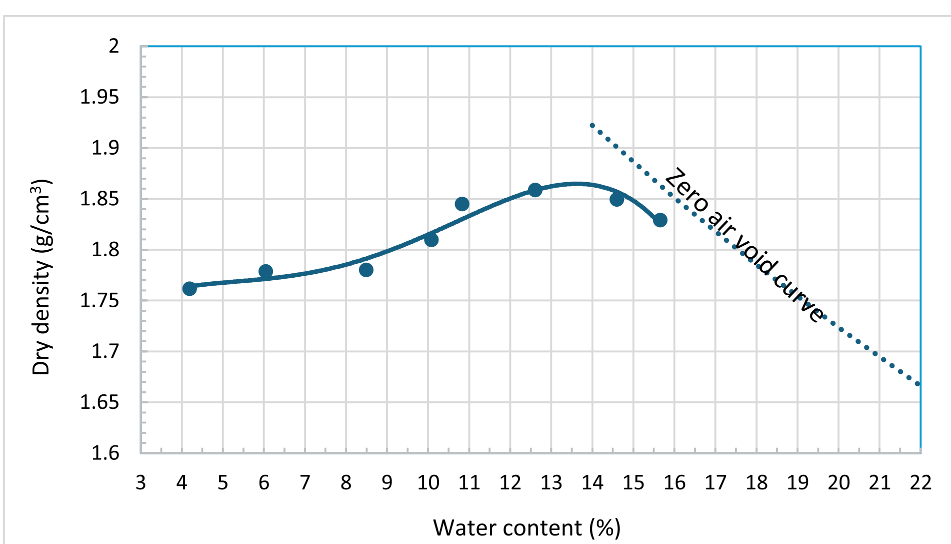

Fig. 2. Relationship between water content and dry density for the tested material from Trosa.

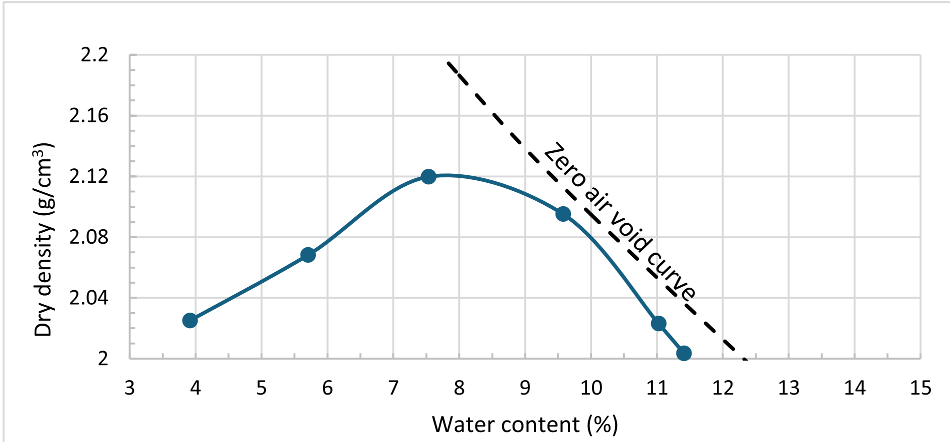

Fig. 3. Relationship between water content and dry density for the tested material from Sveg.

while keeping it on the narrow roadway without losing material to the ditches. In addition, when attempts were made to dig deeper, larger stones came to the surface, some with a diameter of 20–30 cm.

The irrigation equipment, originally designed for salting, initially had difficulty adjusting, leading to delays in the first water delivery. However, applying the liquid in several batches proved to be a beneficial method. The contractor had watered the road several days before the project, which improved the workability of the material. The moisture content was carefully checked using a ball test at various locations, which revealed a high moisture level. Therefore, it was decided to use a minimum application of 1 liter per m^2 to effectively dilute the products planned for this project.

For the section of road stabilized with a mixture of Road Stabilizr (RS) and Dust Blokr-Sugar Blend (DB-SB), the quantities used for the road included an initial mixed application of 1250 litres of DB-SB with approximately 1500 litres of water and 5.5 litres of RS, applied in 7 to 8 passes. A topical seal was performed the following morning with 250 liters of DB-SB and 1000 liters of water, applied in 6 to 7 rounds, see Fig. 4.

The compaction of the test section was performed with an 8-ton roller. The uneven distribution of road aggregate on the surface posed challenges during compaction, resulting in weaker points where the pressure was not high enough. This led to a need for surface sealing with approximately 200 ml DB-SB per m^2, in order to stabilize these weaker areas and bind any loose material remaining after compaction.

The combined use of DB-SB and Road Stabilizr is often justified, especially in areas with clay soils that can lead to clayiness and low bearing capacity.

The application rate on the section stabilized with Terrazim closely followed the manufacturer's guidelines. The recommended application rate was one liter of Terrazim per 24 cubic meters of soil.

Fig. 4. Stabilization of a selected forest road in Trosa using low environmental impact additives. Photo by Jan Tikkunen, Vumos (Finland).

Note that both Sections 1 and 3 were compacted with an 8-ton roller, and both sections were also leveled during the process.

5. Traffic simulation

To compensate for low traffic on the pilot road in Trosa, a controlled simulation was conducted, with a truck making approximately 30 passes before the final measurements. Supervised by Holmen's forestry experts, the simulation ensured accurate load replication. The truck, equipped with built-in scales, provided essential weight data for the cost-benefit analysis, with a total weight of 27.1 tons distributed across its axles.

6. Test points and measurement layout

To thoroughly evaluate the condition of the road sections constructed by Holmen, both immediately after construction and following exposure to weather and traffic, a series of detailed assessments were carried out. These included six profile measurements and twenty-eight LWD tests, conducted during each of the three test phases (initial, intermediate, and final), with measurements taken at various intervals between these phases. Additionally, moisture content evaluations and visual inspections of both the test sections and surrounding terrain were performed. The specifics of these assessments will be discussed in the following sections.

Fig. 5 illustrates the locations where profile measurements and lightweight deflectometer (LWD) tests were conducted at selected points along the test sections. In the initial phase, the LWD tests were carried out at the exact locations shown in Fig. 5. However, during the intermediate and final phases, the test points were moved slightly - approximately 30 cm from their original positions - to avoid the recompaction that could occur if the same points were tested repeatedly.

7. Post-construction evaluation of road performance after weather and traffic exposure

The initial measurements were taken immediately after the road sections were built, just before they were exposed to the weather. Intermediate measurements were taken four months later, after exposure to the weather but before the traffic simulation. The final measurements were taken after the traffic simulation. These initial, intermediate and final measurements provide a baseline against which the performance of the road can be assessed and potential problems caused by environmental and traffic-related factors can be identified.

For the Trosa pilot road, additional profile measurements were taken during the final phase using advanced UAV drone technology, a Road

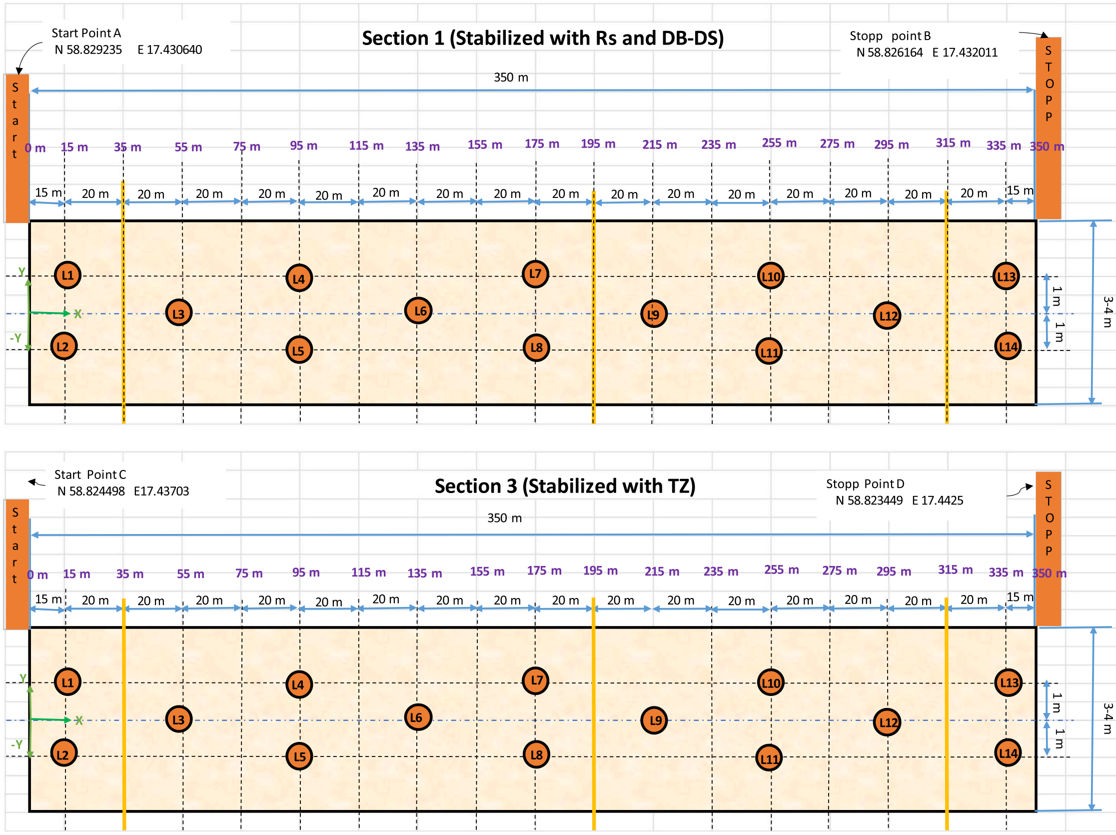

Fig. 5. Test points and profile layout for the road Sections 1 and 3 in Trosa.

Surface Measurement Vehicle (RST) and Rotating Laser Levelling (RLL). A comparison of the results from these three methods showed minimal mean absolute differences: 1.1 cm between UAV and RST, 1 cm between UAV and RLL, and 0.7 cm between RST and RLL. Detailed results of this comparison are reported by Kuttah and Waldemarson (2024).

7.1. *Light weight deflectometer and moisture content measurements*

Figs. 6 and 7 present the results of the LWD test from the initial, intermediate and final measurement phases for Sections 1 and 3. The dotted lines with corresponding Evd values represent the average Evd (MPa) for each section and measurement occasion.

Figs. 6 and 7 demonstrate the variation in Evd values across different testing phases. During the intermediate tests, which were conducted after exposure to environmental conditions but before traffic simulation, both sections showed an increase in Evd values compared to the initial measurements. This increase highlights the positive effect of stabilization, which continued to improve over time, suggesting that the wetting

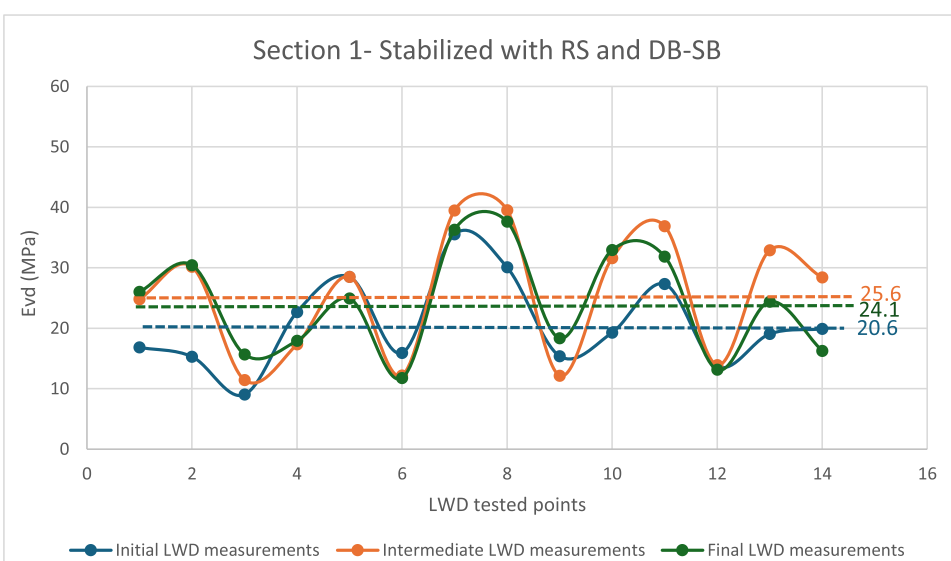

Fig. 6. The Evd values from the initial, intermediate and final LWD measurements for Section 1.

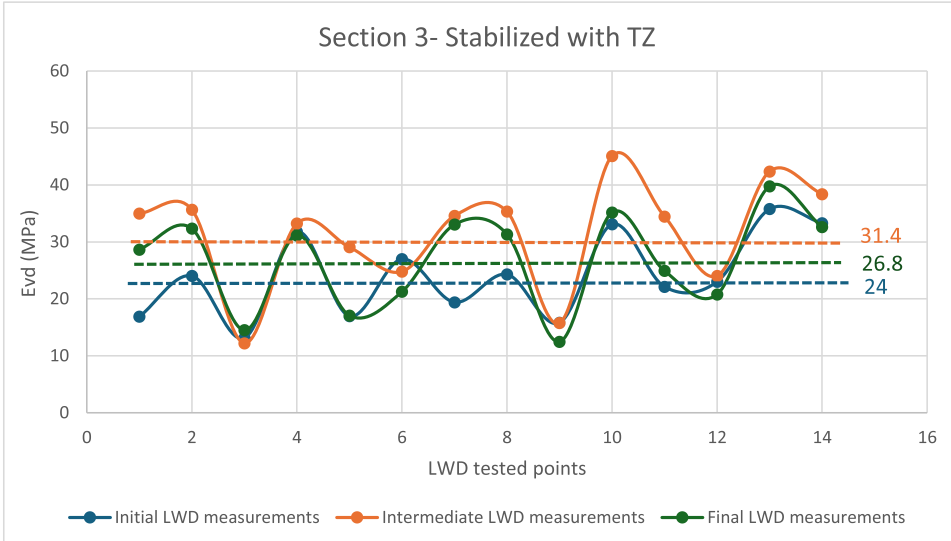

Fig. 7. The Evd values from the initial, intermediate and final LWD measurements for Section 2.2.

and drying cycles over the summer contributed to an overall strength gain.

In Section 1, data analysis reveals that stabilizing the section with a mixture of RS and DB-SB resulted in a significant improvement in LWD measurements. Specifically, Evd increased by approximately 18.5 % after stabilization and exposure to weather conditions. However, traffic-induced changes led to a 6 % decrease in Evd between the intermediate and final measurements. Despite the common trend of Evd decreasing with higher water content, the overall strength gain from the initial to the final Evd measurements was about 17 %. This is particularly impressive considering that the average moisture content in Section 1 was 6.4 % during the initial phase, rose to 8.8 % during the intermediate phase, and then decreased to 7.7 % by the final phase. Note that the typical trend of Evd is decreasing with higher moisture content. Additionally, the intended stabilization depth of 20 cm could not be fully achieved in practice. Nevertheless, a reasonable increase in strength was still observed. These results demonstrate that stabilization significantly enhances road strength, even in the face of fluctuating moisture content, once the stabilizing agents have cured and taken effect.

For Section 2.2, stabilized with TZ, the data shows a more modest improvement in LWD measurements following stabilization. After exposure to weather conditions, Evd increased by 16 %. However, traffic-induced effects led to a 14.8 % decrease in Evd between the intermediate and final measurements. The overall strength gains from the initial to the final Evd measurement was 11.4 %. It is noteworthy that the moisture content fluctuated between 7 % and 8 % during the initial, intermediate, and final phases.

For both sections, the final measurements, taken after traffic simulation, showed a decline in Evd values for all tested sections compared to the intermediate measurements. This decrease reflects the effects of repeated loading.

7.2. Profile measurements

Profile measurements were conducted on the road sections both before and after exposure to weather and traffic impacts, allowing for a comparative analysis of changes over time. The data reveals variations in height, cross-sectional shape, and material distribution across different sections. Figs. 8 and 9 illustrate these measurements for Sections 1 and 3, respectively, providing valuable insight into potential issues such as uneven wear, rutting, and material displacement.

For road Section 1, stabilized with RS and DB-SB, Fig. 8 shows a strong consistency between the measurements taken at three different times for profiles 1 and 3. However, this consistency is not observed for profile 2. The discrepancy in profile 2′s measurements is attributed to a shift in the reference point rather than an actual change in the profile, as the recorded profiles across the three measurements follow a consistent pattern but are slightly offset.

In contrast, for the stabilized Section 2.2 with TZ, shown in Fig. 9, profiles 1, 2, and 3 exhibited noticeable changes between the measurements taken before and after exposure to weather and traffic effects.

In summary, Section 1 demonstrated better performance in terms of profile measurements as well.

7.3. Visual assessment of the road sections

The visual assessment was conducted during the final measurement under gray, overcast skies with drizzle and a temperature of approximately 10 °C. Earlier rainfall during the week had filled the ditches with water.

In Section 1, stabilized with RS and DB-SB, the images showed grass growing in the middle of the road. Clay and water were present in the left wheel track between 0/000 and 0/030, up to profile 1 at 35 m, with minor ridges observed between 0/050 and 0/115 (see Fig. 10). The wheel tracks were damp and muddy. A cross-sectional check confirmed that there was no corrugation or potholes. Rutting was observed, but there was no significant dust formation, and only a few areas with loose gravel, mainly in the center of the road.

In Section 2.2 (TZ), the images showed grass growing in the middle of the road, with less vegetation toward the end of the section, as well as muddy wheel tracks (see Fig. 11). Ridges were observed between 0/090 and 0/120, as well as between 0/170 and 0/200. Water accumulation was noted along the right roadside between 0/155 and 0/160. The cross-section followed the leveling, with no signs of corrugation. A possible pothole was observed at 0/150 on the right wheel track. Rutting followed the road's leveling, with no significant dust formation. Loose gravel was present only in isolated areas, mainly in the center and along the roadside.

8. Key observations and insights

In this study, both tested stabilization methods (RS/DB-SB and TZ) showed improved road performance, with LWD tests confirming increased structural strength after weather and traffic exposure, as reflected in the Evd values during the final measurements, compared to the initial measurements. However, this improvement came at a higher

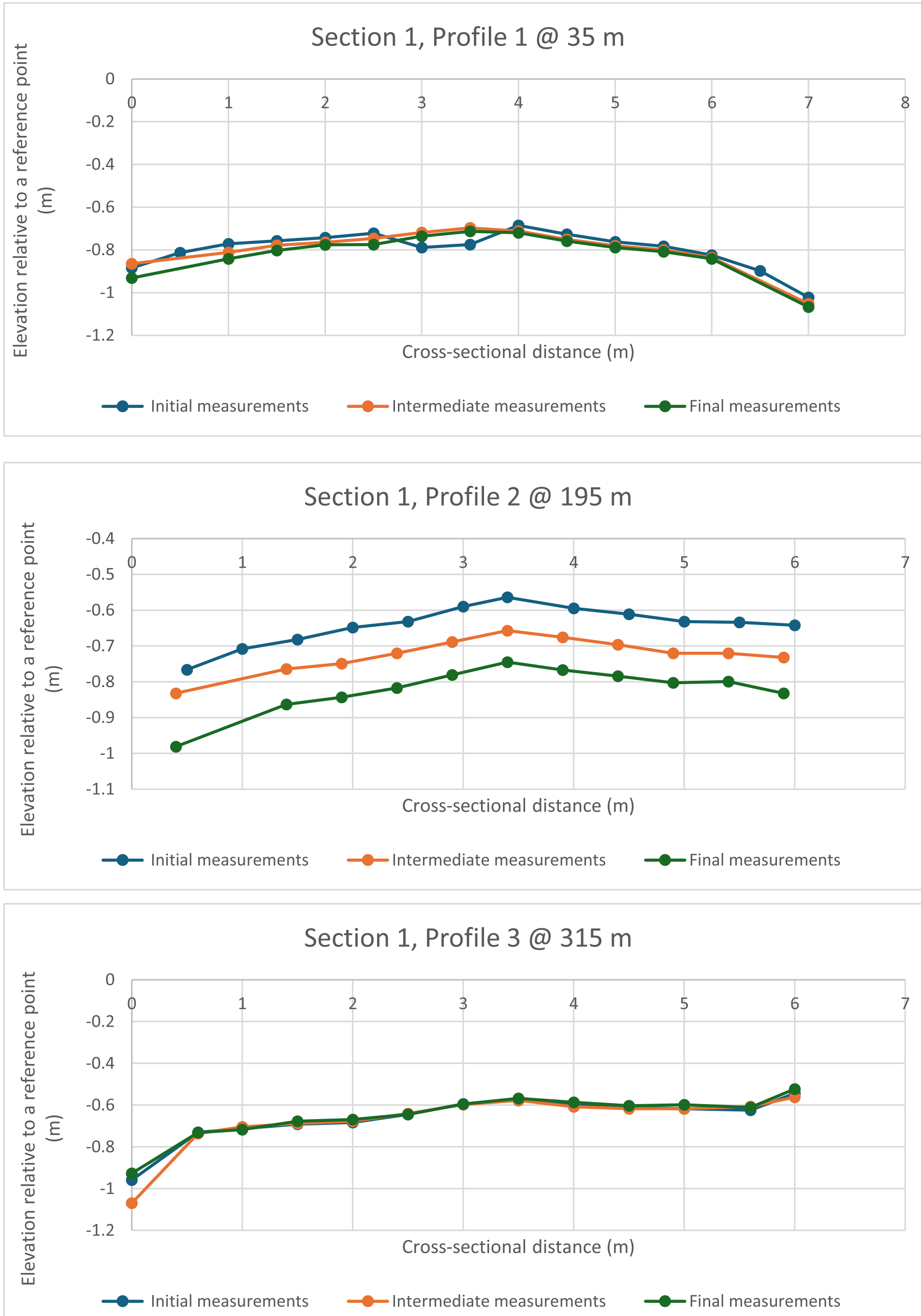

Fig. 8. Initial, intermediate and final profile measurements for road Section 1 stabilized with RS and DB-SB.

cost.

In terms of strength gain, Section 1, stabilized with RS and DB-SB, showed an overall increase in Evd of approximately 17 % from initial to final measurements. In contrast, Section 2 showed an increase of 11.4 % over the same period. According to Kuttah et al. (2025), the cost-benefit analysis showed that stabilizing Section 1 cost approximately SEK 205 per meter (for a 4-metre wide road), while stabilizing Section 2.2 with TZ cost 79 SEK per meter road.

When comparing cost-effectiveness, the cost of stabilizing Section 1 was approximately SEK 12 per meter per 1 % increase in Evd, while the cost of stabilizing Section 2.2 was approximately SEK 7 per meter per 1 % increase in Evd. This indicates that stabilization with TZ is more cost effective than a combination of RS and DB-SB to achieve the same percentage increase in bearing capacity (dvs Evd). The higher cost of Section 1 was mainly due to the transport of DB-SB, which required large quantities of material, necessitating the use of tankers, which significantly increased the cost compared to the smaller quantities required for enzymes such as RS and TZ.

On the other hand, the road section stabilized with RS/DB-SB has shown long-term dust resistance, with the effect lasting for several months and expected to continue for a long time. This reduction in dust not only improves the durability of the road, but also has a positive impact on health. It is important to note that potential cost savings from reduced dust and maintenance have not been included in this cost comparison.

These findings align with previous research on enzyme-based soil

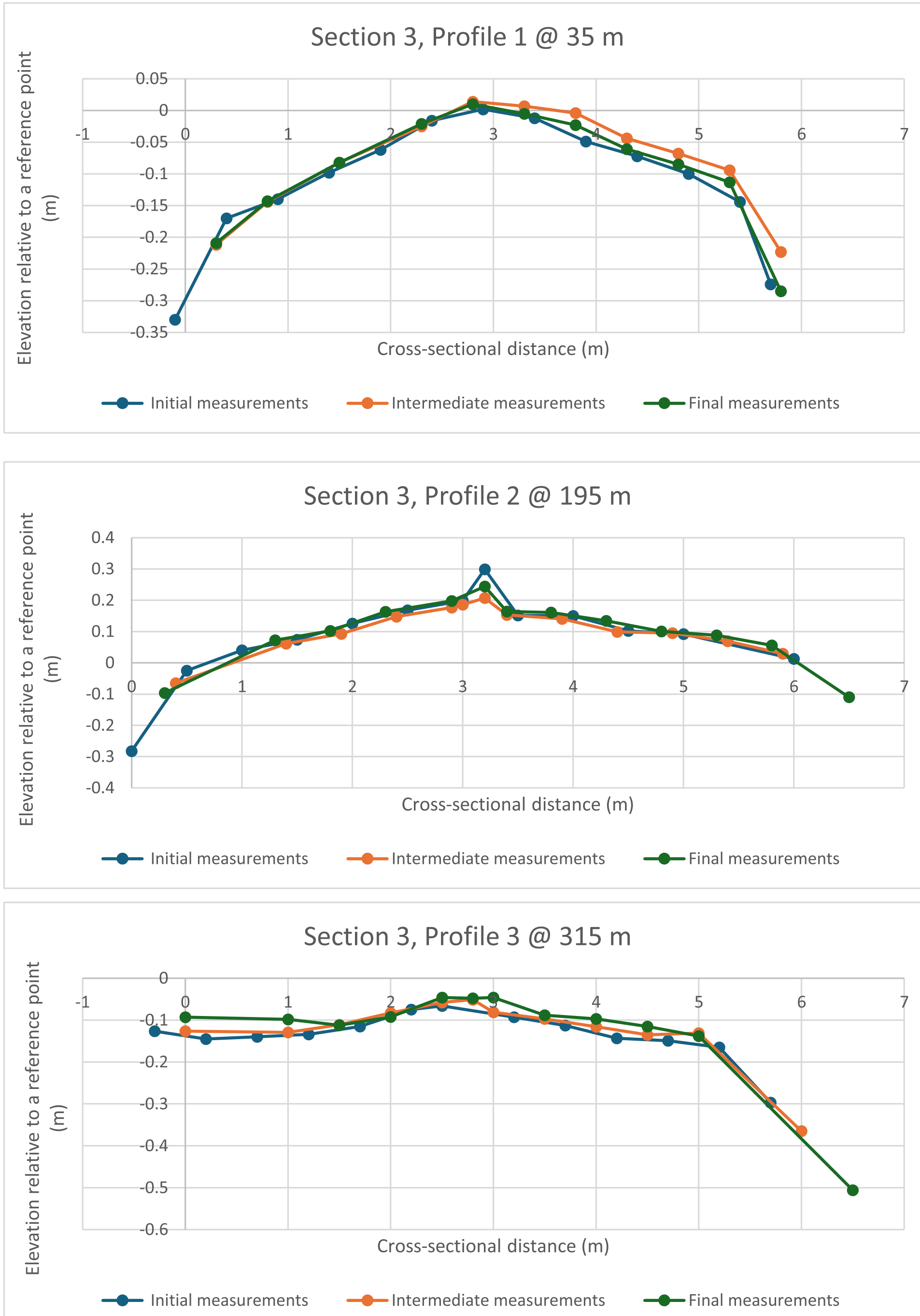

Fig. 9. Initial, intermediate and final profile measurements for road Section 2.2 stabilized with TZ.

stabilization. Based on Suokone Oy and Vumos Oy (2023), on August 21st, 2023, a section of the Tenetinkuja road surface was stabilized using Road//Stabilizr and Dust/Blokr Sugar Blend. This road represents a typical Finnish unpaved countryside road, commonly afflicted by issues such as potholes, rutting, and softening during periods of excessive rainfall. Despite the shallow clay content, the lane treated solely with Road//Stabilizr demonstrated commendable performance. The adjacent lane, where both products were applied, exhibited even better conditions. This outcome underscores the efficacy of combining both products for stabilization and dust suppression projects in Europe.

Similarly, Chaurasia et al. (2020) used TerraZyme in improving the engineering properties of black cotton soil (BCS) and red soil (RS) for road construction. The addition of TerraZyme significantly increased the strength of both black cotton and red soils. Using the Indian Roads Congress (IRC) method for pavement design, the required thickness of pavement on TerraZyme-stabilized soil was reduced by 25–40 %, indicating substantial material and cost savings.

In the current study, for both sections, a significant proportion of the expenditure was attributed to pre-stabilization watering of the road sections, which resulted in significant additional costs. In the future, these costs could be minimized by starting stabilization after a rainy day, thereby eliminating the need for artificial watering. Further cost reductions could be achieved through increased experience in the use of enzymes and the use of more cost-effective machinery.

Fig. 10. Section 1 with RS and DB-SB. Photo: Andreas Waldemarson, VTI.

Fig. 11. Section 2.2 with TZ. Photo by Andreas Waldemarson, VTI.

9. Conclusion and recommendation for future research

The study underscores the potential of enzyme-based stabilization as a sustainable alternative for enhancing forest road performance while minimizing maintenance needs something which goes well with similar studies, among others the studies performed by Chaurasia et al. (2020) and Suokone Oy and Vumos Oy (2023). Implementing these stabilization techniques can support Sweden's goal of reducing CO_2 emissions while maintaining efficient timber transport. Future research should also focus on long-term monitoring to assess durability under varying climate conditions and explore alternative eco-friendly stabilization materials for enhanced cost efficiency and environmental benefits. Furthermore, future studies are recommended to evaluate dust emissions and associated health costs in order to gain a more comprehensive understanding of the overall cost-effectiveness of the stabilization agents.

CRediT authorship contribution statement

Dina Kuttah: Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Nils Anders Olsson:** Visualization, Validation, Resources.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dina Kuttah reports financial support was provided by Sweden's Innovation Agency. Nils Anders Olsson reports financial support was provided by Holmen. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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