Heavy metal removal performance of materials for treatment of road runoff in roadside trenches

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Sammendrag

Fjerning av tungmetaller med materialer for behandling av veiavrenning i veikantgrøfter. Veitrafikk bidrar signifikant til miljøforurensning, spesielt gjennom forurenset overvann. Lokal håndtering av forurensing kan redusere negativ påvirkning av omkringliggende miljø. Infiltrasjon i veigrøftene er en attraktiv behandlingsmetode på grunn av sin enkelhet, kostnadseffektivitet og lave vedlikeholdsbehov. Men dette er ikke alltid tilstrekkelig effektivt for veier med stor trafikktetthet og områder med sårbare resipienter. Denne studien hadde som mål å identifisere kostnadseffektive og lett tilgjengelige materialer, og utvikle formuleringer for effektive filtermedier som kan brukes til å forbedre infiltrasjonsgrøftene langs veiene. Det ble gjennomført tester med ni forskjellige filtermediekombinasjoner, bestående av sand, kompost, LECA, Olivin og biokull. Testene ble gjennomført i kolonneforsøk i laboratorieskala. I tillegg ble evnen til å adsorbere tungmetaller i kompost, LECA og Olivin analysert gjennom isotermprøver. Blant de testede materialene hadde medier som Olivin best kapasitet og best resultat både i isoterm- og kolonnetester. Biokull og LECA viste også betydelig evne til å fjerne metaller. Inkluderingen av kompost i filtermediene ga en forbedring av effektiviteten for fjerning av tungmetaller. Alle undersøkelsene ble gjennomført i et kontrollert laboratoriemiljø. Basert på disse funnene ble det senere gjennomført pilotstudier i større skala med bruk av overvann fra motorveien, E18, på en dedikert teststasjon i Bamble

Summary

Road traffic is a major contributor to environmental pollution, particularly through contaminated runoff water. To mitigate this pollution, treating road runoff before it impacts the surrounding environment is essential. Roadside infiltration has emerged as an appealing treatment method due to its simplicity, cost-effectiveness, and low maintenance requirements.

However, it may not be sufficient for roads with heavy traffic and areas with vulnerable recipients. The present study aimed to identify cost-effective and readily available materials to develop formulations for efficient filter media that can be used to improve roadside ditches. Nine different filter media compositions, comprising sand, compost, LECA, Olivine, and biochar, were tested in laboratory scale column tests. Additionally, the heavy metal adsorption capabilities of compost, LECA and Olivine were measured in isotherm tests. Among the materials tested, media with Olivine demonstrated the highest performance in both isotherm and column tests. Biochar and LECA also exhibited significant metal removal capabilities. The inclusion of compost in the filter media enhanced heavy metal removal efficiency. All experiments were conducted in a controlled laboratory conditions. Based on these findings, large-scale pilot studies using runoff water from the European highway E18 was carried out at a dedicated test station at Bamble.

Keywords: Road runoff infiltration; column test; heavy metals; isotherm; road runoff.

Introduction

Road traffic is a significant source of environmental pollution, stemming from road surface wear, wear of vehicle components such as brakes and tires, oil leaks, and exhaust emissions. The types and concentrations of pollutants generated depend on factors like road surface materials, ambient air quality, traffic density, and vehicle types.

Traffic-related Road runoff water (RRW) during rain or snowmelt carries pollutants such as suspended particles, heavy metals, organic micropollutants, nutrient salts (e.g., nitrogen and phosphorus), and microplastics (Eriksson *et al.*, 2007). These contaminants are either deposited in the soil along roads or discharged into nearby water bodies, potentially causing harm to ecosystems and human health. Consequently, minimizing these pollutants in terrestrial and aquatic environments is crucial (Huber *et al.*, 2016; Lerat-Hardy *et al.*, 2022).

Treatment of RRW becomes essential when runoff discharge surpasses the tolerance limits of a water body. Norwegian Public Roads handbooks implimented demands based on the vulnerability of the water body and the annual average daily traffic (AADT) volume (SVV, 2016). Table 1 outlines these guidelines, which distinguish between two cleaning stages: stage 1 focuses on removing particulate-bound pollutants, while stage 2 targets dissolved pollutants. Treatment requirements are often more stringent in urban areas, where the cumulative AADT within water catchment zones tends to exceed that of rural regions.

Table 1. Demands for the treatment of runoff water from roads in Norway (Vegnormal N200 vegbygging (SVV, 2024))

Number of vehicles (AADT)	Recipient's vulnerability	Probability of biological damage to the water body	Necessary treatment measures
< 3000	Independently	Low	No treatment measures needed, run-off over the road shoulder and infiltration into the ground
3 000 – 15 000	Low	Low	No treatment measures needed, run-off over the road shoulder and infiltration into the ground
	Moderate/high	Moderate/high	Treatment stage 1
15 000 – 30 000	Low	Low	No treatment measures needed, run-off over the road shoulder and infiltration into the ground
	Moderate	Moderate	Treatment stage 1
	High	High	Treatment stage 1 & 2
> 30 000	Independently	Independently	Treatment stage 1 & 2

In Norway, nature-based solutions are preferred because of their potential to deliver fair treatment efficiency with relatively low operational demands. However, these systems have a significant drawback due to the slow kinetics especially in cold environments, investment costs associated with establishing RRW collection systems and constructing treatment facilities.

Two primary types of RRW treatment solutions are commonly employed worldwide: sedimentation to remove particles (stage 1 treatment) and filtration through filter media to eliminate dissolved substances (stage 2 treatment). Åstebøl (2012) reported that Norway has extensive experience with sedimentation ponds and infiltration systems, with over 100 RRW treatment facilities, the majority of which are sedimentation basins. According to information from SVV, there are now more than 200 RRW treatment facilities in Norway. To achieve stage 2 treatment, new systems incorporate sedimentation ponds combined with adsorption filters. Improved infiltration systems, by contrast, can address both stages simultaneously, removing both particles and dissolved pollutants.

Despite the widespread adoption of these systems, evidence on their efficiency in removing traffic-related pollutants remains insufficient, and the available data is often unconvincing. Additionally, these systems are associated with high capital and operational costs, limiting their feasibility. In contrast, improved roadside infiltration may offer a simpler and more cost-effective alternative for treating RRW. While most Norwegian roads and highways already feature roadside ditches, these are primarily designed to manage runoff volumes rather than to filter pollutants.

For Norwegian roadside trenches, a topsoil mixture with 5 % compost is recommended (SVV, 2024). Soils inherently possess some capacity to remove pollutants through mechanisms like straining, adsorption, and cation exchange. However, many soils have limited pollutant retention capabilities, potentially leading to pollutant accumulation or groundwater contamination. Enhancing the treatment efficiency of roadside ditches requires careful design and the selection of appropriate filter media.

The aim of the presented study was to identify readily available materials suitable for pilot-scale experiments to enhance the pollutant removal efficiency of roadside ditches. Additionally, the study evaluated the water quality of road runoff and the changes in water quality after infiltration through an existing roadside infiltration ditch.

Methods and materials

A specialised test station at the European highway E18 at Rugtvedt in Bamble, Norway, was established to facilitate the collection and analysis of RRW. This station covers a 20-meter section of a 10-meter-wide road segment with an AADT of approx. 15.000. The station is equipped with advanced instrumentation, including autosamplers, pumps, and water quality monitoring equipment for parameters such as pH, conductivity, and temperature. Additionally, the site includes a weather station for comprehensive environmental data collection. RRW for this study was collected using this test station.

As part of the study, water quality was analysed after infiltration through the existing roadside ditch. The existing ditch contained a 40 cm soil layer composed of natural sandy soil collected from the roadside and mixed with organic material. The ditch was covered with grass. Five Prenart vacuum samplers were installed 30 cm beneath the soil surface of the roadside ditch, adjacent to the road runoff water (RRW) collection system. These samplers enabled consistent collection of infiltrated water. Figure 1 provides a visual overview of the RRW test station where the water for this study was collected, highlighting the infrastructure and instrumentation deployed.

Nine column tests were conducted in the laboratory using various filter media to evaluate their efficiency in removing heavy metals. Columns were made of glass, with an internal diameter of 4.8 cm and a length of 50 cm. Each column was filled to a hight of 30 cm with 540 ml filter media. Table 2 shows the composition of the nine columns and Figure 2 shows the test

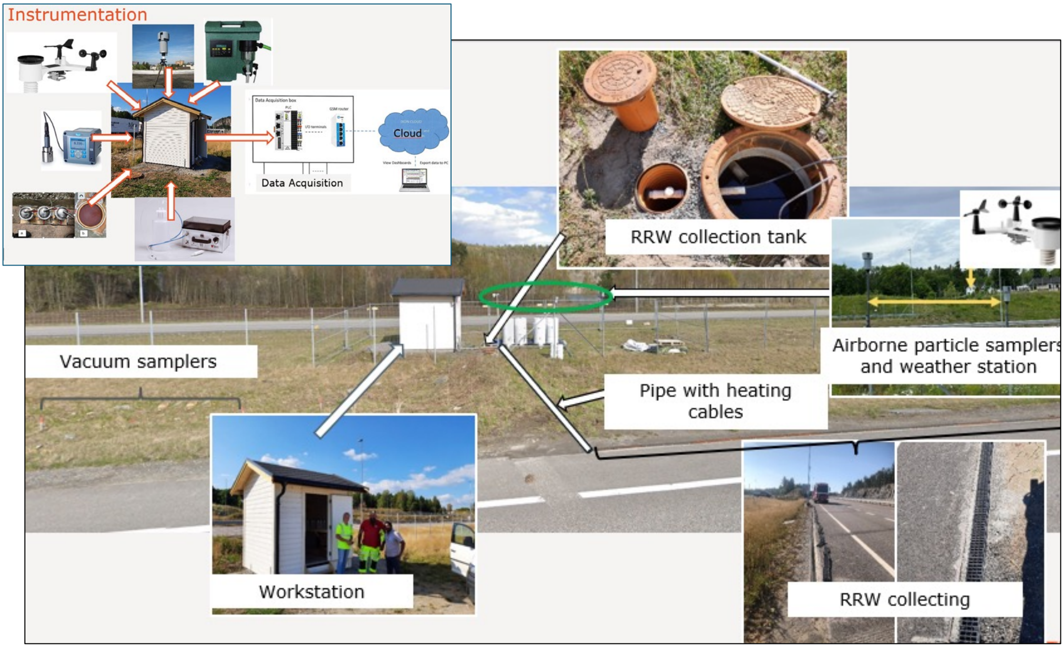

Figure 1. Road runoff water test station at Bamble, Norway.

setup. Sand was used as the basis for the filter medium. Filtralite is an expanded clay material, is commonly used as an environmentally friendly media for filtering contaminated wastewater. Leca Filtralite HMR (LECA) is an improved product of "Lightweight Expanded Caly Aggregate" that is reported for the removal of heavy metals (Almås and Krogstad, 2019) from polluted water. LECA grain size is 0.5-2 mm, and it has a specific surface area of 40 m^2/g. Filter 4 was filled with LECA alone and only a 5 cm layer was employed in the filter 2.

Olivine is a naturally occurring mineral that has various applications, including its use in water treatment. Olivine is reported to adsorb heavy metals like iron, manganese, and copper from water (Genuchten *et al.*, 2023). Blueguard is an Olivine-based filter media developed for the water treatment process. Blueguard grain size is 1-3 mm, and it has a specific surface area of 2 m^2/g. Filter 5 was filled with Olivine alone and a 5 cm Olivine layer was employed in filter 6 (Granøien, 2022).

Seven sampling campaigns, each consisting of composite samples collected over 14-20 days, were conducted for RRW and filtered water from the roadside ditch between autumn 2021 and summer 2024. RRW was analyzed for both total and filtered metal concentrations. Only filtered metal concentrations were analyzed in the water from the ditch, as the water had already been filtered during sampling with sampling probes.

For laboratory experiments, synthetic model water was prepared to simulate heavy metal contamination. This mixture was formulated using $ZnSO_4·7H_2O$, $CuSO_4·5H_2O$, $CdSO_4·H_2O$, $PbSO_4$, and $NiSO_4·H_2O$, yielding concentrations of 1075 µg Zn/L, 187.5 µg Cu/L, 1100 µg Cd/L, 280 µg Pb/L, and 637.5 µg Ni/L.

Filters 7 to 9 were specifically designed to evaluate the heavy metal removal efficiency of compost, using three different compost volumes to assess its performance. Filter 3 employed a commercial mixture of compost and biochar. The exact composition of this product was proprietary and not disclosed by the manufacturer.

The column tests were conducted under controlled laboratory conditions at a temperature of 16 ± 1 °C. Model water was pumped

Table 2. Composition of the 9 test columns

Column	Media	Composition
1	Sand (2-4 mm grain size)	540 ml sand mixture
2	5 cm LECA layer in sand filter	513 ml sand mixture + 27 ml LECA
3	Soil, compost & biochar mixture	540 ml of premixed product
4	LECA	540 ml LECA
5	Olivine	540 ml Olivine
6	5 cm Olivine layer in sand filter	90 ml Olivine + 450 ml sand mixture
7	Sand and compost mixture (50:50)	270 ml sand mixture + 270 ml compost
8	Sand and compost mixture (75:25)	405 ml sand mixture + 135 ml compost
9	Sand and compost mixture (95:5)	513 ml sand mixture + 27 ml compost

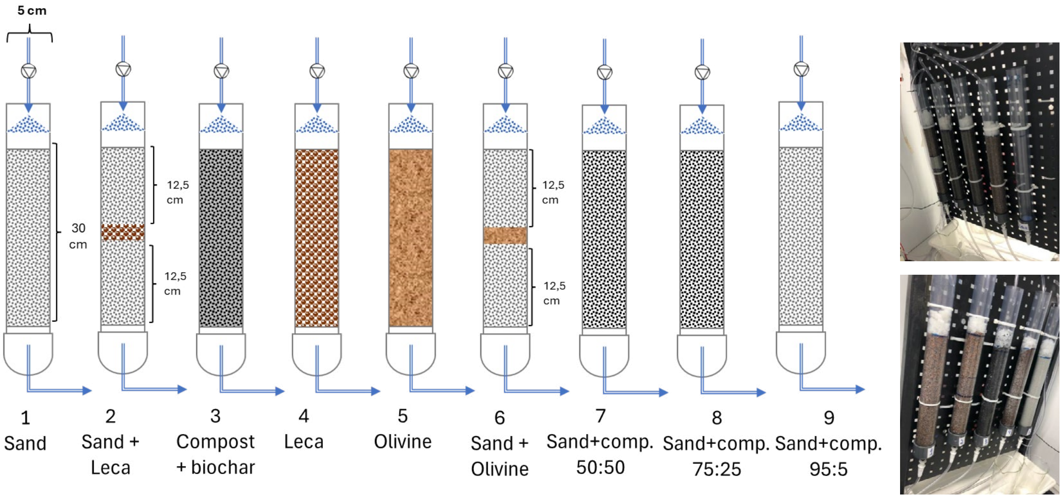

Figure 2. Column 1= control (sand). Column 2 =sand + 5 cm Leca layer, Column 3= a mix of compost and biochar; Column 4= only Leca; Column 5 = only Olivine, Column 6 = sand + 5cm Olivine layer, Column 7 = mixture of sand and compost (50%:50%), Column 8 = a mixture of sand and compost (75%:25%), and Column 9 =a mixture of sand and compost (95%:05%).

through the columns at a loading rate of 0.25 L/hr to simulate realistic infiltration rates.

The experiments were conducted continuously over nine days, with daily sampling to monitor the performance of each filter medium. This approach allowed for a detailed assessment of the heavy metal removal capacity of the different materials and combinations tested.

The adsorption capacities of compost, LECA, Olivine powder, and Olivine granules (Blueguard) were evaluated through isotherm tests (IS) using synthetic model water. The model water was prepared with concentrations of 13.8 mg Cd/L, 1.84 mg Cr/L, 14.4 mg Cu/L, and 21.5 mg Zn/L. For each substrate, six bottles were set up with varying amounts of the material: 0.1, 0.3, 1.0, 3.0, 6.0, and 10 grams, mixed with one liter of model water. The bottles were shaken at room temperature (20 ± 1 °C) for 100 hours to ensure thorough interaction between the substrates and the contaminants. At the end of the shaking period, samples were collected from the bottles, filtered, and analysed. These tests provided insights into the adsorption efficiency and capacity of each substrate for heavy metal removal.

Experimental samples were analysed at NMBU, while RRW and infiltrated water samples were analysed at Eurofins Laboratory using the ICP-MS method.

Results and discussion

Heavy metals in RRW samples

Previous studies (Backström *et al.*, 2003; Kluge *et al.*, 2014; Fronczyk, 2017) indicate that the chemical composition of runoff water varies in different sampling locations and over time. Table 3 presents a comparison of the concentrations of Cr, Cu, Ni, and Pb measured in present study with results from the three other studies. Although Zn concentrations were measured in the samples, they are not presented in this paper due to potential contamination concerns during sampling. The table illustrates the variation in heavy metal concentrations across different RRW sources. The average concentrations observed in the present study are slightly higher than those reported by Vollertsen *et al.*, (2018), but they remain consistent with the values found in other studies.

Table 3. Comparison of the concentrations observed in road runoff in different literature with the present study. Min.= minimum concentration, Max.= maximum concentration.

	Hober *et al.*, 2016			Jiménez *et al.*, 2022	Vollertsen *et al.*, 2018	Present study		
	Min.	Average	Max.	Average	Average	Min.	Average	Max.
Cr	2	12	24,2	8,1	1,7	1,2	16,5	52,0
Cu	7	64.6	280	55,1	13,7	15,1	52,5	140,0
Ni	3,8	16,3	35	7,4	2	1,4	16,5	49,0
Pb	3,7	32,3	136	17,5	0,67	0,2	8,3	36,0
Zn	23	285	1000	173	36,9	-	-	-

Table 4. Average heavy metal concentrations in road surface runoff and roadside infiltrated water from seven sampling campaigns, along with the percentage removal achieved by the roadside infiltration trench treatment. With in brackets show (minimum / maximum) concentrations measured in samples.

	Road runoff average (µg/l)	Roadside ditch (µg/l)	% Removal
Hg (dissolved)	< 0.002	<0.002	
Hg (total)	<0.005		-
As (dissolved)	0.58 (0.25 / 1.4)	0.44 (<0.2 / 1.04)	24 %
As (total)	1.87 (0.34 / 6.3)		
Pb (dissolved)	0.50 (0.02 / 1.9)	0.24 (<0.2 / 0.73)	51 %
Pb (total)	8.28 (0.2 / 36)		
Cd (dissolved)	0.03 (<0.004 / 0.17)	0.04 (<0.1 / 0.09)	-55 %
Cd (total)	0.11 (<0,01 / 0.47)		
Cu (dissolved)	16.8 (3.2 / 43)	11.4 (1.3 / 36)	32 %
Cu (total)	52.5 (15,1 / 140)		
Cr (dissolved)	1.63 (0.14 / 4)	1.5 (<0.5 / 4.4)	8 %
Cr (total)	16.5 (1.2 / 52)		
Ni (dissolved)	3.3 (0.23 / 7.3)	2.9 (1.3 / 6.3)	12 %
Ni (total)	16.5 (1.4 / 49)		

Table 4 summarises the analyses of seven different sampling campaigns of infiltrated water from the roadside ditch, along with RRW samples collected from the surface of E18, relevant to the infiltrated water sampling campaigns. At the Bamble facility, the collected RRW exhibited an average total Cu concentration of 52.5 µg/L, of which 16.8 µg/L was in dissolved form. Additionally, Ni and Pb were detected at concentrations of 16.5 µg/L and 8.3 µg/L, respectively, indicating relatively high levels of these metals in the water samples.

In the infiltrated samples, the sampling probes had a pore size of 1 µm, meaning the water was already filtered. Consequently, only dissolved metal concentrations were measured in the ditch samples, revealing significant removal efficiencies. The roadside ditch effectively reduced metal concentrations, with removal rates of 51% for Pb, 32% for Cu, and 12% for Ni.

These findings highlight the potential of infiltration systems in mitigating heavy metal pollution in runoff while suggesting the need for improved removal of metals like Ni and Cu.

Isotherm (IS) experiments

The results of the isotherm experiments, as shown in Figure 3 (left), demonstrate the maximum removal efficiency of each metal when 10 grams of adsorbent were used. Olivine granules exhibited the highest removal performance, achieving approximately 90% removal of Cd and nearly 99% removal of the other metals Cr, Cu, and Zn. Olivine powder, on the other hand, removed 10 % of Cd, 98 % of Cr, 61 % of Cu, and 14 % of Zn. LECA achieved removal rates of 29 % for Cd, 30 % for Cr, 45 % for Cu, and 33 % for Zn, while compost showed removals of 19 %, 30 %, 49 %, and 28 % for Cd, Cr, Cu, and Zn, respectively.

The adsorption capacities of the materials were evaluated using both the Langmuir and Freundlich models. The Langmuir model provided the best correlation and was therefore used to calculate the adsorption capacities. **Figure 3 (right)** presents the adsorption capacities of compost, LECA, Olivine powder, and Olivine granules, as calculated using the Langmuir model, with the assumption of 90 % removal. Olivine granules exhibited the highest adsorption capacity for all the heavy metals tested. Specifically, Olivine granules had a total metal adsorption (sum of all 4 metals) capacity of 538 mg per kg, while Olivine powder showed a capacity of 234 mg per kg. Compost and LECA had much lower capacities, with total metal adsorption of 6 mg per kg and 4 mg per kg, respectively.

These findings highlight the superior efficiency of Olivine granules in removing heavy metals compared to the other materials tested, making Olivine a promising option for environmental remediation of heavy metal contamination.

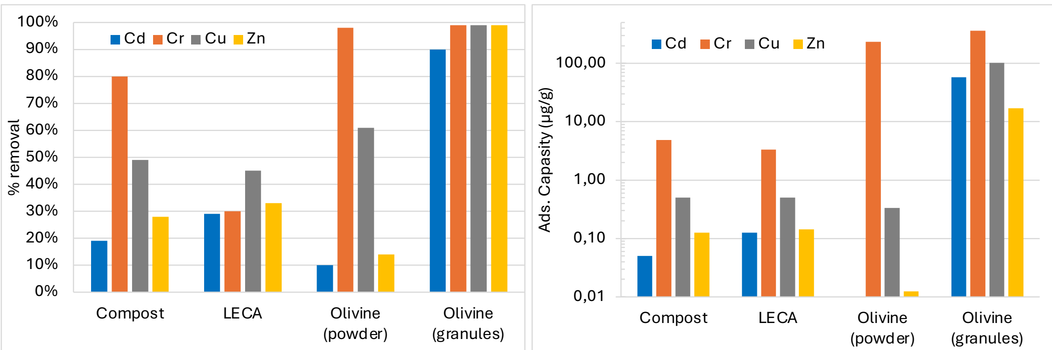

Figure 3. Maximum removal (with 10 g substrate) of each metal with different materials used for isotherm tests (left). Adsorption capacities of compost, LECA, Olivine powder and olivine granules were calculated using Langmuir's model. Y axis is in log scale (right).

Column experiments

The column experiments were conducted continuously over nine days, with daily water samples taken and analysed for heavy metal concentrations. The breakthrough curves from these experiments are shown in Figure 4.

Columns 1 (sand only) and 9 (sand with 5 % compost) exhibited the lowest removal capacities for all tested heavy metals. In column 1, all metals except Pb reached a concentration ratio (C/C_0) of 0.5 (indicating 50 % removal) within 20 bed volumes, while in column 9, the same metals reached 50 % removal within 40 bed volumes. In column 2 (with a 5 mm LECA layer), column 7 (with a 50:50 sand and compost mixture), and column 8 (with a 70:25 sand and compost mixture), Ni, Zn, and Pb reached C/C_0 = 0.5 within 65, 75, and 45 bed volumes, respectively. Cu and Pb removal were particularly high in these columns. Columns 3 to 6, which included various filter media combinations, showed minimal metal concentrations in the effluent, indicating effective removal.

The column experiment results suggest that Olivine, biochar, and LECA can significantly improve the heavy metal removal capacity of soils. Olivine was the most effective material, successfully removing the five studied metals. A 5 cm Olivine layer was sufficient to achieve high removal rates throughout the testing period. In contrast, a 5 cm LECA layer was not as effective. Sand and the filter medium with 5 % compost performed poorly in removing the tested metals.

Columns 7 and 8 demonstrated an improvement in metal removal with increasing compost content. Specifically, the removal of Cu and Pb showed significant enhancement with higher compost usage. This result indicates that although compost on its own has a relatively low removal capacity, increasing its proportion in the filter medium can substantially improve its effectiveness in removing heavy metals from water.

Conclusions

Both column and isotherm experiments demonstrated that the removal of heavy metals in roadside trenches can be significantly enhanced by amending the filling materials with Olivine (90 % Cd and nearly 99 % Cr, Cu, and Zn),

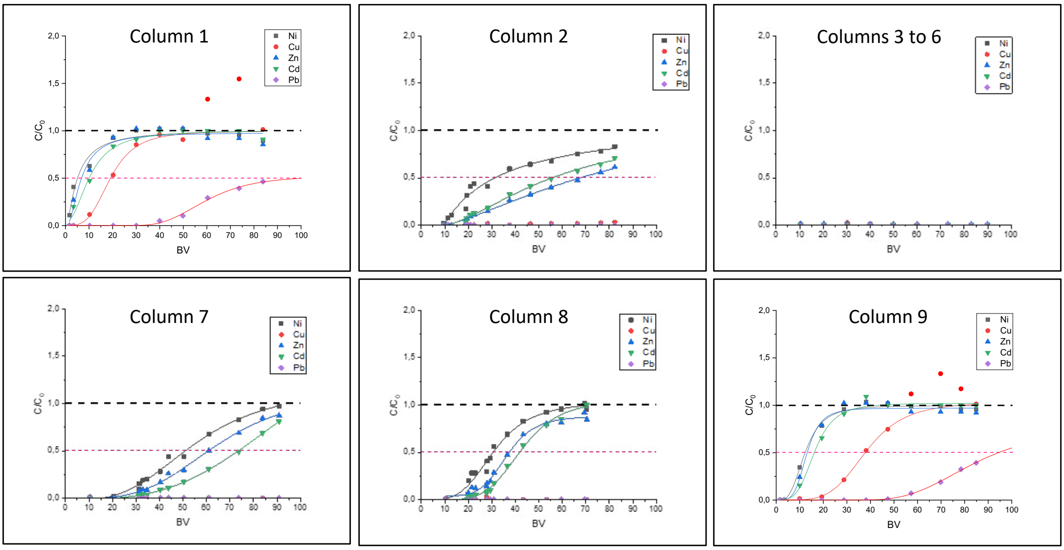

Figure 4. Breakthrough curves from the column tests. Column 1= sand, Column 2= sand + Leca, Column 3= Compost + biochar, Column 4= Leca, Column 5= Olivine, Column 6= Sand + Olivine, Column 7= sand + compost (50:50), Column 8= sand + compost (75% : 25%) and Column 9= sand + compost (95% : 5%). BV =bed volume.

LECA (29 % Cd, 30 % Cr, 45 % Cu, and 33 % Zn), or compost (19 % Cd, 30 % Cr, 49 % Cu, and 28 % Zn). The effectiveness of these materials varies, with Olivine showing the highest removal capacity, followed by LECA and compost. Although compost has a relatively lower removal capacity, its performance improves when its content is increased in the filter mixture.

The results of the isotherm experiments aligned with the findings from the breakthrough studies, confirming the consistency of the materials' adsorption and removal capacities. These studies were conducted under controlled laboratory conditions, providing reliable data on heavy metal removal.

Based on the promising results from these experiments, pilot studies have been initiated in large-scale columns at the Bamble test station, utilising RRW collected from E18. These studies aim to further assess the practical application of these materials in real-world conditions and optimise heavy metal removal in roadside trenches.

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