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CRUSHED STONE SUPPLY CHALLENGES FOR INFRASTRUCTURE DEVELOPMENT IN HUNGARY

The rapid expansion of Hungary's infrastructure projects, especially in railway construction, has significantly increased the demand for crushed stone. Both national and EU-funded initiatives have strained supply chains, resulting in logistical challenges and material shortages. With limited domestic production capacity, efficient resource management is crucial to keeping projects on track. This paper evaluates Hungary's supply chain for crushed stone, identifying key weaknesses and proposing solutions to enhance sustainability.

Purpose. This study investigates the logistical and supply chain difficulties in delivering crushed stone for Hungary's railway infrastructure projects. It evaluates current supply limitations, proposes ways to improve domestic resource management, and offers strategies to reduce reliance on imports while emphasizing sustainability.

Methodology. The research applies Geographic Information System (GIS) modeling to analyze transportation routes for crushed stone, suggesting ways to streamline logistics. It examines the production capacities of Hungarian quarries, some producing 15,000–25,000 tons monthly, and assesses the impact of European and Hungarian regulations on material quality and availability. The potential for integrating recycled materials into the supply chain is also explored.

Findings. Hungary's domestic quarries cannot meet the high demand for railway ballast, estimated at 192,000 tons annually, leading to import reliance. GIS modeling shows optimized transportation routes could cut costs and carbon emissions. Incorporating smaller stone fractions and recycled materials could mitigate shortages, with recycled materials potentially comprising 40 % of railway ballast.

Originality. By integrating geological, logistical, and regulatory insights, this paper provides novel approaches for addressing Hungary's crushed stone supply chain challenges. The use of GIS modeling and recycled materials offers innovative solutions for reducing environmental impacts.

Practical value. The findings present actionable strategies for improving Hungary's supply chain efficiency, promoting recycling, and optimizing logistics. These solutions are applicable to Hungary and other regions facing similar infrastructure material supply challenges.

Keywords: *crushed stone supply, construction materials, infrastructure logistics, railway construction projects*

Introduction. The continuous global advancement of modernization has led to increasing societal demands for advanced infrastructure. This is no different in Hungary. The continuously growing and developing transportation infrastructure networks require significant amounts of raw materials, primarily sourced from stone and gravel quarries. In both road and railway construction, sustainability considerations are increasingly emphasized. These include the CO_2 emissions from the construction and maintenance of structures, the widespread use of recycled materials [1–3], as well as minimizing energy requirements during construction and maintenance processes [4].

It can be stated, however, that at the current level of technological development, these construction and maintenance tasks cannot be achieved solely through recycled materials. Nonetheless, the volume of their use shows a growing trend year by year. As a result, the development of transportation infrastructure still heavily relies on primary raw materials. These resources cannot be considered sustainable, as they are available in finite quantities, and their depletion can be predicted [5]. The depletion timeline for these resources is fundamentally determined by extraction schedules, which are influenced by market processes, business policies, relevant regulations, and technical requirements.

Mineral resources considered critical from a raw material supply perspective are those where availability is limited compared to demand. Factors contributing to this include the quality requirements for stone materials and the poor production yield of products required by specific market segments relative to the total quantity of extracted minerals (i.e., an insufficient proportion of the required product is yielded during production). It should be noted that stone and gravel are not classified as critical raw materials [6]. Technical requirements for such materials typically vary in different countries' specific regulations (NADs). As a result, infrastructure elements, roads, highways, and railways that are operated at similar service levels may be constructed with stone materials that meet different standards despite serving similar functions. In other words, stone material suitable for use in one country's transportation infrastructure, designed to the same service level, may not meet the quality standards for use in another country.

From a scientific perspective, it is worth raising the question of what factors may contribute to differing technical standards for stone materials across countries, even when intended for the same purpose. Answering this question is quite complex, considering different countries' varying construction "traditions" and practices, their climatic, topographical, hydrographic, and morphological conditions, and the quantity and quality distribution of the mineral resources available in the region.

The scope of this article does not allow for a comprehensive scientific examination of every detail of this issue. However, the current paper's authors aim to highlight the supply chain risks associated with raw materials, pointing out the potential negative societal impacts of this complex, multi-industry, and multidisciplinary issue. The paper will also discuss possible measures to mitigate these impacts in light of the increasing demand for raw materials in infrastructure development and maintenance (with a focus on railway infrastructure) and society's growing expectations regarding sustainability.

Literature review. Crushed stone is critical for infrastructure projects like railway ballast and highway surfaces. In Hungary, the supply is increasingly strained by limited domestic sources and rising demand from national and EU-funded projects. European standards, such as EN 13450:2002 [7 (1)] (it has to be mentioned that this paper contains a lot of references; in this way a supplementary document was prepared where the standards, regulations and decrees are collected with the appropriate citation format. After the reference in the main text there will be a rounded bracket with the item's ID. in this supplementary document, e.g., [7 (1)]), reveal quality issues with local materials like andesite and basalt, which affect infrastructure durability [8]. Ensuring a steady supply of ballast is particularly challenging due to inconsistencies in stone quality, especially for railway and highway construction. To address shortages, smaller crushed stone fractions (0/4 and 0/8 mm) are being used in asphalt [9], optimizing material use despite supply constraints [10, 11].

Hungary's geographical and logistical barriers further complicate the crushed stone supply chain, similar to issues seen in Poland's Lower Silesia [12]. It is worth mentioning that recent studies have emphasized the importance of optimizing granite crushing techniques for high-quality cubiform aggregates [13], managing changes in mineral composition caused by blasting operations [14], and improving logistical strategies for the shipment of non-metallic mineral resources [15] to enhance supply chain efficiency and sustainability. Despite its high costs, reliance on trucking adds to these inefficiencies. The research suggests optimizing logistics through advanced simulation models and tools like Geographic Information Systems (GIS) can enhance coordination and reduce waste [16]. The use of automated technologies could also improve quality control in quarry operations, addressing the variability of domestic stone quality, particularly for meeting railway ballast standards [17]. Implementing new quarrying technologies and policy reforms promoting local sourcing and recycling could strengthen the supply chain [18].

Historically, Hungary has depended heavily on volcanic rocks like andesite and basalt. However, the growing demand for infrastructure projects is increasing pressure on domestic suppliers [19]. Despite efforts to comply with European standards like the Los Angeles and micro-Deval tests, outdated production infrastructure limits the ability to consistently meet quality requirements [20]. Stricter environmental regulations also restrict the development of new quarries. In contrast, countries like Austria have adopted more advanced technologies and improved integration into the European market, while Slovakia has focused on sustainability to bolster its supply chain [21]. Hungary's slower response to EU environmental policies puts it at a disadvantage in cross-border projects.

Recycling crushed stone, especially for railway ballast, offers significant environmental and cost benefits. Studies from Central Europe suggest that recycled aggregates are viable alternatives in infrastructure projects, providing economic and environmental advantages [22]. However, dependence on foreign sources for crushed stone brings logistical challenges, including long transportation distances and inconsistent quality, further driving up costs [23]. Exploring local alternatives, such as oligomictic alluvial gravel and recycling mining waste, could reduce reliance on imported materials [24]. While rail transport could offer a more efficient solution, Hungary's outdated rail infrastructure remains a barrier. Developing efficient multimodal transportation systems that combine rail and road could help reduce these logistical challenges and cut costs [25].

Recycling is gaining traction in Hungary, with studies showing that recycled aggregates can perform as well as natural ones in infrastructure projects [26]. Although EU regulations encourage recycling, challenges remain in aligning Hungary's practices with these standards. Incorporating technical ratios, such as replacing 50 % of natural aggregates with recycled concrete, could optimize both performance and sustainability. However, widespread adoption is slowed by economic and technological barriers. Raising public awareness and introducing policy reforms could increase the acceptance of recycled materials. Supply constraints, high transportation costs, and the over-reliance on trucking continue to create bottlenecks [27]. Environmental regulations further restrict the development of new quarries, adding pressure on existing reserves [28]. Using smaller stone fractions and recycled materials is crucial to meet growing demand [29].

A stable supply of crushed stone is vital for Hungary's construction sector, as shortages can delay infrastructure projects and raise costs. Investment in quarry management and new technologies is necessary to ensure a steady supply of materials [30]. A recent study by Ézsiás, et al. (2024) [31] explored the relationships between specific properties of crushed stone aggregates, providing insights into how material characteristics affect construction projects. The effective management of transport enterprises can greatly enhance logistical efficiency, especially when utilizing specialized management systems tailored to the industry's needs, as discussed by Volkov, et al. (2020) [32]. Integrating sustainable practices and innovative technologies will be essential for meeting the challenges posed by increasing demand and stricter environmental regulations [33].

The purpose of the article. This article investigates the logistical challenges and supply chain constraints associated with providing crushed stone for infrastructure projects in Hungary, mainly focusing on railway construction. Crushed stone, a crucial material for infrastructure development, faces increased demand driven by domestic and European Union-funded projects. This article explores the current state of crushed stone supply, identifies the industry's specific challenges, and proposes strategies to optimize resource use while ensuring sustainability in railway infrastructure projects.

This research is particularly relevant given the heightened demand for raw materials and the limited domestic sources of crushed stone. By analyzing national regulatory frameworks and European standards, the article seeks to identify areas where improvements can be made to mitigate supply chain risks. It also explores the potential role of recycling and alternative materials in reducing reliance on primary resources, which aligns with broader sustainability goals in infrastructure development.

Ultimately, the article comprehensively examines the intersection between logistics, sustainability, and resource management. Its findings are intended to offer actionable insights for industry stakeholders, policymakers, and construction professionals aiming to enhance the efficiency and environmental impact of crushed stone supply chains in Hungary's infrastructure development projects.

Methods. The methodology adopted in this article involves a detailed analysis of Hungary's existing crushed stone supply chain, focusing on domestic sources, production capacities, and the transportation challenges associated with delivering these materials to infrastructure projects. The research includes a review of relevant Hungarian and European regulatory standards, such as EN 13450, to assess how these standards influence the availability and quality of crushed stone for railway construction. The study further evaluates the economic and environmental impacts of different transportation methods, such as road versus rail, in terms of cost efficiency and CO_2 emissions.

In addition to examining the current state of crushed stone production and logistics, the study assesses the potential for using recycled materials to supplement natural aggregates. This involves analyzing existing recycling practices in Hungary and Europe, focusing on the challenges and opportunities of integrating smaller stone fractions and recycled aggregates into infrastructure projects. The research draws on quantitative data, such as production yields and transportation costs, and qualitative insights from industry reports and regulatory documents.

Finally, the study uses advanced simulation tools, including Geographic Information Systems (GIS), to model potential improvements in the logistics of crushed stone supply. These tools help evaluate how changes in transportation routes, quarry management, and resource allocation could reduce bottlenecks and improve the overall efficiency of the supply chain. Such models allow the research to propose actionable strategies to enhance sustainability and cost-effectiveness in future infrastructure projects.

Findings. The findings section discusses Hungary's regulatory landscape for aggregates, highlighting that European standards like EN 13450 provide a common framework for railway ballast but have not kept pace with modern technological and market demands (subsection "Regulation environment, assessment of current requirements from an international perspective"). Due to limitations in domestic supply, Hungary increasingly depends on importing crushed stone from foreign sources, which presents logistical and economic challenges (subsection "Possibilities to meet domestic needs from foreign sources"). The environmental and economic assessment emphasizes the country's heavy reliance on road transport, leading to higher costs and emissions than rail (subsection "Environmental economic assessment and status of transport of aggregates"). To address these challenges and strengthen environmental objectives, potential interventions include increasing the use of recycled materials in infrastructure projects and implementing policy changes that encourage sustainable practices, such as optimizing transport routes and sourcing more materials locally to reduce environmental impact (subsection "Possible interventions to strengthen environmental objectives").

Regulation environment, assessment of current requirements from an international perspective. European standards foster better understanding between member states by creating a unified framework and foundation for member-specific regulations in the European region. This is no different in the field of railway construction. The uniform framework for railway ballast stone materials is defined by the EN 13450 product standard [7 (1)], which has been in force since 2002 and labeled as MSZ EN since 2003 [7 (2)]. Although it has undergone minor changes since then, its 2013 revision was quickly withdrawn, meaning that the regulatory framework has been in place for more than 20 years and has not kept up with the technological, economic, and other changes that have occurred since.

Currently, the standard exists in the regulatory system as a draft standard under the designations prEN 13450-1:2021 [7 (3)] and prEN 13450-2:2021 [7 (4)]. In terms of content, it addresses the requirements for railway ballast stones used in track superstructures in a more detailed and comprehensive manner than the previous version, which is still in force. It explicitly covers natural, manufactured, and recycled unbound aggregates and their mixtures that can be used in the track superstructure. However, it does not cover ballast that has already been used, cleaned on-site, or recycled without being reintroduced into the market.

The current standard allows for a multi-criteria, uniform classification, defining, among other things, the particle size of the stone material in terms of geometry ($d_{\min}/d_{\max}$), its distribution (based on boundary curves *A, B, C, D, E, F*), the shape of the particles (*FI*, *SI*), and its physical parameters such as (*LA*, *MDE*, *MS*, etc.). Member states select and define their own requirements from this framework, similar to choosing from a "menu". In Central and Eastern European countries, German/Austrian dominance is a common trend in this field.

In Hungary, the MÁV PHMSZ 102345 [7 (5)] directive was introduced in 1995 and has undergone several modifications since then. This significantly affects the range of stone materials used in railway track structures and the number of potential suppliers. Following the *4^th^* amendment, the regulation is currently consolidated [7 (6)] and its revision and modification have been in progress since 2023, with plans to issue it later as Directive MÁV D.26 [7 (7)] (it has to be mentioned that this regulation has not been placed in force yet).

The regulation has undergone numerous changes throughout its decades-long existence. For example, in its *3^rd^* amendment, it was more permissive in specific parameters of railway crushed stone materials (allowing a "plus 2" deviation for *LA* and *MDE* limit values), a provision that was abolished with the introduction of the current version. As a result, the number of quarries eligible for railway projects has decreased further, limiting them to just a few, which significantly impacts domestic production capacity, transportation costs, and the expected lifespan of the diminishing available resources (or, more precisely, the remaining time predicted until their depletion).

European countries using EN 13450 [7 (1)] as a framework standard also have country-specific requirements and regulations, including National Application Documents (NADs) or other sector-specific regulations. Application criteria and limit values are typically determined based on track speed, axle load, or traffic volume.

The framework standard specifies the particle size range using the d/D ratio, where d denotes the nominal smallest particle size and D the largest, with defined limits (*A, B, C, D, E, F*). In most countries, the sizes 31.5/50 and 31.5/63 mm, selectable under the standard, are used, except for France, where the preferred size is 25/50 mm, which falls outside the options provided by the common European framework. In other respects, the French regulatory system also differs from general European regulations in several details.

Based on Table 1, it is clear that the Hungarian regulations are neither the strictest nor the most lenient. Although they regulate applicability through fewer qualifying parameters than other countries, they still provide supply opportunities for only a few material extraction sites and quarries. This suggests that, compared to European countries, the domestic requirements are not overly stringent; however, considering the quality, distribution, accessibility, and volume of available resources, they still act as a significant filter for eligible sources.

Regarding natural conditions, Hungary does not possess significant, well-metamorphosed rock formations with outstanding physical properties. Therefore, only the available reserves of primarily andesite, basalt, limestone, and dolomite can be considered. Among these, the use is restricted to the andesite and basalt raw materials from a few quarries, which accelerates the depletion rate of these mines and reduces the lifespan of their accessibility.

Possibilities to meet domestic needs from foreign sources. Based on the aggregated data from 2017–2022, the amount of railway ballast crushed stone used on the MÁV rail network averaged 192,000 tons per year [7 (8)]. This is likely an exceptionally high figure compared to previous years, probably with significant peaks in one or two years due to the construction work on the Budapest-Belgrade railway line. Considering this data, it is important to also highlight the mining of stone materials.

It is essential to note that stone materials are naturally formed, so their quality is not homogeneous or isotropic in different deposits. Quarrying operations must account for technological and planning processes to ensure a continuous supply of appropriately high-quality raw materials. According to industry experience, in quarries producing suitable quality materials, due to the physical properties of the rocks and the characteristics of the crushing and grading technologies, this fraction only represents 30–40 % of total production at most.

Currently, the producing quarries in Hungary are located in the country's mountainous regions, meaning that about 80 % of them are situated in or near Natura 2000 (Natura 2000 is a network of protected areas across the European Union, established to conserve biodiversity by protecting vulnerable habitats and species of European importance) or other protected areas, making their expansion rather difficult or even impossible. Opening or reopening new quarries often faces significant challenges due to public opposition. In recent years, the opening (or reopening) of several quarries has been hindered by this (e.g., Pilisvörösvár, Sümegprága, etc.).

Establishing a quarry plot is a legal procedure preceded by several years of exploration and permitting processes, which

Table 1

The most strict requirements for railway ballast in European countries [7 (8)]

Specified parameters (based on [7 (1)])	Czech Rep. [7 (9)]	Austria [7 (10)]	Germany [7 (11)]	Poland [7 (12)]	France [7 (13)]	UK [7 (14)]	Finland [7 (15)]	Hungary [7 (6)]
d_{min}/d_{max}, mm/mm	31.5/63	31.5/63 and 16/31.5	31.5/63	31.5/50 and 31.5/63	25/50	–	–	–
PSD (particle size distribution) category	D	D	D	ABCDEF	–	A	CEF	ABCDE
$d < 1.6$ mm, %	–	–	–	–	0.50	–	–	–
$d < 0.5$ mm, %	1.20	1.00	1.00	0.60	–	0.60	1.00	1.00
$d < 0.063$ mm, %	1.00	1.00	1.00	0.50	–	–	–	1.00
FI, %	15	–	35	15	15	35	–	15
SI, mm	20	5/30	5/30	–	–	–	20	–
L, mm	–	6	–	4	The weight ratio of 92 mm particles on a 50 mm sieve is 7	4	12	–
C, mm	–	100	–	99	–	–	–	–
LA, %	14	22	12	16	19	20	12	16
SZ, %	18	22	14	–	–	–	–	–
MDE, %	11	16	–	7	6	7	11	11
LA + *MDE*, %	–	–	–	–	High-speed railway lines $LA + \mathbf{5} \times MDA \leq 44$ Traditional railway network $LA + 2 \times MDA \leq 33$	–	–	–
MS, %	–	declared	declared	declared	–	–	–	–
WA24, %	0.50	0.50	0.50	0.50	–	–	0.50	–
ρ, t/m^3	2	declared	declared	–	–	–	–	–
F, %	1	–	–	–	–	–	–	–

confirm the quality and quantity of the available useful material. The entire process for an open-pit quarry can take 5–7 years, so supply security can only be ensured with long-term, proper planning.

In operating quarries, the annual production is limited to the quantity authorized in the environmental permit and the technical operational plan and can be expanded by a maximum of 25 % over five years. (Similarly, waste management operations in urban areas face similar optimization challenges, where schedule optimization can drastically reduce operational inefficiencies, as explored by Saukenova, et al. (2022) [34] in the context of garbage collection in metropolitan areas.) However, increased production requires additional equipment and human capacity, although this can be facilitated by mobile technological elements.

The largest quarries in the country, such as Komló (andesite), Tállya (andesite), and Uzsa (basalt), can continuously supply 15,000–25,000 tons of material per month at the required quality. Smaller quarries, such as Bazsi, Zsunypuszta, and Egerbakta, can contribute a few thousand tons monthly, often with only occasional production. Unfortunately, production data shows that output is not continuous, as demand is often unevenly distributed. Specific periods, influenced by EU funding, political factors, etc., experience significant peaks, which put the operations in a difficult position, leading to capacity and quality issues. The extreme demand often focuses on just a few fractions (31.5/50, 8/11.2 mm), causing problems for quarries in handling and transporting the remaining fractions internally.

Fig. 1 represents the quantities of production of non-ore mining products in Hungary according to the time interval between 2002 and 2022 according to the Supervisory Authority for Regulated Activities [7 (16)]. Based on the data detailed in the diagram (Fig. 1), it can be seen that the quantity of raw materials for mineral mining was approximately 4–5 million tons, with a relatively low variation in the considered time range.

Connecting to Fig. 1 and supplementing it, there are further production data for 2023 [7 (16)]:

- clay: 1.4256 Mt;
- sand and gravel: 37.9322 Mt;
- tone: 25.5186 Mt;
- total: 61.8762 Mt.

Environmental economic assessment and status of transport of aggregates. The demand for crushed stone largely influences the volume of product sales. Few quarries in Hungary supply

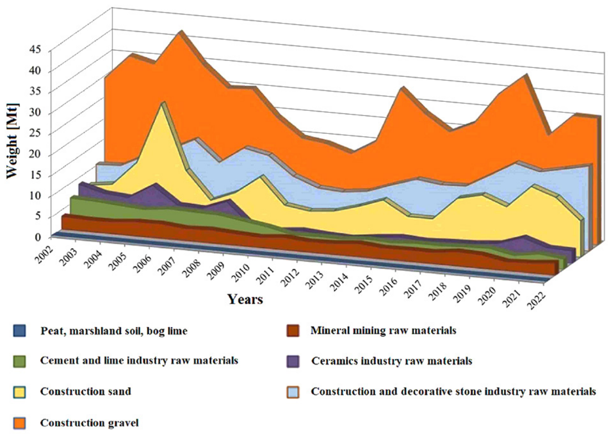

Fig. 1. Production of non-ore mining products in Hungary 2002–2022 (Mt means million tons; on the basis of [7 (16)])

raw materials meeting the parameters set by the ERRI (European Rail Research Institute). The quarries in Tállya, Komló, and Uzsa can produce hundreds of thousands of tons of raw material, but even this combined output falls short of meeting the country's total demand. Additionally, there are several quarries with an annual production capacity of 100,000 to 300,000 tons, but despite the high quality of their materials, their smaller output limits their ability to supply larger quantities. In these quarries, typically, multiple products are manufactured from one ton of extracted rock, with only about a third being railway ballast.

Considering these factors, the domestic industry is forced to rely on imports to support its development efforts. Many European quarries meet the strict requirements, making imports the only viable economic option for the Hungarian market. To mitigate future economic burdens, there may be a need to revise the ERRI requirements applied in Hungarian regulations in certain areas. This would naturally involve further laboratory testing, as it is essential to assess the usability of domestic raw materials through appropriate studies.

Transportation can be carried out by both rail and road. The logistics are primarily governed by the so-called 7M and 9M principles, which define logistical tasks. Rail transportation is far more limited compared to road, often requiring crushed stone to be transported to areas without direct rail connections. In such cases, the material is offloaded from the train at the nearest station capable of accommodating freight trains and transferred to trucks for delivery to the worksite, further increasing costs.

Table 2 summarizes the advantages and disadvantages of rail and road transport.

In international terms, between 1990 and 2019, the total greenhouse gas emissions from fuel combustion in transportation increased by 24.0 % or 162 million tons of CO_2 equivalent. These figures do not include international aviation and maritime transport. In 2020, due to the impact of the COVID-19 crisis on transportation, these emissions decreased by 13.6 % compared to 2019. The final energy consumption in the EU's transport sector in 2020 was 252 million tons, representing a 10.0 % decrease compared to 2010. However, this overall trend hides a 3.2 % increase between 2010 and 2019, followed by a 12.8 % annual decrease in 2020, mainly reflecting the impact of the COVID-19 crisis. Regarding transportation, it is essential to mention renewable energy sources. In this regard, renewable energy sources primarily include liquid biofuels and electricity from renewable sources. In the EU, the share of renewable energy in transport grew from 5.5 % in 2010 to 10.2 % by 2020 [35]. According to statistical data from the Hungarian Central Statistical Office [36], in the first quarter of 2022, the total freight transport performance was 13.6 billion ton-kilometers, showing a 4.6 % decrease compared to the same period of the previous year, and an 11 % decrease compared to the first quarter of 2019. Domestically, road transport accounts for the largest share (80 %) of freight transport, while the performance of rail and inland waterway freight transport decreased. A similar trend can be observed internationally, where road transport decreased by 4.9 and rail by 14 %. According to the Hungarian Association of Logistic Service Centers (HALSC, in Hungarian language MLSZKSZ) [37], the total performance of domestic freight transport decreased by over 7 % in 2023, attributed to international political impacts and the consequences of the European recession. Due to these factors, less freight was transported by road, rail, and water. Based on the data managed by HALSC, 2023 showed a further decline, similar to the data from 2022. Compared to the data from 2022, the total volume of domestic transport decreased by 7.1 %, while its performance dropped by 10.3 %. According to HALSC, the decline in rail freight was significantly influenced by frequent track closures, mass speed restrictions imposed due to poor track conditions, and border crossing difficulties, all of which negatively impacted the sector. However, the share of intermodal transport has increased in recent years. According to HALSC data, the vast majority (99 %) of intermodal transport in 2023 entered the country through three Central Hungarian combined terminals (Rail Cargo Terminal – BILK, Mahart Container Center, METRANS). Based on the trends of recent years, it is expected that 2024 will not be favorable for transport either, but HALSC anticipates that the share of intermodal transport will continue to grow. The organization is urging the development of rail infrastructure. They expect that with the completion of ongoing industrial investments, "we will need to account for 30–40 additional freight trains per day, which the Hungarian rail network will only be able to handle with intensive and well-organized developments" [37].

Table 2

Advantages and disadvantages of rail and road transport

Road transport		Rail transport	
Adv.	Disadv.	Adv.	Disadv.
Dense network	Heavily dependent on weather and traffic	Less affected by weather	Outdated rail network
Shorter transit time	One of the highest operational costs	Almost anything can be transported	Transporting over long dist. is time-consuming
Almost all types of goods can be transported	Environ. harmful (noise, dust, exhaust emissions)	More environ. friendly compared to road transport	High construction costs
Minimal external effects on transported goods	Limited ability to transport goods	Much larger transportable weight	Requires significant force to move

The UEPG (European Aggregates Association) Roadmap [38], which became available in June 2023, clearly states that aggregates (i.e., sand, gravel, and crushed rock) are crucial for achieving the objectives of the EU Green Deal [39], including strategies for mitigating and adapting to climate change. While these materials are abundantly available, they are becoming increasingly difficult to access due to lengthy permitting processes. Nevertheless, they are inert, highly durable, 100 % recyclable, and inexpensive products. According to available and reliable sources, based on the life cycle analysis and environmental product declaration (EPD) of aggregates, the carbon footprint of quarries, from extraction to use (raw material extraction, internal transport, and aggregate production [raw material supply + raw material transport + aggregate production]), is estimated to average 5 kg CO_2-eq/t for aggregates. The Roadmap [38] emphasizes that various technological innovations (equipment efficiency, renewable energy, etc.) are insufficient to achieve decarbonization goals. Instead, production and/or transport must also be aligned with local needs, markets, and economic expectations. It highlights that due to the bulky nature and low cost of aggregates, local transport of these materials will be vital to ensuring the environmental and economic sustainability of the industry in the future [38].

As transportation and freight are among the largest contributors to CO_2 emissions [40], reducing emissions in infrastructure projects – especially in large-scale crushed stone transport – is becoming critically important. Several solutions are available in every construction project – whether high-rise or civil engineering – to reduce transport's environmental impact.

1. Prioritizing local sources: Sourcing construction materials locally reduces transportation distances and, consequently, emissions from transportation [41].

2. Using recycled materials: The use of recycled construction materials can reduce the amount of construction and demolition waste and harmful emissions [42].

3. Energy-efficient transportation methods: Rail transport is often a more energy-efficient and environmentally friendly alternative to road transport [42].

4. Optimized transportation routes: Optimizing transportation routes can reduce distances traveled and fuel consumption [42].

5. Using eco-friendly vehicles: Electric or hybrid vehicles can reduce harmful emissions during transportation [43].

These steps can contribute to increasing the sustainability of the construction industry and reducing environmental impact.

Transportation also faces other cost- and administration-increasing legal and economic regulations, such as the Electronic Road Freight Transport Control System (ERFTCS, in Hungarian language the abbreviation is EKÁER). Additionally, transportation speed and distance are significantly affected by potential traffic factors, the level of infrastructure development, and related weight and height restrictions.

The decree [7 (17)], also known as the toll decree, defines a distance-based toll for using motorways, expressways, and main roads. The payment obligation is categorized based on the number of axles and environmental classification.

Regulation 561/2006/EC [7 (18)] regulates driving time, which cannot exceed 56 hours per week, as well as break and rest periods. All vehicles over 3.5 tons gross weight must be equipped with a tachograph, a device that records data about the vehicle, including when it stops, for how long, speed and the distance traveled.

The ERFTCS, introduced in 2015 and later amended [7 (19–20)], aims to make freight transport in Hungary more transparent. The system helps customs and tax authorities monitor freight traffic, reducing tax evasion. Since 2021, only products classified as high-risk need to be reported. Products falling under the scope of ERFTCS include certain construction materials, such as crushed stone, which must be reported if transported in quantities over 500 kg.

General principles: a) Product acquisition within the European Community, directed to Hungary, according to the Value-Added Tax Act (intra-community acquisition of goods) or other imports; b) Product sales from Hungary to other EU member states, or other exports, according to the Value-Added Tax Act; c) The first sale of goods subject to VAT within Hungary, when not sold directly to the end user [7 (21)].

The decree [7 (22)], created in 1990 and amended multiple times, regulates the maximum allowable length, width, height, gross weight, and axle load of vehicles and vehicle combinations used for passenger and freight transport in road traffic. In exceptional cases, authorities or road operators may permit deviations from the general standards outlined in the decree [7 (23)]. Traffic regulations for roads are defined by the [7 (24)]. Based on these, the road operators (Magyar Közút Nonprofit Zrt. – MK –, and MKIF Magyar Koncessziós Infrastruktúra Fejlesztő Zrt. – MKIF) determine the usage conditions for specific road sections based on their technical parameters, which are communicated to users.

Generally, two-axle vehicles equipped with pneumatic tires cannot exceed 18 tons, three-axle vehicles 25 tons, and four-axle or more vehicles 40 tons. For axle load, non-driving axles must not exceed 10 tons, while driving axles must not exceed 11.5 tons [7 (25)].

Fig. 2 represents an example for the bridges in the Borsod-Abaúj-Zemplén County in Hungary.

It is important to note that stone materials can undergo significant changes during transportation. (The ride properties of electric vehicles, particularly in urban environments, have also been scrutinized in terms of safety and performance, as shown by Dižo and Blatnický (2019) [45].) Impact forces are primarily at play during loading and unloading, while abrasion occurs during transport. Therefore, transportation can lead to quality changes, and MSZ EN 13450 [7 (2)] also provides guidelines regarding sampling and testing, determining the potential degradation of ballast stone and its extent. The table in Annex B of

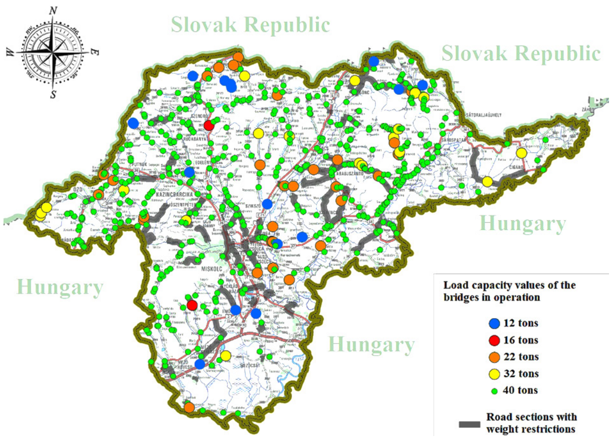

Fig. 2. Bridges with a total load capacity of 40 tons or less on the road network of Borsod-Abaúj-Zemplén County in Hungary (*on the basis of* [44])

the standard (MSZ EN 13450 [7 (2)]) lists the threshold values that, if not exceeded in test results, indicate that the damage caused by transportation or abrasion to the railway ballast stone is still considered acceptable. However, during transshipment and transportation, the physical effects on the stone material alter its grain structure, causing segregation, though specific physical properties of the stone (*LA*, *MDE*) may improve to some extent [46]. Another difficulty arises from transportation challenges, as in many cases, the location of raw material ordering and usage are not in the same country, meaning the customer and supplier of crushed stone fall under different national regulations. In this regard, there is no unified standard and/or guideline regarding the quality of railway ballast crushed stone [47].

Possible interventions to strengthen environmental objectives. One of the critical issues within the environmental protection field today is the amount of waste generated during certain industrial activities, including railway construction and/or modernization, as well as its reduction and re-utilization. In this context, waste refers to the complete replacement, extraction, and reinstallation of ballast stone material and any activity carried out with it. A significant portion of this material could become an essential raw material source. Exploring recycling and re-use routes for this waste material, such as crushed stone, could reduce countries' dependence – especially Hungary – on raw material imports in the long term and significantly decrease the amount of new materials that need to be extracted. Of course, detailed studies are required in this area to determine which industries or activities could benefit from the extracted and processed rock material after its removal from the railway track structure.

Currently, in the European regulatory framework, waste is increasingly viewed as a potential resource, encouraging its reuse in some form. The central element of the European Union's current regulations is Directive 2008/98/EC [7 (26)] on waste and repealing certain directives, which sets out the general rules for waste management. This approach, emphasizing sustainability and cooperation between industrial players, underpins the future of waste management by building a more material- and energy-efficient economic model [48].

The definition of waste is outlined in Article 2, Section 23 of [7 (27)] (hereinafter: Waste Act). Beyond the general definition, waste can be further categorized based on its characteristics. The category of production waste includes waste generated during extraction, processing, services, maintenance, and transportation activities. It can originate from industrial, agricultural, or transportation activities and may be technological (from production activities or material transformation) or depreciation-related (discarded equipment and tools). Common features of these wastes are that they can be generated in predictable quantities with specific compositions, depending on production processes. The definition of construction activities, including construction-assembly and demolition work, is provided in Article 2, Section 36 of [7 (28)] on shaping and protecting the built environment [49, 50].

During construction activities, the vast majority of waste falls into the category of solid, inorganic, non-hazardous waste. However, hazardous waste must also be considered, as materials used during construction, demolition, or renovation can result in hazardous waste. Government Decree 225/2015 (VIII.7.) [7 (29)] sets out detailed rules regarding hazardous waste activities. Most materials utilized in the construction industry do not harm the natural environment, but in some instances, materials harmful to the environment are used (asbestos-containing materials, certain concrete additives, etc.). Special regulations apply to the handling of these materials. The recyclability of construction waste is determined mainly by its composition based on material quality, which in turn depends on the source of the waste (e.g., highway demolition, manufacturing scrap, building demolition). Waste becomes recyclable if handled selectively from the moment it is generated, and this selective approach continues during its storage by the waste holder [49, 50]).

The National Sustainable Construction Economy Strategy 2021–2023 [7 (30)] highlights that the preparation of construction waste for reuse, recycling, and utilization in road and other construction projects is not yet widespread in Hungary. The current utilization of this waste is estimated to be 30–40 %. Therefore, the strategy addresses increased raw material extraction in the construction sector and the greater future use of backfill materials, secondary raw materials (such as spoil), and waste, which could provide solutions where supply difficulties arise while maintaining appropriate quality standards. Construction and demolition waste contains many valuable materials, and by collecting and processing them separately, critical raw materials can be economically extracted and used as secondary material sources. This could also reduce the challenges of waste disposal [49, 50].

Government Decree 72/2013 (VIII.27) of the Ministry of Rural Development [7 (31)] on the list of wastes, based on the classification of waste types in its main categories and subcategories, separates two types of waste related to railway tracks in Annex 2. Waste code 17 05 07 refers to ballast containing hazardous materials, while code 17 05 08 applies to ballast materials that do not fall into the previous category. Table 3 contains the calculation of the waste quantities from the used railway ballast as well as the required amounts for construction and reconstruction projects in Hungary in the time interval 2016–2022. The data covered only the time interval between 2016 and 2022 because [7 (32)] announced only the valid data until 2022. The data series shows that there is no exact trend, so the extrapolation cannot be applied.

Determining whether the waste generated during construction and/or modernization activities falls under one of the two waste codes is based on the hazardous characteristics of the waste. However, the principle of reusing waste may be compromised if heavily contaminated ballast material is mixed with nearly clean ballast during transportation and taken together to a designated waste storage site. In such cases, a solution would be the separate disposal, storage, and waste treatment to ensure that the investor/contractor complies with European Union principles, thus meeting the conditions of a sustainable and circular economy.

If it is assumed that the non-hazardous waste consists of material from the screening of the track ballast (screened material of 0/22, 0/32 mm particle size), then a waste generation rate of around 5 % of the total volume of the track is a realistic value. Based on a density of 2.1 t/m^3 and considering the protective or supplemental layer built with a subgrade width of $2.6 + 2 \times 0.4$ m, approximately 60,000 km of such layers could be constructed from the 527 km of the renovated sections. Naturally, there are other product or construction possibilities (e.g., P + R parking lots, warehouse foundations, etc.).

Table 3

Calculation of the waste quantities from the used railway ballast as well as the required amounts for construction and reconstruction projects in Hungary in the time interval 2016–2022 (unit t means ton(s); on the basis of [7 (32)] and [51])

Type of waste fraction [1]	Amount of waste generated [t]							
	2016	2017	2018	2019	2020	2021	2022	Total (2016–2022)
Railway track ballast differing from 170507 (170508) [2]	173.0	5,287.5	758.0	48,896.3	10,983.0	1,765.0	18,179.0	86,042.0
Railway track ballast containing hazardous substances (170507) [2]	88.0	302.5	1,913.0	3.7	23.0	167.0	126.0	2,624.0
Total amount of waste	261.0	5,590.0	2,671.0	48,900.0	11,006.0	1,932.0	18,305.0	88,666.0
Reconstructed track length, km	44.7	0.9	110.0	8.0	133.6	169.0	61.0	527.1
New second track, km	0.0	0.9	1.6	0.0	0.0	8.0	3.0	13.5
Quantity of crushed stone ballast material in reconstructed track, t	150,192.0	3,024.0	369,432.0	26,840.0	448,896.0	567,0840.0	204,960.0	1,771,184.0
Quantity of crushed stone ballast material in new second track, t	0.0	3,024.0	5,376.0	0.0	0.0	26,880.0	10,080.0	45,360.0
Total waste ratio to reconstructed track length, %	cannot be interpreted on an annual basis, because it is not certain that the ballast screening/cleaning (waste formation) takes place in the same year as the installation 4.9							5.0
Ratio of non-hazardous waste to reconstructed track length, %								
Length of supplementary layer that can be constructed from screened material with 0.2 m compacted thickness, km [3]	121.1	3,702.8	531.1	34,240.9	7,691.1	1,236.0	12,730.3	60,253.3

[1] Only the type of waste generated during the construction of other buildings and specialized construction was included in filtering the data. Not chemical and/or product manufacturing, transport and storage, etc.

[2] The given data are rounded to one digit.

[3] It is assumed that "Railway track ballast differing from 170507 (170508)" is entirely screened material during track renewal, which can be reused, and/or re-installed

The primary condition for reusing railway ballast is the so-called screening process. In Hungarian practice, about 40 % of the cleaned crushed stone must be reused as ballast or a granular supplementary (reinforcement) layer, such as material type CGM2 (coarse-grain mixture type No. 2 [7 (33–34)]). Recycling smaller, non-standard particles and screened material was not yet resolved at a national level, although experimental incorporations were made as waterproof embankment layers. However, this issue has been resolved using modern subgrade reconstruction machine chains (e.g., Plasser PM 1000, PM 1000 URM, etc.) [7 (33–34)].

Railway developments, particularly those related to ballast stone, are not so straightforward in practice. In most cases, when the ballast material of the railway track becomes contaminated, it is screened, and two options are chosen. The screening machine either deposits the material next to the railway track on the ground and/or slope, or it is removed with a conveyor belt, loaded, and transported to a hazardous waste landfill. However, the potential for reusing the extracted materials during development is much broader, as shown by the data in Table 3. While the material taken to landfills may be reused later, significant CO_2 emissions are generated during multiple transport phases, compared to using the material locally.

Another problem is that the post-sorting and treatment of waste generated during construction and modernization activities significantly increases waste holder or recipient costs. As mentioned earlier, the generated waste has specific characteristics (e.g., composition), and the size of the debris varies. Based on these two crucial factors, recycling often requires a multi-stage preparation process (e.g., selecting the number of crushing and sorting stages). Another factor in waste management is whether the waste is contaminated with any substance and the degree of contamination. Keeping all these factors in mind, the waste holder will be forced to implement significant changes in the future to ensure recyclability. The NEIS (National Environmental Information System; in the Hungarian language, the abbreviation is OKIR) [7 (32)] data clearly shows (Table 3) that nearly 80 % of the generated waste could be reused by establishing appropriate systems (such as reception yards and recycling capacities), along with developing incentive regulations and creating distribution opportunities.

Traditionally, railway tracks with ballast stones account for approximately 90 % of tracks [52]. In their 2022 study, Yunlong, et al. [53] describe the importance of maximizing the lifespan of railway tracks rather than replacing or building new ones, considering the economic strategies of countries aiming to introduce low-carbon and/or carbon-neutral circular economies. They refer to studies, which assessed the life cycle of railway infrastructure. Their results showed that after a lifespan of 50–60 years, tracks with traditional ballast stones have a more minor environmental impact. Yunlong, et al. (2022) [53] also describe various technological developments that have been made to improve the lifespan and performance of ballast stones. For example, studies have shown that if no more than 30 % of the old ballast is mixed with new material, the performance of the layer remains sustainable. Additionally, ballast waste mixed with asphalt can be used for road paving. Furthermore, they mention that if railway waste cannot be reused, waste from other industries, such as steel slag from steel production (a byproduct produced in large quantities in the USA, China, Australia, and some European countries), could be suitable for railway applications.

Originality. This study distinguishes itself through its holistic and interdisciplinary approach to solving Hungary's crushed stone supply chain challenges, particularly for railway infrastructure projects. While the previous research has often segmented the issues – focusing narrowly on technical quality, logistics, or sustainability – this paper innovatively integrates these aspects into a unified framework. Blending geological insights with advanced logistical modeling and sustainability considerations offers a more comprehensive solution to a complex problem. The originality of this research lies not only in the breadth of its scope but also in its application of cutting-edge Geographic Information System (GIS) technology, which is used to optimize the transportation of crushed stone. Unlike traditional approaches concentrating on material quality or sourcing, this study takes logistics one step further by offering a technological roadmap for improving cost efficiency and reducing environmental impacts, such as CO_2 emissions.

Furthermore, this paper breaks new ground by incorporating recycled materials into the analysis of supply chain resilience. The innovative suggestion to integrate smaller stone fractions and recycled aggregates into railway ballast marks a significant departure from conventional reliance on virgin materials. This recommendation aligns with broader global shifts toward circular economies and sustainability, making the research timely and forward-thinking. While recycling has been proposed in other contexts, this study uniquely applies it within the constraints of Hungary's national regulations and the European Union's stringent quality standards, thus ensuring that the proposed solutions are technically feasible and legally sound. The novel combination of these factors makes this study an original contribution to ongoing debates in sustainable construction, material science, and infrastructure logistics.

Additionally, this research offers a fresh perspective by profoundly examining the regulatory landscape in Hungary and Europe, particularly regarding standards like EN 13450 [7 (1)] for railway ballast. By scrutinizing these standards within the context of domestic production capabilities, the paper reveals untapped potential for optimizing Hungary's quarry operations and reducing its dependence on imports. Previous studies have not sufficiently explored the intricate relationships between local regulations, EU standards, and their impacts on material availability and project timelines. This paper fills that gap and uses this regulatory insight as a foundation for proposing practical improvements. Through its multidisciplinary approach – blending technology, regulation, and sustainability – the research stands as an innovative contribution that can serve as a model for addressing similar challenges in other nations and industries facing material shortages and logistical inefficiencies.

Practical value. The practical implications of this study are wide-reaching, offering tangible benefits for stakeholders involved in Hungary's infrastructure development, particularly in railway construction. One of the standout practical contributions is the precise set of strategies for improving the efficiency of the crushed stone supply chain. The paper proposes actionable solutions that can lower costs and emissions by identifying specific logistical inefficiencies, such as the over-reliance on costly and carbon-intensive road transport. For example, Geographic Information System (GIS) modeling provides a precise tool for optimizing transportation routes, ensuring that crushed stone is delivered more efficiently to construction sites. This reduces operational expenses and aligns with growing international and EU mandates for reducing environmental footprints in large-scale projects.

Moreover, the paper offers practical strategies for incorporating recycled materials into the supply chain, which could revolutionize material sourcing for infrastructure projects. The detailed analysis shows that integrating recycled aggregates into railway construction could significantly reduce dependence on limited natural resources, which are becoming increasingly scarce and expensive. This finding has immediate practical value for construction companies, providing a cost-effective alternative to sourcing virgin materials while fulfilling sustainability objectives. As suggested by the study, the incorporation of up to 40 % recycled material into railway ballast demonstrates that infrastructure projects can maintain high technical standards while reducing their environmental impact. This approach supports Hungary's national sustainability goals and positions the country as a potential leader in innovative construction practices across Europe.

In addition to material innovations, the study underscores the importance of modernizing quarry management and logistics, providing practical recommendations that policymakers and industry leaders can implement. The application of advanced simulation tools, such as GIS, can help stakeholders plan better, avoid bottlenecks, and coordinate more efficiently between quarries and construction sites. For instance, the paper's suggestion to shift more transportation from road to rail has the potential to reduce costs and significantly decrease greenhouse gas emissions. The practical value of these solutions extends beyond Hungary, offering a scalable model that can be adapted to other countries facing similar supply chain issues in infrastructure development.

The study also highlights the critical role of policy in shaping the future of Hungary's infrastructure projects. The research provides a roadmap for navigating the complex legal environment in which these projects operate by offering a detailed examination of both Hungarian and European regulatory frameworks. This regulatory insight benefits construction companies and logistics managers, who often face challenges in meeting technical requirements and sustainability targets. The study's findings can help streamline compliance with regulations such as EN 13450 [7 (1)], ensuring that projects remain cost-effective and environmentally responsible. Moreover, the practical strategies for optimizing logistics and incorporating recycled materials can guide future policy reforms aimed at promoting sustainable construction practices on a national and regional level.

In conclusion, this study offers a robust, practical framework for addressing the immediate and long-term challenges facing Hungary's crushed stone supply chain. By providing actionable insights into using recycled materials, optimizing logistics through advanced technologies, and aligning regulatory requirements with sustainability goals, the paper delivers practical value that extends far beyond academia. Its recommendations are highly relevant for industry practitioners, government agencies, and policymakers tasked with improving the efficiency and sustainability of infrastructure projects in Hungary and beyond. Implementing these strategies can lead to more sustainable, cost-efficient, and environmentally friendly outcomes in large-scale construction projects, making this research invaluable for future infrastructure development.

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Проблеми постачання щебеню для розвитку інфраструктури в Угорщині

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Швидке розширення інфраструктурних проєктів Угорщини, особливо у сфері залізничного будівництва, значно збільшило попит на щебінь. Національні та ініціативи, фінансовані ЄС, спричинили перевантаження ланцюгів постачання, що призвело до логістичних труднощів і дефіциту матеріалів. Через обмежені потужності внутрішнього виробництва ефективне управління ресурсами є ключовим для забезпечення вчасного виконання проєктів. У цій роботі оцінюється ланцюг постачання щебеню в Угорщині, визначаються основні слабкі місця та пропонуються рішення для підвищення стійкості.

Мета. Дослідження вивчає логістичні й ланцюгові труднощі в постачанні щебеню для залізничних інфраструктурних проєктів Угорщини. Воно оцінює поточні обмеження постачання, пропонує способи покращення управління внутрішніми ресурсами та надає стратегії для зменшення залежності від імпорту з акцентом на стійкість.

Методика. Дослідження використовує моделювання геоінформаційної системи (ГІС) для аналізу маршрутів транспортування щебеню, пропонуючи способи оптимізації логістики. Також розглядаються виробничі потужності угорських кар'єрів, деякі з яких виробляють 15 000–25 000 тонн на місяць, і оцінюється вплив європейських (EN 13450) та угорських норм на якість і доступність матеріалів. Досліджується потенціал використання перероблених матеріалів у ланцюгу постачання.

Результати. Внутрішні кар'єри Угорщини не можуть задовольнити високий попит на залізничний баласт, який оцінюється у 192 000 тонн на рік, що змушує країну залежати від імпорту. Моделювання ГІС показує, що оптимізація маршрутів транспортування може зменшити витрати й викиди вуглецю. Використання дрібних фракцій каменю та перероблених матеріалів може допомогти зменшити дефіцит, причому перероблені матеріали можуть складати до 40 % залізничного баласту.

Наукова новизна. Інтегруючи геологічні, логістичні й нормативні аспекти, ця робота пропонує нові підходи до вирішення проблем ланцюга постачання щебеню в Угорщині. Використання ГІС-моделювання та перероблених матеріалів пропонує інноваційні рішення для зменшення впливу на довкілля.

Практична значимість. За результатами роботи запропоновані дієві стратегії для покращення ефективності ланцюга постачання щебеню в Угорщині, сприяння переробці сировини та оптимізації логістики. Ці рішення можуть бути застосовані як в Угорщині, так і в інших регіонах із подібними викликами у постачанні матеріалів для інфраструктури.

Ключові слова: *постачання щебеню, будівельний матеріал, інфраструктурна логістика, залізничні будівельні проєкти*

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