JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(2), 234–242
https://doi.org/10.12911/22998993/211437
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.08.15
Accepted: 2025.12.15
Published: 2026.01.15

Surface and ground water quality affected by coal mine tailings as road construction material

Oussama Khodjet El Fehem[1*], Nabil Bella[1], Ilham Aguida Bella[1], Amel Boudia[1], Khadhra Allali[1], Yassine Rahimi[1]

[1] FIMAS Laboratory, University of Tahri Mohammed, Bechar, Algeria
* Corresponding author's e-mail: khodjetelfehm.oussama@univ-bechar.dz

ABSTRACT

Coal mine tailings occupy approximately 20% and 70% of the area suitable for urban development in Bechar and Kenadsa, respectively (southwestern Algeria). These tailings pose environmental risks, as toxic contaminants can leach into groundwater and surface water if improperly managed. This study investigated the potential use of coal mine tailings as embankment or road pavement material and its environmental impact, particularly on water resources. Cement and lime were independently used to treat an optimal mixture of coal mine tailings and tuff to enhance contaminant retention and maintain water quality. Leaching tests were conducted on four soil samples, and the leachate was analyzed for heavy metals (Cd, Pb, and Zn) using atomic absorption spectroscopy (AAS). Results suggest that utilizing treated coal mine tailings as a pavement base layer or embankment material may mitigate associated pollution. Leaching tests demonstrated that cement treatment effectively retained heavy metals and other toxic elements, potentially protecting surface and groundwater from contamination.

Keywords: coal mine tailings, groundwater, heavy metals, pavement base layer, soil pollution, surface water.

INTRODUCTION

The mining industry has long been a cornerstone of economic development, yet its environmental footprint remains a profound sustainability concern. In response, recent research increasingly emphasizes waste valorization strategies, particularly the incorporation of industrial byproducts into construction materials (Mashaan and Yogi, 2025). Among these, coal mine tailings (CMTs) the residual materials from coal extraction and processing have emerged as a promising alternative aggregate for road construction (Srivastava and Jha, 2025). These tailings, often stored in dams or disposal facilities, represent both an environmental burden and an underutilized resource. When poorly managed, they pose significant ecological threats, including particulate emissions, acid mine drainage, and heavy-metal leaching.

Recent research underscores the growing potential of mine tailings as valuable inputs for sustainable construction materials. A global bibliometric analysis by Zetola et al. (2024) revealed a significant increase in studies exploring the recovery of mining waste particularly tailings for use in construction, with notable attention to concrete production (El Machi et al; 2024). heavy-metal stabilization, and durability performance. Building on this trend, Guo et al. (2025), provided an in-depth evaluation of the physicochemical properties, activation methods, and environmental safety of mine tailings incorporated into cementitious (Guan et al., 2021) and alkali-activated systems. Their findings demonstrate that, when appropriately processed, tailings can replace substantial proportions of conventional raw materials while improving mechanical performance and reducing environmental impacts, thereby aligning with circular economy and sustainability goals.

In the context of southwestern Algeria, the heritage of coal mining presents both environmental risks and opportunities for resource recovery (El Fehem et al., 2024). Following the discovery of coal deposits in Béchar by Flamand in 1907, intensive mining from 1918 to 1975 generated approximately 3.7 million cubic meters of CMTs (ONRGM, 2003). These tailings now occupy roughly 20–70% of land viable for urban development in Béchar and Kenadsa, fueling environmental pressures through spontaneous combustion (Jelínek et al., 2015) and heavy-metal contamination of surface and groundwater (Nelson, 2013). Traditional disposal methods including relocation and mine re-injection—have proven both costly and environmentally precarious (ONRGM, 2003). Nonetheless, earlier regional studies have demonstrated the technical feasibility of using CMTs in construction, with experimental road sections exhibiting satisfactory performance (Benkhedda and Rikioui, 2011; Himouri et al., 2013; Slimane et al., 2013). However, the environmental implications particularly regarding water quality of such applications remain inadequately studied.

This investigation addresses that gap by pursuing two key objectives: (1) developing optimal CMT–tuff mixtures stabilized with cement or lime for road construction, and (2) evaluating their environmental impact on water resources. We employ modified leaching tests (CEN/TS 16637-2, 2014) to assess the mobility of heavy metals (Cd, Pb, Zn), with a focus on immobilization mechanisms through cement hydration (Taylor, 1990) and lime stabilization. The outcomes aim to inform sustainable CMT utilization strategies that balance engineering performance with environmental protection in mining-affected regions advancing circular economy approaches in mine-waste management.

MATERIAL AND METHODS

The materials utilized in this study were sourced locally. Specifically, coal mine tailings were collected from former coal mining sites located in Kenadsa, near the town of Béchar in southwestern Algeria. Mining operations in this region commenced in the 1930s and were discontinued shortly after Algeria gained independence. The tuff used in this study was supplied by the SARL PRODAG200 company. It is a silico-calcareous material commonly employed as a base layer in pavements and for embankment construction in the Béchar region. The cement utilized was CEM I 42.5 N-SR3, a Sulfate Resisting Portland Cement (SRPC), chosen for its durability in sulfate-rich environments. The burnt lime, primarily composed of calcium oxide (CaO) and calcium hydroxide [$Ca(OH)_2$], was used as a stabilizing agent. The major chemical compositions of the coal mine tailings (CMTs), tuff, cement, and lime are summarized in Table 1. Tuff exhibits a high content of calcium oxide (CaO, 43.89%) and silicon dioxide (SiO_2, 16.73%), which supports its application in embankment construction. CMTs are characterized by elevated levels of SiO_2 (23.54%) and aluminum oxide (Al_2O_3, 10.30%), with significant amounts of carbon dioxide (CO_2, 44.15%) and iron oxide (Fe_2O_3, 8.46%). The cement is predominantly composed of CaO (63.58%) and SiO_2 (20.60%). Lime contains more than 80% CaO, with less than 2% SiO_2 and Al_2O_3, aligning with its primary function in soil and material stabilization.

A geotechnical study was conducted to determine the optimal dosage of CMT and tuff. The optimal composition was 75% Tuff and 25% CMT (designated as CMT-T), which yielded acceptable geotechnical characteristics for road base material (Bella et al., 2020). Cement and lime were used separately to treat the optimal CMT-T soil mixture to immobilize toxic elements and mitigate impacts on surface and groundwater quality. The soil mixtures studied are summarized in Table 2.

Leaching tests were carried out on four compacted soil types: T, CMT-T, CMT-TC, and CMT-TL. For each type, three replicate specimens were

Table 1. Major composition of CMTs, tuff, cement, and lime

Oxide (%)	Tuff	CMTs	Cement	Lime
SiO_2	16.73	23.54	20.60	< 2
Al_2O_3	3.67	10.30	4.64	< 1
CaO	43.89	1.79	63.58	> 80
Fe_2O_3	1.15	8.46	4.29	/
MgO	0.81	1.52	3.31	> 5
Na_2O	0.01	0.11	0.21	/
SO_3	0.43	7.94	2.57	/
K_2O	0.44	1.63	0.79	/
CO_2	33.85	44.15	2.21	/

Table 2. Studied soil mixtures

Parameter	Tuff	CMT+Tuff	CMT+Tuff+Cement	CMT+Tuff+ Lime
Abbreviation		CMT-T	CMT-TC	CMT-TL
Tuff (%)	100	75	75	75
CMT (%)	/	25	25	25
Cement (%)	/	/	4	/
Building lime (%)	/	/	/	4
Water (%)	8	8	8	8

prepared in cylindrical rigid plastic molds (11 cm in diameter and 22 cm in height; Figure 1a). Approximately 3 kg of soil was compacted in three successive layers using a standard Proctor rammer. Each layer received 30 blows from a 2.5 kg hammer with a flat circular face (50 mm diameter) dropped from a height of 0.305 m.

The experimental procedure followed the method described by Bellagh (2017), which is based on the CEN/TS-16637-2 (2014) protocol. Each compacted specimen was immersed in a leaching reactor containing distilled water at a liquid-to-solid (L/S) ratio of 10. Individual samples were placed in separate sealed containers (30 L buckets) filled with distilled water, ensuring a clearance of at least 5 cm between the specimen and the container walls and maintaining a water layer of no less than 5 cm above the specimen surface (Figure 1b).

The immersion start time was recorded as t_0. After six hours, 300–400 mL of leachate was collected for analysis, and an equal volume of distilled water was replenished to preserve the L/S ratio. This sampling process was repeated at the standard leaching intervals of 6, 24, 54, 96, 120, 140, and 168 hours (CEN/TS-16637-2, 2014).

Analyses of the leachates included measurements of pH, electrical conductivity, total dissolved solids (TDS), and salinity using an EXTECH Exstik EC500 multimeter (Extech Instruments Corporation, Nashua, NH, USA). Chloride, sulfate, and total suspended solids (TSS) concentrations were also determined. Heavy metals (Cd, Pb, and Zn) were quantified by flame atomic absorption spectrometry (Agilent 240 FS AA, USA), with each measurement performed in triplicate to calculate average concentrations.

RESULTS

Potential of hydrogen measurement (pH)

Figure 2 illustrates the temporal evolution of pH in the leaching solutions. The pH results indicate two distinct leachate behaviors: Tuff, CMT-T, and CMT-TL produced near-neutral values, suggesting minimal alteration of the leachate's acidity–alkalinity balance, while CMT-TC yielded strongly alkaline leachates, consistent with the release of hydroxyl ions from cement hydration.

Conductivity, total dissolved solids and salinity

Figures 3, 4, and 5 depict the temporal changes in conductivity, total dissolved solids

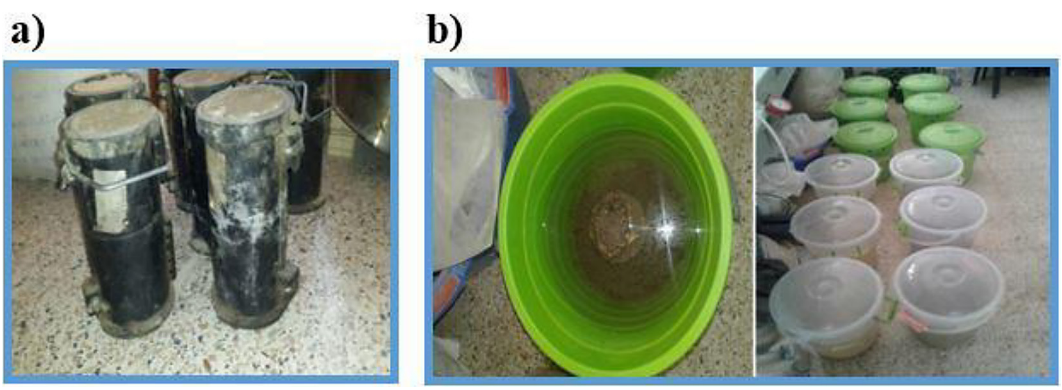

Figure 1. Plastic rigid molds (a) and soil Specimen placed in a bucket and the buckets with lids (b)

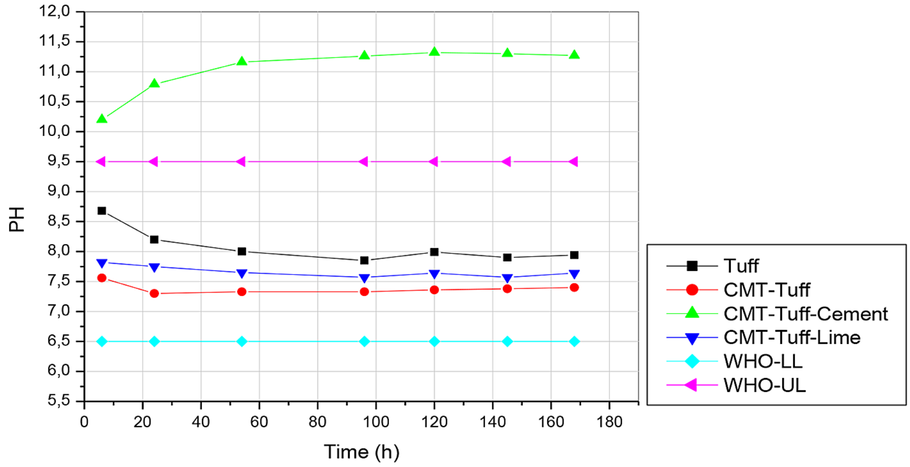

Figure 2. pH of leachates solutions, LL:lLower limit and UL: upper limit

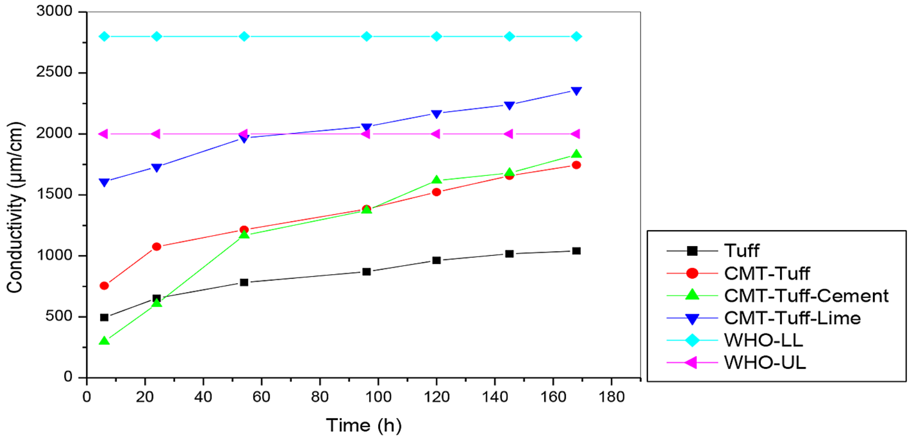

Figure 3. Conductivity of leachates solutions, AS: Algerian standard, OR: other research, and UL: upper limit

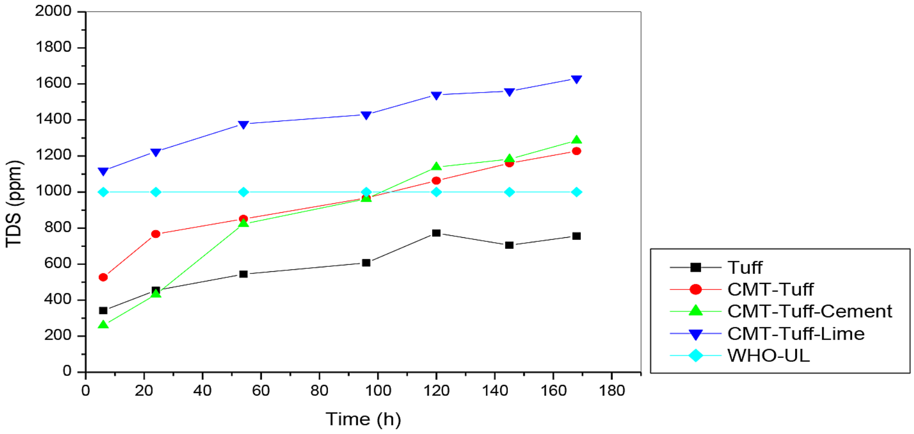

Figure 4. TDS of leachates solutions, UL: upper limit

(TDS), and salinity, respectively. The curves for all soil types exhibited similar shapes, as TDS and salinity are derived from conductivity measurements. Most treatments showed low conductivity, indicating limited ion release, while CMT-TL exhibited higher and increasing conductivity over time. TDS patterns followed a similar trend, with only the control soil consistently remaining within WHO limits; CMT-TL exceeded these limits at all times, and CMT-TC surpassed them after 7 days. Salinity results also identified CMT-TL as the only treatment consistently above recommended thresholds.

Chloride, sulfate and total suspended solids

Figures 6, 7, and 8 illustrate the temporal evolution of chloride, sulfate, and total suspended solids (TSS) contents in the leachate solutions, respectively.

Chloride content

The World Health Organization (WHO, 2017) recommends a maximum chloride content of 250 mg/L for drinking water, while the Algerian standard (JORADP, 2011) sets a limit of 500 mg/L. All studied soils met these standards. The CMT-T soil mixture exhibited the lowest chloride content after 168 hours (7 days). Soils treated with cement and lime showed slightly higher contents but remained below the recommended limits.

Sulfate content

WHO (2017) recommends a sulfate content limit of 500 mg/L, while the Algerian standard (JORADP, 2011) sets a limit of 400 mg/L. The sulfate content in CMT-T soil remained below 500 mg/L after 6 and 96 hours, decreasing to below 100 mg/L after 168 hours. For CMT-TL soil, sulfate content was approximately 650 mg/L after 6 hours, 800 mg/L after 96 hours, and 400 mg/L after 168 hours. CMT-TC soil exhibited sulfate content below 100 mg/L after 6 and 96 hours, increasing to approximately 700 mg/L after 168

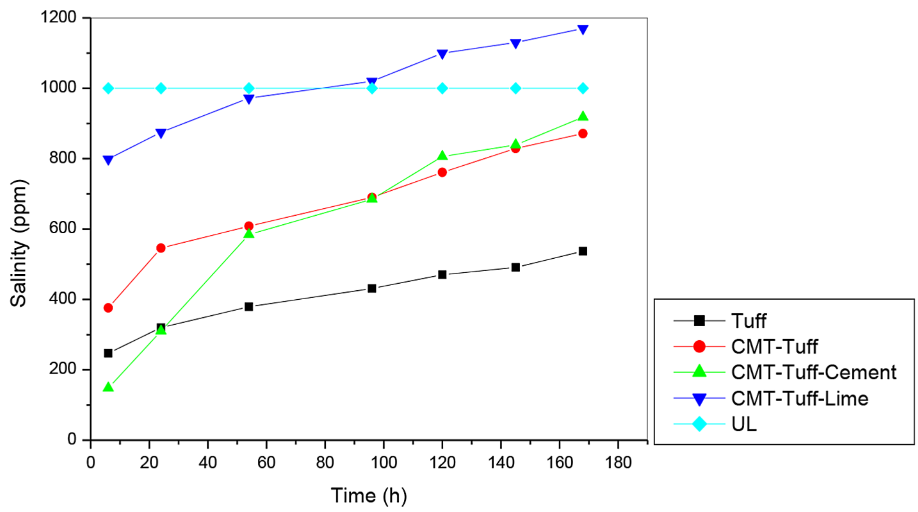

Figure 5. Salinity of leachates solutions, UL – upper limit

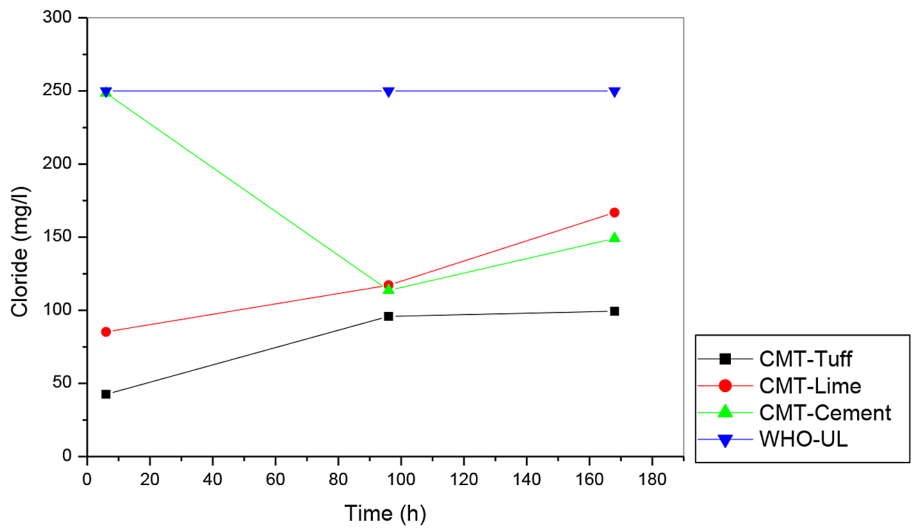

Figure 6. Chloride content of leachates solutions, UL – upper limit

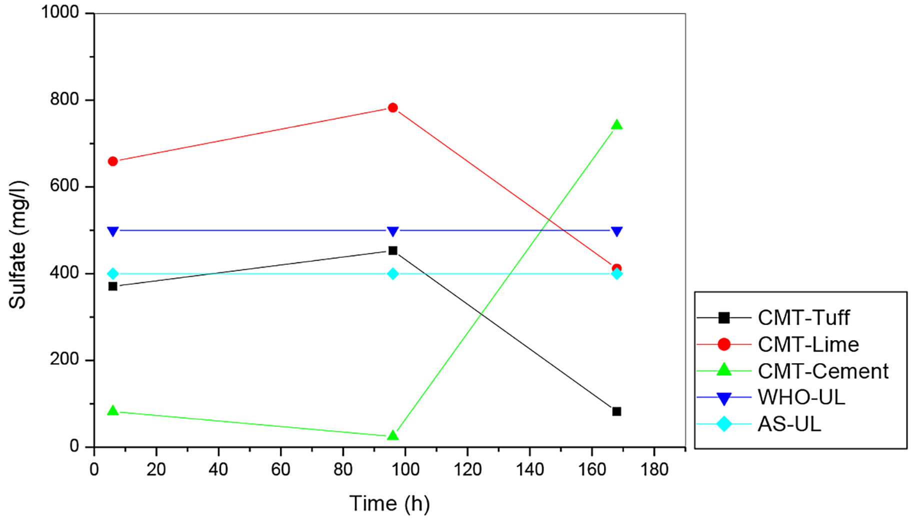

Figure 7. Sulfate content of leachates solutions, AS – Algerian standard, UL – upper limit

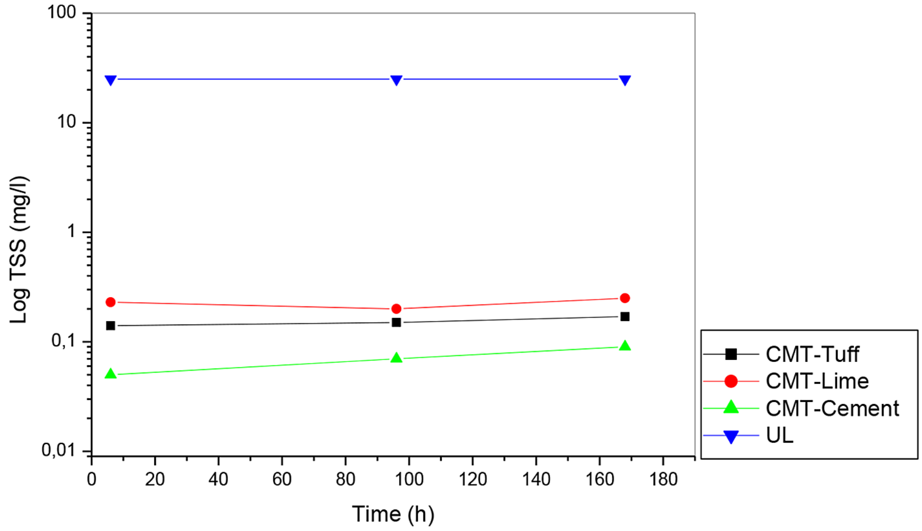

Figure 8. TSS content of leachates solutions, UL – upper limit

hours. The observed sulfate behavior in CMT-TC can be explained by cement hydration reactions (Taylor, 1990). Initially, calcium sulfate reacts with tricalcium aluminate ($3CaO·Al_2O_3$ or C3A) to form ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}·26H_2O$). After calcium sulfate depletion, ettringite reacts with remaining C3A to form calcium monosulfate ($Ca0·Al_2O_3·CaSO_4·12H_2O$ or $C_4Al_2H_{12}$), resulting in elevated sulfate content in the CMT-TC soil leachate solution. This effect can be mitigated by using low C3A content cement or cement additives.

Total suspended solids (TSS)

TSS in leachate solutions represent solids that can be trapped by a filter (Shvets et al., 2025). While neither WHO (2017) nor local standards (JORADP, 2011) provide recommended TSS values, Rossi et al. (2006) suggest a maximum limit of 25 mg/L. All soil leachate solutions met this condition, with CMT-TC exhibiting the lowest TSS value.

Heavy metal content

Atomic absorption spectroscopy (AAS) analysis of heavy metal content in the leachate solutions and the corresponding limits set by WHO and local standards are summarized in Table 3. The selection of tested heavy metals was based on the chemical composition of CMT (Table 3). All soil leachate solutions exhibited zinc (Zn) content below the standard maximum limits. However, lead (Pb) and chromium (Cr) content

Table 3. Content of heavy metals of different treated soil

Parameter	CMT-T	CMT-TL	CMT-TC	WHO and Algerian standards
Zn (mg/L)	0.0010	0.0051	0.0006	3 (5)*
Pb (mg/L)	0.0400	0.0650	0.0250	0.01
Cd (mg/L)	0.0525	0.0510	0.0430	0.003

Note: * limit of Algerian standard.

exceeded the maximum limits for all soil samples, with CMT-TC showing the lowest values among the tested soils. It's important to note that all soils were tested after a 4-day curing period. The use of lime (specifically burnt lime or quicklime) to treat CMT-T soil did not demonstrate significant improvement in heavy metal retention.

DISCUSSION

This study examined the leaching behavior of untreated and treated coal mine tailings (CMT) in relation to water quality indicators, including pH, ionic content, major anions, total suspended solids (TSS), and heavy metal mobility, to assess their potential environmental suitability for road construction applications. The near-neutral pH values recorded in Tuff, CMT-T, and CMT-TL leachates indicate good chemical stability, suggesting a reduced risk of acidification in adjacent water bodies. Conversely, the strongly alkaline pH of CMT-TC leachates is attributed to the presence of cement hydration products such as calcium hydroxide, which can promote the immobilization of some contaminants but may adversely impact aquatic life if discharge is not properly managed (Shively et al., 1986; Yilmaz et al., 2023). The conductivity, total dissolved solids (TDS), and salinity patterns highlight that cement treatment (CMT-TC) initially limits ionic release compared to lime treatment (CMT-TL), which showed consistently higher levels of dissolved solids. This aligns with previous findings that lime-treated materials can exhibit higher ionic mobility over time due to gradual dissolution of lime phases (Li et al., 2022). The consistently low chloride content across treatments supports the hypothesis of chloride incorporation into cementitious phases such as Friedel's salt (Suryavanshi and Swamy, 1996), although partial remobilization is possible under certain environmental conditions (Dehwah, 2006). A late-stage increase in sulfate in CMT-TC leachates is likely linked to the transformation of ettringite to monosulfate during prolonged curing (Taylor, 1990; Neville, 2011). While the observed TSS values indicate that all treatments generated relatively clear leachates, cement treatment showed the highest particle retention efficiency. However, heavy metal analyses revealed that Pb and Cd concentrations exceeded WHO permissible limits in all cases, despite reductions achieved by cement treatment. This finding is consistent with reports that cement-based stabilization often reduces but does not entirely eliminate heavy metal leaching (Butler et al., 2010; Sun et al., 2021). Potential mitigation strategies include extending curing durations (Bellagh, 2017), incorporating supplementary cementitious materials (SCMs) such as fly ash or slag, or exploring alternative binders like hydraulic lime, which have demonstrated improved heavy metal retention capacities (Arulrajah et al., 2020). Overall, the results suggest that cement-treated coal mine tailings can satisfy several water quality standards—particularly for pH, chloride, sulfate, and TSS but further optimization is essential to minimize Pb and Cd release before large-scale road construction use can be considered environmentally sustainable.

CONCLUSIONS

This study assessed the environmental risks and potential reuse of coal mine tailings (CMTs) from Béchar and Kenadsa, Algeria, as pavement base layers or embankment materials. The results revealed that CMTs present considerable health and environmental hazards, mainly through surface and groundwater contamination. Incorporating CMTs into construction materials offers a promising pathway to reduce these impacts. A mixture of 25% CMT and 75% tuff (CMT-T) exhibited satisfactory geotechnical properties for road base applications; however, in its untreated form, it showed limited capacity to retain heavy metals under flooding conditions. Treating CMT-T with 4% cement significantly enhanced heavy metal and toxic element retention, effectively minimizing leaching and protecting water resources. Conversely, burnt lime treatment did not yield substantial improvements. Overall, cement-stabilized CMT-T mixtures demonstrate strong potential for sustainable road construction and embankment use, providing both environmental protection and waste valorization. Future research should explore the performance of hydraulic lime as an alternative binder, the influence of extended curing on heavy metal retention, and the long-term durability and environmental impact of treated CMT materials under field conditions.

Acknowledgements

This research was supported by DGRSDT (Directoral General for Science Research and Technical Development) and ATRST (Thematic Research Agency in Science and Technology) grant number DMU-TR 007, and PRFU grant number A01L02UN080120180003. Some water analysis were done in LTPO Bechar, for that, we thank Rikioui Tayeb and Assouli Mostafa.

REFERENCES

1. Amrani, M., Taha, Y., Kchikach, A., Benzaazoua, M., Hakkou, R. (2019). Valorization of phosphate mine waste rocks as materials for road construction. *Minerals, 9*(4), 237. https://doi.org/10.3390/min9040237
2. Arulrajah, A., Mohajerani, A., Piratheepan, J. (2020). Reuse of coal mine tailings in geotechnical applications. *Construction and Building Materials, 237,* 117601. https://doi.org/10.1016/j.conbuildmat.2019.117601
3. Bellagh, K. (2017). Effect of curing time on the leachability of heavy metals from cement-stabilized industrial waste. *Journal of Environmental Chemical Engineering, 5*(4), 3350–3357. https://doi.org/10.1016/j.jece.2017.06.021
4. Bella, N., Dahane, M. A., Mebarki, T. A., Benhadda, C., Benallal, M. (2020). Investigation on real scale road test section using coal mine tailings as road base layer material: Short and long term characterisation. *Algerian Journal of Environmental Science and Technology.* (Submitted).
5. Benkhedda, C., Rikioui, T. (2011). Formulation of lightweight concrete bases of the expanded shale region Bechar. *Journal of Science Research, 1*(1), 9–16. https://asjp.cerist.dz/en/article/15142
6. Butler, L., West, J. S., Tighe, S. L. (2010). The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. *Cement and Concrete Research, 40*(9), 1466–1476. https://doi.org/10.1016/j.cemconres.2010.04.001
7. CEN/TS 16637-2. (2014). *Construction products—Assessment of release of dangerous substances—Part 2: Horizontal dynamic surface leaching test.* European Committee of Standardization.
8. Dalmasso, E. (1962). Une cité minière au Nord-Sahara: Béchar-Djedid. *Méditerranée, 3*(1), 21–50. https://doi.org/10.3406/medit.1962.1026
9. Dehwah, H. A. F. (2006). Effect of sulphate contamination on chloride-binding capacity of plain and blended cements. *Advances in Cement Research, 18*(1), 7–17. https://doi.org/10.1680/adcr.2006.18.1.7
10. El Fehem, O. K., Bella, N., Boudia, A. (2024). Mechanical behavior of calcareous tuff and coal mine tailings mixture as an embankment material for road construction. *Studies in Engineering and Exact Sciences, 5*(2), e5759. https://doi.org/10.54021/seesv5n2-023
11. El Machi, A., El Berdai, Y., Mabroum, S., Safhi, A. E. M., Taha, Y., Benzaazoua, M., Hakkou, R. (2024). Recycling of mine wastes in the concrete industry: A review. *Buildings, 14*(6), 1508. https://doi.org/10.3390/buildings14061508
12. Guan, X., Chen, J., Zhu, M., Gao, J. (2021). Performance of microwave-activated coal gangue powder as auxiliary cementitious material. *Journal of Materials Research and Technology, 14,* 2799–2811. https://doi.org/10.1016/j.jmrt.2021.08.106
13. Guo, S., Zhang, H., Yuan, C., Bi, Y. (2025). Alkali-activated steel slag–coal gangue cementitious materials: Strength, hydration, and heavy metal immobilization. *Case Studies in Construction Materials,* e05120. https://doi.org/10.1016/j.cscm.2025.e05120
14. Guo, Y., Qu, F., Li, W. (2025). Advancing circular economy and construction sustainability: Transforming mine tailings into high-value cementitious and alkali-activated concrete. *npj Materials Sustainability, 3,* Article 8. https://doi.org/10.1038/s44296-025-00049-9
15. Himouri, S., Bendani, K., Acid, M. (2013). Valorisation des schistes houillers dans les béton bitumineux. *Algérie Équipement, 52,* 33–44. http://enstp.edu.dz/revue/files/article/52/article%205.pdf
16. Jelínek, P., Marschalko, M., Lamich, D., Yilmaz, I., Zastěrová, P., Bednárik, M., Růčková, H. (2015). Monitoring and analysis of burning in coal tailing dumps: A case study from the Czech Republic. *Environmental Earth Sciences, 73*(10), 6601–6612. https://doi.org/10.1007/s12665-014-3883-4
17. JORADP. (2011, March 23). La qualité de l'eau de consommation humaine. *Journal Officiel de la République Algérienne Démocratique et Populaire,* N° 18. https://www.joradp.dz/FTP/jo-francais/2014/F2014013.pdf

18. Li, X., Li, Y., Wu, S. (2022). Long-term leaching behavior of lime-treated soils and implications for environmental risk assessment. *Journal of Hazardous Materials, 424,* 127545. https://doi.org/10.1016/j.jhazmat.2021.127545
19. Liu, L. (2018). Study on the influence of coal resources over-exploitation on land resources and countermeasures for sustainable development. *Chemical Engineering Transactions, 66,* 541–546. https://doi.org/10.3303/CET1866091
20. Manjarrez, L., Zhang, L. (2018). Utilization of copper mine tailings as road base construction material through geopolymerization. *Journal of Materials in Civil Engineering, 30*(9), 04018201. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002397
21. Mashaan, N., Yogi, B. (2025). Mining waste materials in road construction. *Encyclopedia, 5*(2), 83. https://doi.org/10.3390/encyclopedia5020083
22. Nelson, P. F. (2013). Environmental issues: Emissions, pollution control, assessment and management. In D. Osborne (Ed.), *The coal handbook: Towards cleaner production. Volume 2: Coal utilisation* 557–590. Elsevier. https://doi.org/10.1016/B978-1-78242-116-0.50020-7
23. Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson Education Limited.
24. Nielsen, D. L., Brock, M. A., Rees, G. N., Baldwin, D. S. (2003). Effects of increasing salinity on freshwater ecosystems in Australia. *Australian Journal of Botany, 51*(6), 655–665. https://doi.org/10.1071/BT02115
25. ONRGM. (2003). *Étude des conditions de prise en charge des terrils des villes de Béchar et de Kenadsa* [Unpublished report]. National Office of Geological and Mining Research.
26. Rodier, J., Legube, B. (2009). *L'analyse de l'eau.* Dunod. (in french). https://www.dunod.com/sciences-techniques/analyse-eau-eaux-naturelles-eaux-residuaires-eau-mer-0
27. Rossi, L., Fankhauser, R., Chevre, N. (2006). Water quality criteria for total suspended solids (TSS) in urban wet-weather discharges. *Water Science and Technology, 54*(6–7), 355–362. https://doi.org/10.2166/wst.2006.623
28. Shively, W., Bishop, P., Gress, D., Brown, T. (1986). Leaching tests of heavy metals stabilized with Portland cement. *Journal (Water Pollution Control Federation), 58*(3), 234–241. http://www.jstor.org/stable/25042886
29. Shvets, I., Zbykovskyy, Y., Bohomaz, O. (2025). Groundwater quality in coal mines of Ukraine: Possibility of using it as drinking water. *Journal of Ecological Engineering, 26*(10). https://doi.org/10.12911/22998993/204961
30. Srivastava, V., Jha, P. K. (2025). Environmental impacts of coal mining and mitigation measures: A review. *Environmental Monitoring and Assessment, 197*(5), 545. https://doi.org/10.1007/s10661-025-13939-1
31. Sun, Y., Li, S., Chen, H. (2021). Cement-based solidification/stabilization of heavy metals in contaminated soils: A review. *Journal of Environmental Management, 277,* 111387. https://doi.org/10.1016/j.jenvman.2020.111387
32. Suryavanshi, A. K., Swamy, R. N. (1996). Stability of Friedel's salt in carbonated concrete structural elements. *Cement and Concrete Research, 26*(5), 729–741. https://doi.org/10.1016/S0008-8846(96)85010-1
33. Taylor, H. F. W. (1990). *Cement chemistry.* Academic Press.
34. World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed., incorporating the 1st addendum). WHO. http://apps.who.int/iris/bitstream/handle/10665/254637/9789241549950-eng.pdf
35. Yilmaz, G., Kaya, A., Ekinci, A. (2023). Environmental implications of alkaline leachates from cement-treated industrial wastes. *Journal of Cleaner Production, 387,* 135961. https://doi.org/10.1016/j.jclepro.2022.135961
36. Zetola, V., Keith, B. F., Lam, E. J., Montofré, Í. L., Rojas, R. J., Marín, J., Becerra, M. (2024). From mine waste to construction materials: A bibliometric analysis of mining waste recovery and tailing utilization in construction. *Sustainability, 16*(23), 10314. https://doi.org/10.3390/su162310314