USE OF LECA-LIGHTWEIGHT AGGREGATE IN RAILWAY STRUCTURES

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KEYWORDS

lightweight aggregate, railway embankment design, cyclic loading, numerical modelling, ground improvement

ABSTRACT

Railway embankment design is crucial for passenger and operator satisfaction, focusing on comfort, safety, and timely operation. This paper examines Leca LWA's suitability in railway structures, determining optimal cover depth and location, and assessing its performance under high-cycle loads. The evaluation may lead to a potential use of Leca LWA in railway embankments in the future.

Simulation results show that placing Leca LWA below a 300-mm extra subballast layer improves bearing capacity and stability. The study also finds that Leca LWA can withstand cyclic loading regardless of cover depth. Recommendations include an 1150-mm cover depth, comprising a 550-mm ballast layer, a 300-mm subballast layer, and a 300-mm extra subballast layer, above Leca LWA, based on a maximum embankment height of 2.5 m and a maximum axle load of 25 tons, as studied. Further investigation is needed to assess the impact of increased height or load. The findings, after further validations, may aid in creating practical guidelines for using Leca LWA in railway embankments.

1. INTRODUCTION

From a geotechnical perspective, railway embankment design in cold regions like the Nordic and Baltic countries must prioritize bearing capacity, stability, settlement, and frost heave prevention for safety and efficiency.

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In Nordic countries, railway tracks often cross soft clay and peat areas. Such soils may have insufficient strength, as well as may settle too much to serve as a basis for a railway embankment. Ground improvement techniques like, for example, the replacement of weak soil with lightweight aggregates (LWA) can enhance stability, particularly when combined with methods like preloading and column stabilization.While models exist for static loads, limited attention has been given to embankments under cyclic loading typical of railways, which can impact settlement and passenger comfort.

This study aims to assess Leca® lightweight aggregates (Leca LWA) in railway embankments, focusing on optimal cover depth and performance under high-cycle train loads. Through analysis and simulation, the study will enhance the understanding of LWA behaviour in railway conditions, validated by the Plaxis Soft Soil Creep (SSC) model. The scope will include static and moving traffic loads, with consideration of a maximum railway speed of 160 km/h.

2. RAILWAY EMBANKMENT

Railway embankments support tracks and endure train loads, typically consisting of ballast, subballast, and subgrade layers. A frost protection layer may also be required in Nordic countries, as frost action can affect performance, especially if the subgrade is frost susceptible. To prevent this, a non-frost susceptible frost protection layer is necessary. (Li et al., 2015; Nurmikolu & Silvas, 2013)

Leca lightweight aggregate

Leca LWA is a ceramic material produced at high temperatures, expanding clay to five times its original volume. Its hard exterior and porous interior make it versatile for engineering applications, offering low bulk density, water permeability, insulation, strength, durability, and recyclability.

With properties akin to medium-dense sand but significantly lighter, Leca LWA effectively reduces earth pressure while maintaining strength. In railway embankment structures, it enhances stability, reduces settlement, improves drainage, and prevents frost damage in the subgrade.

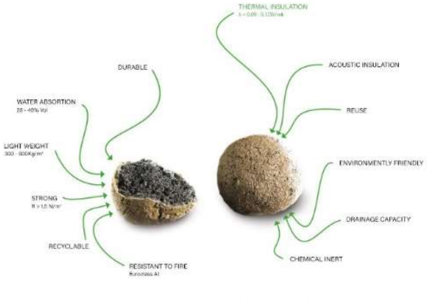


Figure 1 Leca® LWA physical properties (Leca website).

Studied railway embankment profile

The studied profile, as shown in Figure 2, is taken from RATO 3, referring to it as a technical regulation for railway tracks. The dimensions of cross sections are presented in Table 1.

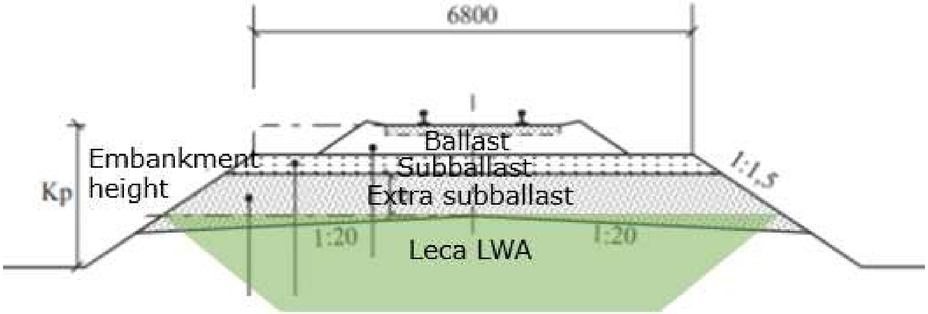


Figure 2 Typical railway cross section om Finland (Finnish Transport Agency).

Table 1. Studied dimensions of the cross section.

Components	Dimensions
Width of sleepers (single track)	2.6 m
Embankment height	1.5 m / 2.5 m
Ballast layer	0.55 m
Subballast layer	0.3 m
Extra subballast layer	0 m – 1 m (varied)
Leca LWA layer	1 m / 1.5 m / 2 m / 3 m

3. METHODOLOGY

Plaxis is commonly used for advanced geotechnical engineering modeling. The SSC-model in Plaxis computes creep deformation over time, suitable for simulating cyclic loading by considering increasing plastic strain. Leca LWA conducted cyclic compression tests, correlating deformation over cycles. The high-cycle accumulation model correlates PLAXIS deformation over time with Leca's cycle-based deformation. This approach is applied to validate the HCA model with Leca laboratory data.

The lab results of cyclic compression tests on 2 LWA samples were replicated by the High cycle accumulation (HCA) model, as shown in Figure 3. The HCA model was established by Wichtmann et al. (2005) and can predict strain or stress accumulation under cyclic loading with numerous cycles and small strain amplitudes ($\varepsilon^{ampl} < 10^{-3}$). It finds applications in railways, water gates, and offshore wind turbine foundations. Developed from cyclic triaxial drained tests on sand specimens, the model considers factors like strain amplitude, preloading history, average stress, density, and grain size distribution, influencing strain accumulation direction and intensity (Wichtmann et al., 2005).

Wichtmann et al., (2009) proposed the following equation to describe the effect of different functions on the intensity of accumulation:

$$\dot{\varepsilon}^{acc} = f_{ampl}\dot{f}_N f_e f_p f_Y f_\pi$$

,where f_{ampl}=strain amplitude, f_N=cyclic preloading, f_e=average void ratio, f_p = average mean stress, f_Y = average stress ratio, f_π = polarization change.

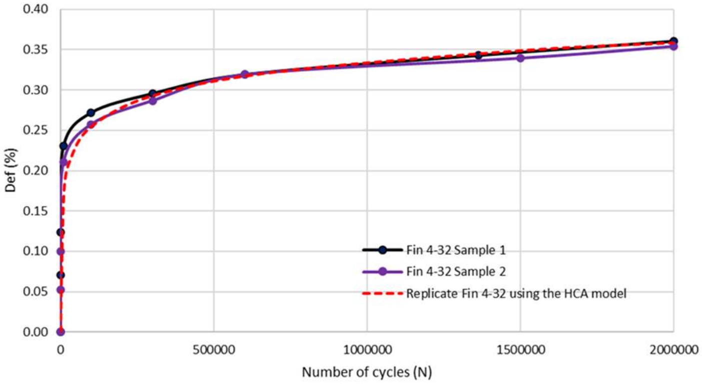
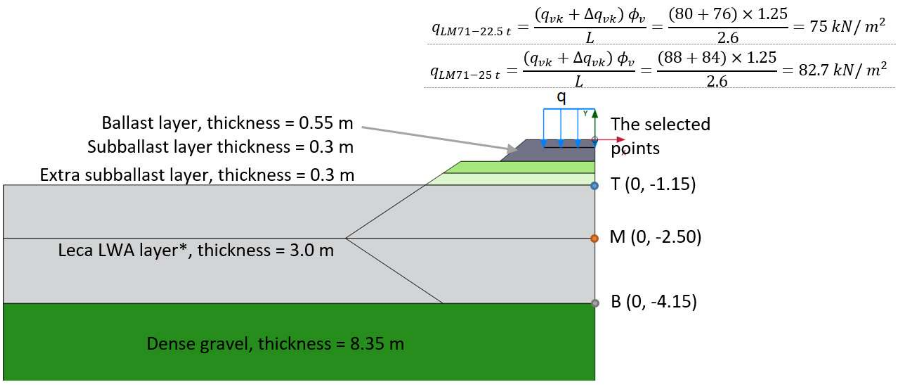


Figure 3 Replication of Fin 4-32 samples under cyclic compression tests by using the HCA model.

A Plaxis model, as shown in Figure 4, has been created to extract values such as strain amplitude and stresses because the laboratory test conditions differ from those on the construction site. With adjustments made to the amplitude and stresses in the HCA model, the correlation between the number of cycles (HCA model) and time (Plaxis) is presented in Figure 5.



$$q_{LM71-22.5\,t} = \frac{(q_{vk} + \Delta q_{vk})\,\phi_v}{L} = \frac{(80 + 76) \times 1.25}{2.6} = 75\,kN/\,m^2$$

$$q_{LM71-25\,t} = \frac{(q_{vk} + \Delta q_{vk})\,\phi_v}{L} = \frac{(88 + 84) \times 1.25}{2.6} = 82.7\,kN/\,m^2$$

*Figure 4 Plaxis model for cyclic loading analysis *This approach of modelling Leca LWA (without proper excavations) must ensure the sufficient embankment stability.*

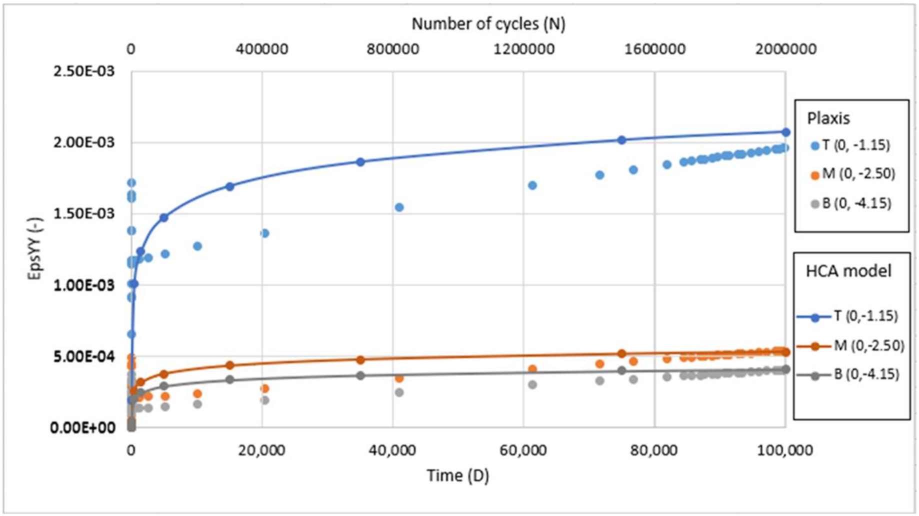


Figure 5 Vertical strain correlation between number of cycles (N) and time (T)

Nurmikolu (2004) reported that 3 million cycles can be approximated to represent 150 million tons of railway track load when using two adjacent 250 kN axle loads as one cycle. Therefore, the number of cycles per year for the selected route can be estimated using the same approximation. For example, the gross tonnage per year is 17.2 million from Lahti to Kouvola (Väylävirasto, 2019). Thus, the estimated number of cycles per track per decade is 1.7 million.

4. ANALYSIS AND RESULT DISCUSSION

All parameters used for calculations and models can be found in the first reference, which is the master's thesis of the main author.

Bearing capacity

To verify sufficient bearing capacity at the top of subballast layers when using Leca LWA with different cover depths, this study employs the Odemark method for calculation. A minimum bearing capacity of 180 MPa must be achieved when conducting the plate loading test (InfraRYL, 2020). The adopted Odemark E modulus for subballast is 300 MPa (InfraRYL, 2020), and for Leca LWA, it is 50 MPa (Pahkakangas et al., 2020). The results suggest that a 300-mm thick extra subballast layer is optimal because the minimum required bearing capacity at the top of the subballast layer can be achieved regardless of the subgrade bearing capacity.

Embankment stability

The cross-sectional dimensions vary (see Table 1). A Python script runs 52 analyses in Plaxis. The HS soil model is used for ballast, subballast, extra subballast, and Leca layers, with parameters sourced from Kalliainen & Kolisoja

(2017), Watn et al. (2004), and Høva et al. (2009). Parameters for subgrades are derived from the Murro test embankment (Koskinen et al., 2002), representing typical Finnish soil conditions with a thin dry crust over soft clay.

The results indicate a clear improvement in the factor of safety against slope failure as the thickness of the extra subballast layer increases from 0 to 0.3 m. However, there is no clear indication from the results whether an additional subballast layer further enhances embankment stability when its thickness exceeds 0.3 m. This finding supports the same optimal location, beneath a 300-mm extra subballast layer, for Leca LWA as determined from bearing capacity calculations using the Odemark method.

Displacement in Leca LWA layers

The displacement occurs in Leca LWA layers including the plastic displacement induced by cyclic loading and the elastic displacement caused by static train load.

As it is verified using 0.3-m thick subballast layer has been proven a positive impact in terms of bearing capacity and embankment stability.

As mentioned in the last chapter, the gross tonnage per year is 17.2 million from Lahti to Kouvola (Väylävirasto, 2019). Thus, the estimated number of cycles per track per decade is 1.7 million. under the axle load of 25 tons, this corresponds to 2.0 mm displacement at T, 1.4 mm at M, and 0.9 mm at P (positions of T, M, and B refer to Figure 4) when the thickness of the extra subballast layer is 0.3 m.

Nevertheless, these values are relatively small and can be almost neglected, especially for lower classifications of railway substructures. In other words, Leca LWA materials can satisfactorily withstand cyclic loading caused by moving trains, regardless of the cover depth.

5. CONCLUSION

This paper shows that placing Leca LWA below a 300-mm extra subballast layer significantly boosts railway embankment stability. However, limited improvement is seen with extra subballast layers over 300 mm. Leca LWA withstands cyclic loading regardless of cover depth, but these findings are specific to certain embankment setups.

Displacement from cyclic loading is analyzed using the Plaxis SSC model, validating the HCA model by Wichtmann et al. (2005). While helpful for estimating plastic strain under high-cycle train loads, there are limitations. For instance, Plaxis simulations show a linear relation, differing from the logarithmic one in the HCA model, leading to initial plastic strain underestimation. Also, differences between sand and Leca LWA pose test condition challenges.

This study evaluates Leca LWA for bearing capacity, embankment stability, and cyclic loading, guiding geotechnical designers. It also highlights simulation model feasibility for assessing plastic strain from high-cycle loads.

Future studies could explore higher cycle numbers in compression experiments for understanding long-term displacements from cyclic loading. Verifying assumptions about pre-consolidation pressure through test embankments with Leca LWA layers would be valuable. Additionally, combining Leca LWA with other ground improvement methods could offer cost-effective railway embankment designs.

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