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Investigating the Ecological Footprint of Deep Mixing

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In railway construction practice, we are increasingly faced with the problem of having to pass our new lines through areas with unfavorable subsoil conditions or with the need to reinforce the substructure of our existing lines due to increasing traffic demands (speed, axle load). The low strength, high compressibility, and low permeability of unfavorable subsoil will result in stability problems and prolonged consolidation with extremely high settlements, respectively. One of the effective technologies to counter the geotechnical problems is the deep mixing. The technology requires the addition of a binder (cement, lime) to the local soils. These materials have a high installed CO_2 emission, thus significantly increasing the ecological footprint of infrastructure development. Due to the increasing demands on reducing CO_2 emissions, secondary raw materials, e.g., fly ash or slag, have been increasingly prioritized. The study reports the methodology for calculating the ecological footprint of deep-mixing as an embankment foundation. Based on a simple case, the effect of different cement content (5 and 8%), and the application of slag and fly ash as a secondary raw material is analyzed, and the ecological footprint is calculated separately. The results show that the ecological footprint of deep mixing can be drastically reduced; under the conditions of the study, the reduction compared to clean cement is 40% for slag stabilization and 50% for fly ash.

1. Introduction

Companies play a prominent role in achieving the sustainability goals (Radácsi, 2011). As one of the largest consumers of natural resources and fossil energy, the construction industry is at the center of the debate on sustainable development. The Sustainable Development Goals (SDGs) provide comprehensive guidelines for the promotion of sustainable development in terms of environmental, social, and economic dimensions in all sectors of the economy, including the construction industry (Opoku et al., 2022). Society, the environment, and the economy are three areas that are significantly affected by the built environment. Attention to the environmental impact of buildings highlights the importance of using environmentally friendly technologies and processes in the construction industry (Tatari and Kucukvar, 2011) and their eco-efficiency issues in green buildings (Alawneh et al., 2018). One of the important directions of settlement development is the examination of the ecological footprint of settlements and the built environment. The footprint of built-up areas is a defining component of the ecological footprint. Reducing it (Harangozó et al., 2019) and controlling it is a technical challenge in addition to regulation. In recent years, researchers have made many attempts to replace the additives used in the production of cement composites as one of the directions of the pursuit of sustainability. Individual solutions can be an excellent strategy for achieving the SDGs and creating the goal of a circular economy. In Hungary, the practical application of ecological footprint calculation is in its initial phase (Harangozó et al., 2016). This statement is also valid for industrial projects. In everyday practice, during the design of geotechnical structures, the emphasis is on the verification of their technical, durability, and economic parameters. The design procedures based on practical experience are supplemented by laboratory tests and, increasingly, using modern geotechnical finite element software (Varga and Czédli, 2018). These two options allow the designer to select the optimal structure and technology for different locations (Varga et al., 2022). In recent decades, different ground improvement technologies have become increasingly accepted as a foundation for industrial and infrastructure projects. Instead of traditional geotechnical structures' execution, the structures' foundation is usually solved by improving the soil mass with a binder. However, binder technologies will be more

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beneficial than traditional structures in the long term only if we do not use cement in a wasteful way. Cement production plays a decisive role in the ecological footprint of geotechnical structures and technologies. Generally, larger industrial and scientific research provides the opportunity for a wider examination of the recipes of the mixtures to be carried out. In connection with these research results, it is possible to investigate individual possibilities not only from a technical point of view but also from an ecological and economic point of view. The study presents the analysis of deep mixing as an embankment foundation technology from an ecological point of view, presenting the procedure for determining the ecological footprint. It presents a general procedure that, at the same time as technical optimization, allows the designer to carry out an ecological-economic analysis and to determine the ecological footprint of the planned solution and minimize it if necessary. It is important to point out that, even in the case of industrial projects, it is advisable to approach carbon dioxide emissions from a life cycle perspective (Csutora and Harangozó, 2019). It is important to highlight that it is also appropriate to approach carbon emissions in industrial projects from a life-cycle perspective (Csiszárik-Kocsir and Varga, 2022), keeping in mind its safety dimensions (Saáry et al., 2021). From a national economic point of view, the utilization of slags and fly ash deposited as waste can be considered beneficial since by using them as secondary raw materials, the use of primary raw materials can be reduced, and areas can be revitalized due to spoil-reclaiming.

2. Application of deep-mixing as embankment foundation

In recent decades, road and railway embankments have often been constructed on soft, saturated, and organic subsoil in Hungary. There are several reasons for this, and this type of construction is suspected to increase in the future. In the design of transport infrastructure, the main objective is to ensure traffic safety and minimize operating costs, but several other factors also influence the layout. Existing settlements and areas designated for development must be avoided. Land-use plans must be adapted, and it is also recognized that there is no reason to complete the land requirements of transport at the expense of agriculture. Often, these result in constructions on unfavorable subsoil because they cannot be used for other purposes. Reducing the cost of earthworks has been only a secondary aspect, and rerouting the transportation infrastructure is generally not an option (Koch, 2011). The issue is significant in the case of high-speed rail lines, which have been under construction in Western Europe for decades and should slowly be scheduled in Hungary as well. Grossini et al. (2022) highlighted that speeds of more than 150-200 km/h allow only minimal displacement of the embankment crest, which poses a major challenge for the foundation of embankments. According to the literature, in many cases, increasing railway speeds challenge the 'conventional' railway construction technologies and can only do so at a high financial cost and with doubtful results. It is, therefore, essential to find solutions that could be applied to the construction of new lines, the upgrading of old ones, and possibly the widening of earthworks. Deep-mixed soil improvement promises to provide a 'normal' or slightly better receiving surface for the railway superstructure, with the embankment settlements not exceeding those expected for 'normal' soils. Low strength and high compressibility combined with low permeability and high creep potential cause stability problems with extremely large settlements, prolonged consolidation times, and long-term secondary compression. All this becomes particularly critical because construction deadlines are nowadays very tight. Several technologies have been developed to overcome the mentioned geotechnical problems. Roshan et al. (2022) summarize the classification of ground improvement technologies. One of the complex methods is deep mixing, which reduces settlements, reduces consolidation time, and increases safety against overall failure.

The ISO EN 14679:2007 (MSZ EN 14679:2007, 2007) clearly defines that the aim of deep mixing is to improve soil properties, i.e., to increase shear strength and reduce compressibility, by mixing the soil with a binder that reacts with it. The improvement occurs due to ion exchange at the clay surface, bonding of soil particles, and/or filling of voids by chemical reaction products. Deep mixing was developed in Sweden and Japan in the late 1960s with the application of a single mixing tool to produce column-type elements. Since then, new technologies have been introduced using different mixing tools or binder types (Moseley and Kirsh, 2004). Lately, another technology, mass stabilization, based on Finnish research (Lahtinen and Niutanen, 2009), is gaining acceptance, where the whole soil mass is treated generally to a depth of 5 m (Allu Stabilisation System, 2023). Column-type elements, usually 60-100 cm in diameter, are used when the primary goal is to reduce the settlements and the weak subsoil thickness exceeds 5 m, but they can reach great depths of up to 40 m. Mass stabilization is preferable when the subsoil is very weak, e.g., peat, gyttja, or organic and soft clay, but the thickness of the soil mass to be treated is less than 5 m, the height of the embankment is low, and the primary objective is to increase stability. Various treatment patterns may be executed depending on the purpose of deep mixing. Individual columns can be applied, but also groups of columns. Column group, grid, and grid-type solutions are often designed with a 15-20 % improvement ratio. For wet soils, dry mixing is used, where the binder is usually a mixture of cement and lime or cement, lime, gypsum, blast furnace slag, or slag fines. In wet mixing, the binder is usually cement slurry (Moseley and Kirsh, 2004). Figure 1 illustrates the deep-mixing technology.

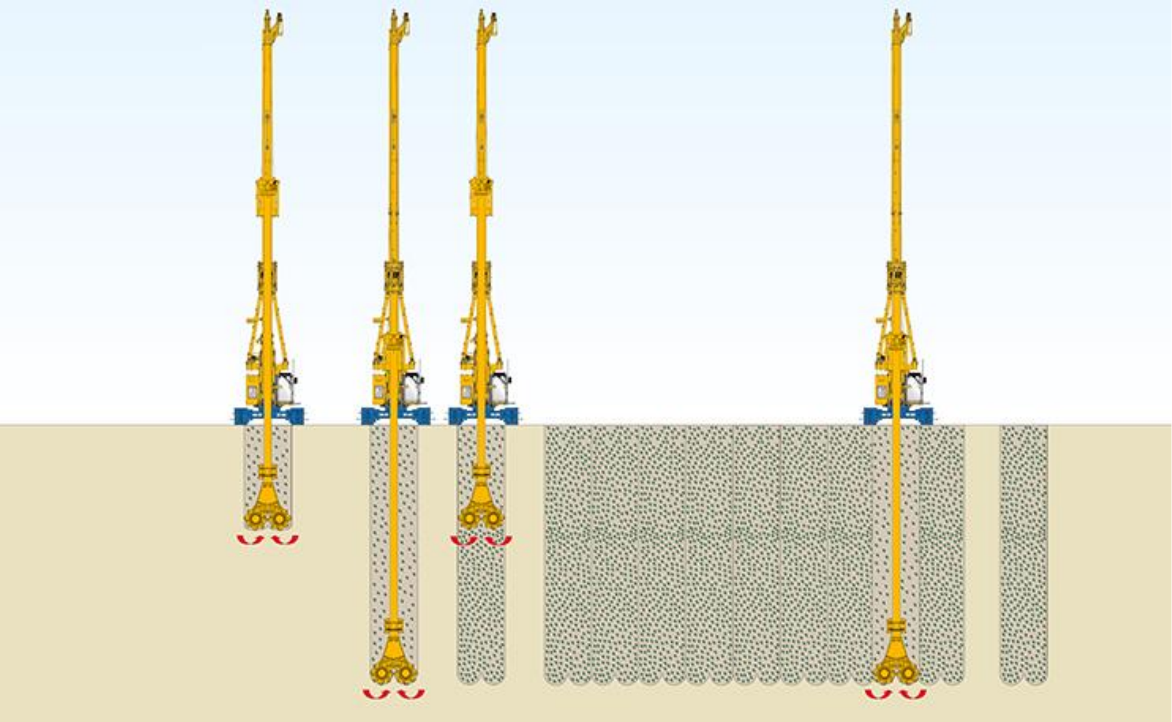

Figure 1: Column-type deep-mixing (Bauer Foundation Corp., 2023)

The quality of the deep-mixed stabilized subsoil as an embankment foundation is generally described with two parameters:
1) unconfined compressive strength, q_u [kPa] measured on a cylindrical specimen,
2) Young's modulus, E [MPa] measured on a cylindrical specimen.
The quality of the mixed-soil depends on the applied binder type, the quantity and the ratio of water to binder in the mixture. These quantities can be expressed by volume or weight. The content of the binder is given by the cement factor and the cement factor in-place determined by Eq(1) and Eq(2) (Filz et al., 2005).

$$\alpha = m_{cement} / V_{soil} = \text{binder weight / soil volume } [kg/m^3] \quad (1)$$

$$\alpha_{inpl} = m_{cement} / V_{mix} = \text{binder weight / mix volume } [kg/m^3] \quad (2)$$

The volume of water is usually related to the volume of cement. It is essential that the water content of the original soil is considered when calculating the water content of the slurry, hence the term of total water/cement or sum of water/cement ratio is used and described by Eq(3).

$$w_T/c = m_{w,mix} / m_{cement} = \text{slurry water weight / binder weight } [-] \quad (3)$$

The cement factor, cement factor in-place and the water/cement ratio are usually determined in the laboratory. These factors provide the input parameters, e.g., unconfined compression strength and Young's modulus for the geotechnical and structural design, either conventional design method or finite element analyses.

3. Methodology

Based on Tóth et al. (2023), the structural analyses enable the identification of the technically optimal solution and the possible utilization of secondary raw material in terms of circular farming. However, Eisinger et al. (2022) highlighted that it is not sufficient to consider only the applicability of the technology; a comprehensive analysis of the entire life cycle behavior is necessary. Concerning Li et al. (2018), understanding the reinforcement effect is crucial in evaluating long-term behavior due to the specific utilization. Besides the technical development, the environmental analysis of geotechnical structures is increasingly important (Vieira, 2022). According to Chen et al. (2020), this approach requires the utilization of specialized binders in some instances.

The geotechnical design may result in a version with the same technical performance but different costs for the same project. Since competition for installation technologies is limited in the market, and it is assumed that there is no significant difference in transport distances, our study is characterized only by the CO_2 emissions from the applied deep-mixed soil on the material side. This study analyzed the effect of different binders on the ecological footprint. 4 different cases were investigated:

1) adding 5 % cement to the natural soil,
2) adding 6 % cement and 2 % lime,
3) adding 8 % ground granulated blast furnace slag (GGBS) and 2% lime,
4) adding 8 % fly ash and 2 % lime.

The specific emissions ($kgCO_2/kg$) of the materials are summarized in Table 1, provided in ICE v1.6a.

Table 1 can only be attended as a set of discrete points and is unsuitable for optimizing different mixtures for deep mixing. However, the sum of the specific emissions taken into account according to the percentage by weight of each component is a good approximation. This is summarized in Table 2, for which the input parameters for the different binders are provided in Table 3. Table 2 contains the calculation of the weighted specific emissions and the difference between the specific emission and the weighted specific emission.

Table 1: Data related to ICE v1.6a (Inventory of Carbon and Energy database, 2023)

Material	$kgCO_2/kg$	Comment
rammed soil	0.023	-
cement stabilised soil (5 %)	0.060	5 % cement content
cement stabilised soil (8 %)	0.082	6 % cement + 2 % lime content
GGBS stabilised soil (10 %)	0.045	8 % GGBS + 2 % lime content
fly ash stabilised soil (10 %)	0.039	8 % fly ash + 2 % lime content

Table 2: Comparison of ICE v1.6a and the calculated data (Inventory of Carbon and Energy database, 2023)

Material	$kgCO_2/kg$	$kgCO_2/kg$ (calculated)	Difference
rammed soil	0.023	1.00*0.023=0.023	0 %
cement stabilised soil (5 %)	0.060	0.95*0.023+0.05*0.73=0,058	3 %
cement stabilised soil (8 %)	0.082	0.92*0.023+0.06*0.73+0.02*0.76=0,080	3 %
GGBS stabilised soil (10 %)	0.045	0.90*0.023+0.08*0.083+0.02*0.76=0,043	5 %
fly ash stabilised soil (10 %)	0.039	0.90*0.023+0.08*0.008+0.02*0.76=0,037	5 %

Table 3: Input parameters for deep-mixing based on ICE v1.6a ((Inventory of Carbon and Energy database, 2023)

Material	$kgCO_2/kg$
rammed soil	0.023
cement (general)	0.73
lime (general)	0.76
GGBS	0.083
fly ash	0.008

One can see the slight difference between the proposed and calculated values in Table 2.

Table 3 suggests that substituting primary raw materials (cement or lime) with secondary raw materials (slag, fly ash) can be effective from an ecological economics point of view due to their lower CO_2 emissions. From the national economic point of view, it is also the fact that materials utilized as waste are used as secondary raw materials. It should be noted that using these materials requires complex laboratory testing.

4. Results

The calculation of the ecological footprint is based on the defined $kgCO_2$ values. A simple example is analyzed to illustrate the comparison of the ecological footprint of different types of mixtures. In the example, the density of the mixed soil mass is uniformly 2,700 kg/m^3, the volume of the mixed soil is 226.2 m^3, and the weight is 610.7 t. It represents 100 columns with 0,6 m diameter and 8 m lengths. In the calculation, it is assumed that the binders presented in Table 1 are technically sufficient. However, technical compliance alone does not represent the technical, economic, and ecological optimum, so it is possible to select an eco-efficient solution by considering all these aspects together. The results of the ecological analysis are summarized in Table 4. As expected, the most significant specific emission is calculated for the cement-stabilised soil using 6 % cement and 2 % lime. Using 5 % clean cement causes a 25 % reduction in specific emissions. Mixing of ground granulated blast furnace slag (GGBS) and lime drastically reduces specific emissions. A mixture of fly ash and lime has a significant effect; the reduction is more than 50 % compared to the cement-stabilised soil (8 %). The calculated emissions in tonnes should be multiplied by 0.338 gha/t. It produces the possibility of comparing the area in gha with the area in gm^2 of land with world average productivity (Lin et al., 2018). Based on the results presented in Table 4, using secondary raw materials to replace the cement can achieve significant CO_2 emission reduction. Of course, their technical suitability needs to be analyzed by laboratory or field trial tests.

Table 4: Results of ecological footprint analysis

Material	t CO_2/t	t CO_2	gha
cement stabilized soil (5 %)	0.060	36.6	12.4
cement stabilized soil (8 %)	0.082	50.1	16.9
GGBS stabilized soil	0.045	27.5	9.3
fly ash stabilized soil	0.039	23.8	8.0

5. Conclusions

In Hungary, the practical application of ecological footprint calculations for industrial projects is still in its early stages. In everyday practice, the design of the different structures focuses on verifying the technical, serviceability, and economic parameters. The ecological footprint of civil engineering, particularly geotechnical structures, is relatively high due to the associated cement industry. In this study, the ecological footprint calculation is presented through the application of deep mixing as an increasingly common ground improvement, and the ecological benefits of using secondary raw materials are highlighted. It has been shown that using secondary raw materials can reduce the ecological footprint by up to one-third to one-half compared to using clean cement.

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Nomenclature

q_u – unconfined compression strength, kPa
E – Young's modulus, MPa
α – cement factor, kg/m^3
m_{cement} – binder weight, kg
V_{talaj} – soil volume, m^3
α_{inpl} – cement factor in-place, kg/m^3
V_{mix} – mixture volume, m^3
w_T/c – total water/cement ratio, -
$m_{w,mix}$ – water weight, kg

References

Alawneh R., Mohamed Ghazali F.E., Ali H., Asif M., 2018, Assessing the contribution of water and energy efficiency in green buildings to achieve United Nations Sustainable Development Goals in Jordan. Building and Environment, 146, 119–132.

Allu Stabilisation System, 2023, Allu Stabilisation System Brochure, Allu <www.ecanet.com/uploads/files/Resources/ALLU-Stabilisation-System-Brochure.pdf>, accessed 14.08.2023.

BAUER Foundation Corp., 2023, About BAUER Foundation Corp., Bauer Foundation Corp. <bauerfoundations.com/en/about/company>, accessed 08.08.2023.

Chen R., Zhu Y., Lai H.P., Bao W., 2020, Stabilization of soft soil using low-carbon alkali-activated binder. Environ Earth Sci, 79, 510.

Csiszárik-Kocsir Á., Varga J., 2022, User perception of environmentally friendly megaprojects, Steps: Towards Sustainability, (in Hungarian), 27, 10-12, <https://kovet.hu/wp-content/uploads/2023/02/Lepesek-87_web.pdf>, accessed 22.11.2023.

Csutora M., Harangozó G., 2019, Carbon accounting in the network economy. (in Hungarian), Vezetéstudomány-Budapest Management Review, 50, 26-39.

Eisinger B., Németh A., Major Z., Kegyes-Brassai O., 2022, Comparative Life Cycle Analyses of Regular and Irregular Maintenance of Bridges with Different Support Systems and Construction Technologies. Chemical Engineering Transactions, 94, 571-576.

Filz G.M., Hodges D.K., Weatherby D.E., Marr W.A., 2005, Standardized Definitions and Laboratory Procedures for Soil-Cement Specimens Applicable to the Wet Method of Deep Mixing, GSP 136 Innovations in Grouting and Soil Improvement. ASCE Geo-frontiers, Reston, Virginia, 1-13.

Grossoni I., Hawksbee S., Jorge P., Bezin Y., Magalhaes H., 2022, Prediction of track settlement at high-speed railway transitions between embankment and bridge in the proximity of a turnout. Transportation Geotechnics, 37, 100879.

Harangozó G., Széchy A.Z., Zilahy G., 2016, The role of sustainability footprint approaches in the sustainability performance evaluation of companies. (in Hungarian), VEZETÉSTUDOMÁNY - Budapest Management Review, 47,2-13.

Harangozó G., Kovács Z., Kondor A.C., Szabó B., 2019, Changes in the consumption-based ecological footprint of the Budapest urban area between 2003 and 2013. (in Hungarian), Regional Statistics, 59, 97-123.

Inventory of Carbon and Energy database, 2023, Embodied Carbon - The ICE Database, Circular Ecology <circularecology.com/embodied-carbon-footprint-database.html>, accessed 24.01.2023.

Koch E., 2011, 3D modeling of subsoil repair with gravel piles. (in Hungarian), XV. International Construction Science Conference (EMT), Csíksomlyó, Romania, 2-5 June.

Lahtinen P., Niutanen V., 2009, Development of In-Situ Mass Stabilization Technique in Finland, Lahtinen P., Niutanen V. <projektit.ramboll.fi/life/stable/images/Okinawa-2009.pdf>, accessed 19.06.2023.

Li Y., Jia S., Liu J., 2018, The Solidification Mechanism of Cement and Fly Ash Towards Contaminated Soil. Chemical Engineering Transactions, 67, 571-576.

Lin D., Hanscom L., Martindill J., Borucke M., Cohen L., Galli A., Lazarus E., Zokai G., Iha K., Wackernagel M., 2018, Working Guidebook to the National Footprint Accounts, Global Footprint Network. <www.footprintnetwork.org/content/uploads/2018/05/2018-National-Footprint-Accounts-Guidebook.pdf>, accessed 19.06.2023.

Moseley M.P., Kirsch K., 2004, Ground Improvement. Taylor and Francis, London, 57-92, 331-428.

MSZ EN 14679:2007, 2007, Execution of special geotechnical works, Deep mixing. (in Hungarian), 2007 Hungarian Standards Board, Budapest, Hungary.

Opoku A., Deng J., Elmualim A., Ekung S., Hussien A.A., Buhashima Abdalla S., 2022, Sustainable procurement in construction and the realisation of the Sustainable Development Goal (SDG) 12. Journal of Cleaner Production, 376, 134294.

Radácsi L, 2011, On the Central European CSR paradox. (in Hungarian), Harvard Business Review, 2011, 29-39.

Roshan M.J., Safuan A., Rashid A., Wahab N.A., Tamassoki S., Jusoh S.N., Hezmi M.A., Daud N.N., Apandi N.M., Azmi M., 2022, Improved methods to prevent railway embankment failure and subgrade degradation: A review. Transportation Geotechnics, 37, 100834.

Saáry R., Csiszárik-Kocsir Á., Varga J., 2021, Examination of the Consumers' Expectations Regarding Company's Contribution to Ontological Security. Sustainability, 13, 9987.

Tatari O., Kucukvar M., 2011, Cost premium prediction of certified green buildings: A Neural Network approach. Building and Environment, 46, 1081–1086.

Tóth A.J., Fózer D., Mizsey P., Varbanov P.S., Klemeš J.J., 2023, Physicochemical methods for process wastewater treatment: powerful tools for circular economy in the chemical industry. Reviews in Chemical Engineering, 39, 1123-1151.

Varga Zs., Czédli H., 2018, Studying the accuracy of orthophotos on the example of various terrain models in study areas in Hungary. Acta geogr. Debr., Landsc. environ. ser., 12, 31-39.

Varga Zs., Czédli H., Kézi C., 2022, Examination of the surface movement of Debrecen based on the national leveling network. (in Hungarian), In: The meeting of theory and practice in GIS XIII., Debrecen, Hungary, 3-4 November 2022, Edited by: Éva Vanda Abriha-Molnár, Debrecen University Press, Debrecen, Hungary, 339-345.

Vieira C.S., 2022, Sustainability in Geotechnics through the Use of Environmentally Friendly Materials. Sustainability, 2022, 14, 1155.