Environmental protection of railway wastewater using natural diatomite sorbents: development and validation of a three-layer filtration strip

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Abstract. The study evaluates the efficiency of a natural diatomite-based sorbent, Diamiks Aqua, for removing petroleum hydrocarbons and suspended solids from railway wastewater. Laboratory tests using a vertical filtration column (0.5 m/h, 30 min contact time) demonstrated up to 98.9 % removal of suspended solids and 99.0 % of petroleum products. A three-layer filtration strip, integrated into railway embankments, provides a reagent-free and energy-efficient treatment process. The proposed design ensures reliable protection of water bodies from diffuse hydrocarbon runoff and contributes to the environmental sustainability of railway transport enterprises.

Keywords: railway transport, wastewater pollution, petroleum products, natural sorbents, diatomite, Diamiks Aqua, surface runoff treatment, filtration strip, environmental protection, anthropogenic pollution, ecological safety.

1. Introduction

Surface water pollution caused by petroleum products from railway facilities remains a serious environmental challenge. The main sources of contamination include fuel spills, leakage during refueling, and the absence of preventive collection systems [1-3]. Hydrocarbon pollution from snowmelt and rainwater runoff at railway yards leads to the accumulation of oil residues and suspended solids in nearby soils and water bodies, reducing their ecological quality [4-6].

While centralized treatment systems for industrial wastewater are well studied, the purification of diffuse surface runoff from transport enterprises is still insufficiently addressed. During long cold periods, hydrocarbons accumulate in the ballast and soil layers, later entering the environment during spring meltwater flow [5, 7]. Studies have shown that the composition of this runoff is highly variable and difficult to treat by conventional filtration or coagulation methods [8, 9].

Recent research on natural mineral sorbents, including diatomite-based materials, demonstrates their potential for deep purification of hydrocarbon-contaminated wastewater without chemical reagents [6], [10], [15]. Their porous structure, large specific surface area, and catalytic properties make them efficient for both adsorption and oxidation processes. However, practical applications integrated into railway infrastructure are still limited.

Therefore, the objective of this study is to evaluate the efficiency of natural diatomite sorbent Diamiks Aqua for treating railway runoff and to develop a scalable three-layer filtration strip that can be embedded into the railway embankment to ensure reagent-free purification and long-term environmental protection.

2. Methods and materials

Laboratory experiments were conducted to evaluate the filtration performance of the diatomite-based sorbent Diamiks Aqua under controlled conditions. Tests were performed in a vertical acrylic column (height 1.0 m, diameter 0.1 m) operating in downward flow mode. The filter bed consisted of Diamiks Aqua granules (0.8-2 mm) pre-washed with distilled water to remove fine particles and ensure uniform packing [4], [8], [11].

Simulated meltwater represented typical contamination of railway runoff, containing 138 mg/dm^3 of suspended solids and 3.9 mg/dm^3 of petroleum hydrocarbons. The influent was supplied at a filtration rate of 0.5 m/h with a contact time of 30 minutes. Each experiment was repeated three times to confirm reproducibility; measurement uncertainty did not exceed ±3 %.

Pollutant concentrations were determined by gravimetric analysis and infrared spectrophotometry. The purification efficiency η (%) was calculated by:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} * 100\ \%, \tag{1}$$

where C_{in} and C_{out} are the influent and effluent concentrations of pollutants (mg/dm^3), and η represents the removal efficiency in percentage (%).

Hydraulic permeability was evaluated according to Darcy's law:

$$Q = K * A * \frac{\Delta h}{L}, \tag{2}$$

where Q is the flow rate (m^3/s), A is the cross-sectional area of the filter (m^2), Δh is the hydraulic head difference (m), L is the filter bed height (m), and K is the filtration coefficient (m/s).

All tests were carried out at 20±2 °C, pH = 7.2±0.1. The obtained data provided the basis for subsequent efficiency evaluation and design of the filtration system [10], [12].

Figure 1 illustrates the laboratory setup used for the vertical column filtration tests. The influent tank supplied simulated wastewater to the column through a controlled pump and flow meter. The effluent was collected in a separate vessel for subsequent quality assessment.

All measurements were carried out under constant temperature (20±2 °C) and pH = 7.2 ± 0.1.

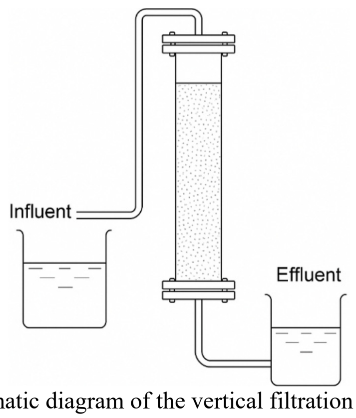

Fig. 1. Schematic diagram of the vertical filtration column setup

The objective of this study is to experimentally evaluate the purification efficiency of the natural diatomite sorbent Diamiks Aqua and to develop a scalable filtration design for railway runoff treatment.

3. Results and discussion

Conventional filter materials, including sand-gravel, opoka-based, and carbon sorbents, are still used in local treatment systems. However, they provide limited removal of fine suspended solids and petroleum hydrocarbons and require frequent regeneration or replacement [6], [7]. Quartz sand, with its smooth surface and low porosity, retains only large particles, quickly clogs, and consumes large volumes of backwash water. Carbon filters, though possessing a high surface area, lose efficiency due to rapid pore fouling by hydrocarbons and organic matter [10], [12]. Opoka-based filters have greater strength but limited pore accessibility and a short service life [13].

By contrast, the Diamiks Aqua diatomite sorbent exhibits high mechanical durability, porosity, and sorption capacity, achieving 2000–2500 g/m³ of solids retention with minimal abrasion (≤ 0.04 %) (Table 1). Its heterogeneous pore structure and catalytic surface enable stable long-term operation without chemical reagents. Laboratory tests confirmed removal efficiencies of 98.9 % for suspended solids and 99.0 % for petroleum hydrocarbons, meeting discharge standards for fishery water bodies (Table 2) [12-14], [16].

Fig. 2. Structure and morphology of Diamiks Aqua granules (schematic representation)

Table 1. Comparative properties of filter media

Filter material	Sand-gravel filter	Carbon filter	Opoka-based filter	Diamiks aqua
Mechanical strength:				
Abrasion, %	≤ 0.09	4-5	0.04-0.06	≤ 0.04
Crushing, %	≤ 2.8	0.5-1	0.08-0.10	≤ 0.06
Comment	–	–	–	High strength of Diamiks Aqua
Filtration efficiency (by contaminant-holding capacity for solids and suspended matter), g/m³	750-1400	750-2500	1800-2000	2000-2500
Comment	–	–	–	Diamiks Aqua provides the maximum contaminant-holding capacity

Table 2. Results of melt wastewater treatment using a column filled with Diamiks Aqua filter-sorbent material

Water quality parameter	Suspended solids, mg/dm³	Petroleum products, mg/dm³
Initial melt wastewater	138	3.9
After treatment with Diamiks Aqua diatomite	1.4	0.04
Discharge requirements for fisheries water bodies (Russia)	2	0.05

The superior performance of Diamiks Aqua is explained by its aluminosilicate structure that combines adsorption, ion exchange, and catalytic oxidation. During filtration, Fe^{2+} and Mn^{2+} ions oxidize to insoluble hydroxides according to:

$$Fe^2 + \frac{1}{4}O_2 + \frac{1}{2}H_2O \rightarrow Fe(OH)_3 \downarrow, \quad Mn^{2+} + \frac{1}{2}O_2 + H_2O \rightarrow MnO_2 \downarrow\ +2H^+. \tag{3}$$

These precipitates form active sites on the diatomite surface, enhancing the catalytic effect and ensuring long-term stability [13], [16].

A three-layer filtration strip (Fig. 3) was developed for railway embankments to treat runoff in a passive, gravity-driven mode. The structure includes:

1) A lower drainage layer (gravel 2-10 mm, 150 mm).

2) A main filtration layer (Diamiks Aqua, 0.8-2 mm, 500 mm).

3) A top regulating layer with coarse gravel and vegetation to stabilize flow and prevent erosion [16], [17].

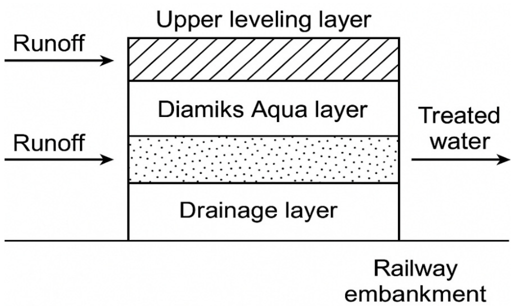

Fig. 3. Schematic diagram of the three-layer filtration strip integrated into the railway embankment

This configuration ensures sequential removal of solids, hydrocarbons, and heavy metals without external power or reagents.

Field simulations show that treating 9,340.7 m^3 of runoff per year prevents the release of ~18.7 kg of petroleum products and ~672.5 kg of suspended matter, avoiding environmental damage estimated at over 75 million RUB during the system's lifetime [18], [19].

The technology provides high efficiency, long service life, and low maintenance – combining mechanical filtration and catalytic purification in one system.

Although filtration rate decreases at low temperatures (< 5 °C), this can be compensated by increasing the contact time or surface area. The system performs best for diffuse, low-flow runoff, while highly concentrated effluents may require pretreatment [17], [19]. Overall, the proposed design supports the sustainable and environmentally safe operation of railway transport enterprises.

4. Conclusions

The conducted studies confirmed the high efficiency of the natural diatomite-based sorbent Diamiks Aqua for the purification of railway wastewater containing petroleum hydrocarbons and suspended solids [12-14]. The developed three-layer filtration strip ensures stable operation and a long service life, combining mechanical filtration, sorption, and catalytic oxidation processes within a single structure [15].

Laboratory tests demonstrated 98.9 % removal of suspended solids and 99.0 % of petroleum products, exceeding environmental discharge standards for fishery water bodies [13], [14]. The system effectively replaces conventional filter media such as quartz sand and carbon sorbents, significantly reducing maintenance frequency and energy consumption [17].

Filtration performance slightly decreases below +5 °C due to increased water viscosity but can be restored by extending contact time, ensuring applicability under various climatic conditions [18].

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The proposed eco-friendly, reagent-free, and energy-efficient filtration system provides reliable long-term protection of water bodies from hydrocarbon pollution and supports the sustainable operation of railway infrastructure [18], [19]. Comparative evaluation confirmed its superior performance over traditional sand, carbon, and opoka filters, making it suitable for large-scale implementation in railway drainage systems [19].

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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