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A feasibility assessment of remediating copper-contaminated soils with construction waste

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Abstract: This study investigated the potential of waste concrete fines and carbonated waste concrete fines as soil amendments for the remediation of copper-contaminated soils through adsorption and solidification experiments. The Langmuir equation indicated that both waste concrete fines and carbonated waste concrete fines achieved high adsorption capacities of 27.71 mg/g and 27.60 mg/g, respectively. These construction wastes were as effective as steel slag and fly ash in stabilizing copper in soils, primarily by converting copper from weakly acid-extractable forms to reducible and oxidized states, while exhibiting no significant effect on the residual state of copper. The results suggest a promising application of construction wastes in soil remediation; however, further investigation is needed to understand their long-term effects and the migration of potentially toxic metals in plants.

Introduction

Potentially toxic metal (PTM) pollution in soil is an increasingly serious environmental problem of global concern that jeopardizes soil health and food safety (Ma et al., 2023). In addition to natural releases, PTMs enter and accumulate in soil systems through human activities, such as mine drainage, smelting, and battery manufacturing, adversely affecting ecosystems (Liu et al., 2018). These PTMs include cadmium, lead, mercury, arsenic, chromium, copper, zinc, nickel, manganese, cobalt, etc. (Zhang et al., 2024). Beyond conventional industrial sources, recent studies have highlighted that military conflicts can also cause significant heavy metal contamination in soils, with copper being one of the predominant pollutants, alongside concomitant declines in soil microbial communities (Moliszewska et al., 2025).

Copper (Cu) is an essential trace element for the growth and development of living organisms; however, excess Cu can be toxic to plants and pose a threat to human health through the food chain (Rehman et al., 2019). In plants, elevated Cu levels can cause physiological disorders in the root system, inhibit growth, and even lead to chlorosis. In animals, excessive Cu exposure can cause damage to organs such as the liver and gallbladder, thereby disrupting normal metabolism.

In addition, Cu pollution can negatively affect the growth of soil microorganisms and the activity of soil enzymes, thereby disrupting the soil ecological balance. Anthropogenic activities, including copper mining, industrial wastewater discharges, and the use of copper-containing pesticides, can result in Cu concentrations in soils that exceed natural background levels, posing a threat to ecosystems (Zhou et al., 2005a; Zhou et al., 2005b).

In recent years, using various amendments to stabilize PTMs in soil and reduce their mobility has gained attention due to the simplicity, efficiency, in situ applicability, and cost-effectiveness of this approach (Rinklebe and Shaheen, 2015). The mechanisms by which amendments reduce PTM mobility are complex; most amendments achieve this by lowering the concentration of soluble and exchangeable PTMs through chelation, adsorption of metal ions, or by altering soil pH (Lu et al., 2015). Industrial and agricultural by-products, such as steel slag (Kong et al., 2023), fly ash (Cui et al., 2016), and biochar (Nguyen et al., 2023), are commonly used materials for green soil remediation. In a study by Meier et al. (2017), it was revealed that biochar originating from chicken manure resulted in a decrease in Cu uptake in Cu-contaminated soil by *Oenothera picensis*. Specifically, Cu uptake decreased from

66.9 mg kg⁻¹ to 36.6 mg kg⁻¹. In addition, biochar application increased soil pH and key soil nutrients, resulting in a significant 3.5-fold increase in shoot biomass and a 3.1-fold increase in root biomass. Kong et al. (2023) used sulphur slag, a by-product of wet fuming sulphur, as a stabilizer and found that the application of sulphur slag reduced the levels of Cd, Cu, Zn, and Pb in the soil, but significantly increased the levels of Cr in the soil due to the presence of Cr. The sulphur slag changed the chemical composition of potentially toxic metals (Cu, Zn, and Pb) in the soil from exchangeable and reducible to oxidizable and residual states.

Construction waste, especially waste concrete that contains a large amount of cement constitutes the largest proportion of solid waste in the city (Li et al., 2023). Its resource utilization has attracted much attention and is commonly used in road paving, recycled brick production, artificial wetlands, soil improvement, etc.; however, research on its use as a soil stabilizer is still relatively limited. The alkali-activated mixture contained in construction waste improves and stabilizes soil through cation exchange, hydration reactions, and enhanced pozzolanic reactions (Ho et al., 2021).

Certain components in waste concrete share similarities with the primary constituents of common inorganic passivators, such as Ca (OH)₂ and silicates, demonstrating potential as a passivator for soil contaminated with potentially hazardous metals. The application of waste concrete in soil remediation remains limited but holds significant potential. The application of waste concrete in soils contaminated with PTMs could significantly reduce the cost and difficulty of remediation. The objective of this study was to assess the feasibility of waste concrete fines and carbonated waste concrete fines as amendments to copper-contaminated soils and to investigate the stabilization performance of construction waste compared to other amendments, such as steel slag and fly ash. The results of this research can provide technological support for broader applications of construction waste.

Materials and methods

Material acquisition

Modifier preparation

The amendments used in this study included fly ash (FF), steel slag (SS), waste concrete fines (WW), and carbonated waste concrete fines (CC). Fly ash and steel slag were procured online, while waste concrete fines were sourced from Jiangsu Shunjia Construction Co., Ltd. Carbonated waste concrete fines were obtained by leaving the waste concrete fines indoors to naturally air-dry and carbonate for six months. During this period, the carbon dioxide concentration was approximately 0.10%, the temperature fluctuated between 20 and 26°C, and humidity ranged from 30 to 60%. All samples were dried and passed through a 100-mesh sieve.

Soil samples

Surface soil samples (0–20 cm) were collected in the winter of 2023 from roadside farmland in Lingkun Island, Wenzhou City, Zhejiang Province, China. The physicochemical parameters of the soil are shown in Table 1, and the concentrations of PTMs are shown in Table 2. According to the “Risk Control Standards for Soil Pollution in Agricultural Land” (GB 15618-2018), the risk screening value for copper

contamination in agricultural land soil is 200 mg/kg. Therefore, the soil was air-dried, pulverized, and mixed with a copper sulfate solution (700 mg CuSO₄/kg soil) and kept at 70% of its maximum water holding capacity for two weeks to reach a Cu concentration of 221.35 mg/kg, thereby creating contaminated soil. The treated soil was then air-dried and pulverized again, and subsequently passed through a 100-mesh sieve.

Adsorption experiments

A copper standard solution at a concentration of 1000 mg/L was prepared using 3.929 g of CuSO₄ and 1 L of deionized water. A 0.01 mol/L NaNO₃ solution was used as the supporting electrolyte, and the pH of the solution was adjusted to 5.5 using either 1 mol/L HNO₃ or 1 mol/L NaOH. The gradient concentrations of Cu standard solutions required for the experiments were 10, 20, 40, 80, 160, and 220 mg/L, respectively. Accurately 0.5±0.01 g of each amendment was weighed and placed separately into 50 ml polyethylene centrifuge tubes. For each amendment, 18 portions were prepared. A 30 ml solution of copper (Cu) at different concentrations, prepared from the Cu standard solution, was added to each centrifuge tube, and each amendment was tested in triplicate at each concentration. The centrifuge tubes were then placed in an incubator at (25 ± 1) °C and shaken at 150 r/min for 24 hours. After equilibration, the tubes were centrifuged at 4000 r/min for 10 minutes. Subsequently, the supernatant was filtered through a 0.22 µm membrane and transferred to a plastic bottle, to which one drop of concentrated nitric acid was added. The samples were then stored in a refrigerator at 4 °C for further testing.

Stabilization experiments

Based on previous experiments, soil stabilization tests were designed to investigate the effectiveness of different amendments in stabilizing Cu in contaminated soil. Different types of amendments were added to each 300 g portion of contaminated soil prepared as described in Section 2.1.2 at 3%, 5% and 10% mass ratios, corresponding to 9 g, 15 g, and 30 g of amendments, respectively. Each amendment was tested in triplicate at each dosage. The soil and amendments are thoroughly mixed through a blender. Water was added to each portion of soil to achieve 70% of the maximum water-holding capacity, and the mixture was transferred to a beaker. The beaker was sealed with a film containing small holes to maintain air-water equilibrium. Incubation was conducted in an automatic incubator at a temperature of 25 ± 2 °C for 28 days. After this period, soil samples were collected, thoroughly pulverized, air-dried, and analyzed for pH and potentially toxic metal forms.

Analytical methods

Adsorption isotherm analysis

The Cu content in the supernatant from the adsorption experiments was determined using inductively coupled plasma mass spectrometry (ICP-MS, NexION 300X, PerkinElmer, USA).

The adsorption of Cu by different amendments was modeled using the Langmuir and Freundlich equations. The Langmuir equation is given as:

Table 1: Physical and chemical properties of soils

DOC mg/kg	OC g/kg	AOC g/kg	IOC g/kg	TN g/kg	ON mg/kg	AON g/kg	ION g/kg	NH ₄ -N mg/kg	NO ₃ -N mg/kg	NO ₂ -N mg/kg	STN mg/kg	SON mg/kg	SO ₄ -S g/kg	TS %	pH	HN mg/kg	TP %	AP m g / kg	TK g/kg	AK mg/kg	TDS g/kg
895.00	11.70	7.49	4.21	1.30	1290.00	0.97	0.32	0.33	7.48	0.26	16.00	7.91	0.07	0.004	7.32	114.00	0.08	14.00	10.70	132.00	0.12

* DOC: dissoluble organic carbon; OC: organic carbon; AOC: active organic carbon; IOC: inert organic carbon; TN: total nitrogen; ON: organic nitrogen; AON: active organic nitrogen; ION: inert organic nitrogen; NH4-N: ammonium nitrogen; NO₃-N: nitrate nitrogen; NO₂-N: nitrite nitrogen; STN: total soluble nitrogen; SON: soluble organic nitrogen; SO₄-S: sulfate; TS: total sulfur; HN: hydrolyzable nitrogen; TP: total phosphorus; AP: effective phosphorus; TK: total potassium; AK: quick-acting potassium; TDS: total salinity

Table 2: Concentration of potentially toxic metals in virgin soil

Pb (μg/kg)	Cr (μg/kg)	Cd (μg/kg)	Zn (μg/kg)	Cu (μg/kg)	Ni (μg/kg)	As (mg/kg)	Hg (mg/kg)
31980.68	82471.74	260.84	71134.37	18419.80	24312.92	6.52	0.86

* Pb: lead; Cr: chromium; Cd: cadmium Zn: zinc; Cu: copper; Ni: nickel; As: arsenic Hg: mercury.

Table 3: Copper species extraction by Improved BCR Extraction

Steps	Extracted copper form
(1) 40 mL 0.11 mol·L ⁻¹ HOAc solution, continuous shaking at (22±5) °C for 16 h and then centrifuging.	F1 (Weak acid extraction state)
(2) 40 mL 0.5 mol·L ⁻¹ NH ₂ OH·HCl, adjusted with HNO ₃ to pH=2, continuously oscillate at (22±5) °C for 16 h and then centrifuging.	F2 (Reducible state)
(3) 10 mL 8.8 mol·L ⁻¹ H ₂ O ₂ (pH=2.0 ~ 3.0), digested at room temperature for 1 h, then heated to (85±2) °C, digested for 1 h and evaporated to dryness; then add 10 mL 8.8 mol·L ⁻¹ H ₂ O ₂ (pH=2.0), digested for 1 h at (85±2) °C, and evaporated to dryness; finally add 50 mL 1 mol·L ⁻¹ NH ₄ Ac (pH=2.0), at (22±5) °C, continuous shake for 16 h, then centrifuge for 20 min.	F3 (Oxidizable state)
(4) 20 mL aqua regia digestion.	F4 (Residual state)

$$Q_e = \frac{C_m K_L C_e}{1 + K_L C_e} \quad (1)$$

(1) where Q_e represents the adsorption amount of potentially toxic metals by the amendment at adsorption equilibrium (mg/g); C_m is the maximum adsorption capacity of the amendment (mg/g), K_L is the constant related to the adsorption binding energy, and C_e is the concentration of potentially toxic metals in the solution at adsorption equilibrium (mg/L).

The Freundlich equation is as follows:

$$Q_e = K_F C_e^n \quad (2)$$

(2) where Q_e indicates the amount of potentially toxic metal adsorbed by the amendment at adsorption equilibrium (mg/g); K_F and n are the Freundlich adsorption constants, and C_e represents the concentration of potentially toxic metal in the solution at adsorption equilibrium (mg/L).

Analysis of potentially toxic metal forms

The chemical forms of potentially toxic metals were analyzed through sequential chemical extraction. The modified BCR sequential extraction method provides good reproducibility and high extraction accuracy, producing data comparable to standardized references; thus, it is widely recognized and used internationally (Zou et al., 2022). The procedure for the modified BCR sequential extraction method is presented in Table 3. The extract was filtered through a 0.22 µm filter membrane and subsequently analyzed using ICP-MS.

Analysis of the Valence State of Metals

X-ray photoelectron spectroscopy (XPS) (Thermo Scientific K-Alpha, USA) was employed to analyze the valence states of potentially hazardous metals. The parameters were as follows: Al Kα radiation ($h\nu=1486.6$ eV) was used as excitation source, with a 400 µm spot size. Under laboratory vacuum conditions exceeding 5.0×10^{-7} mbar, the instrument operated at a working voltage of 12 kV and a filament current of 6 mA. Full-spectrum scanning was performed over an energy range of 150 eV with 1 eV increments, while narrow-scan measurements were performed over an energy range of 50 eV with 0.1 eV increments. Final charge correction was performed using C1s = 284.80 eV as the binding-energy reference. The XPS results were further analyzed and fitted using Avantage software.

Statistical analysis

The experimental data were processed using Excel. Statistical analysis of the BCR data was performed using IBM SPSS Statistics 25, with the significance level set at 0.05. Visualization graphs were generated using Origin 2023b.

Discussion and analysis

Analysis of the adsorption capacity of amendments on Cu

As shown in Fig. 1, the adsorption of Cu by the four amendments gradually increased with the concentration of the Cu solution. As the Cu concentration rose from 10 mg/L to 220 mg/L, the adsorption capacity of steel slag (SS) increased from 0.62 mg/g to 12.99 mg/g, while those of carbonated waste concrete fines (CC) and waste concrete fines (WW) both increased from 0.62 mg/g to 13.07 mg/g. The adsorption capacity of Cu by fly ash (FF) increased from 0.62 mg/g to 8.41 mg/g.

At low Cu concentrations, the four amendments exhibited similar adsorption capacities; however, differences became apparent at higher concentrations, with the order of effectiveness being $CC \approx WW > SS > FF$. Both carbonated waste concrete fines and waste concrete fines demonstrated the highest Cu immobilization capacities, with no significant difference between the two amendments ($p > 0.05$).

The Langmuir and Freundlich equations were used to fit the Cu adsorption isotherms for the different amendments, as presented in Table 4 and Fig. 1. As shown in Table 4, SS, WW, and CC were fitted with correlation coefficients (R^2) greater than 0.90, indicating that both Langmuir and Freundlich equations effectively describe the adsorption behavior of SS, WW, and CC toward Cu. However, the adsorption behavior of FF is better described by the Langmuir equation. The parameter C_m in the Langmuir equation represents the maximum monolayer adsorption capacity of the amendment for pollutants, which can be used to compare the potential adsorption capacities of different amendments (Dai et al., 2009). According to the Langmuir equation, the maximum adsorption capacities of Cu were 20.90 mg/g for SS, 27.60 mg/g for CC, and 27.71 mg/g for WW, while the maximum adsorption capacity for FF was only 7.89 mg/g.

The Freundlich equation is often applied to describe the adsorption behavior of solids with heterogeneous surfaces, where K_F reflects the magnitude of the adsorption binding

energy of the amendment for the pollutant (Arias et al., 2005). In the Freundlich equation, the K_F value for SS in Cu adsorption is 4.21, which is higher than those of CC, WW, and FF, indicating that the adsorption binding energy of SS for Cu is greater than those of the other three amendments.

Characterization of Cu adsorption by various amendments

High-resolution XPS spectra of the Cu2p region for the different amendments were deconvoluted to identify the corresponding chemical species and fitted with component peaks. The different amendments showed distinct Cu2p peaks after Cu adsorption. It was observed that the Cu2p $^{3/2}$ peaks appeared at approximately 933.1, 935.1, and 943.30 eV for the different amendments, corresponding to Cu(OH)₂, CuO, and CuCO₃, respectively (Qian et al., 2023). These results indicate that the Cu adsorbed on the surface of the amendment existed as Cu(II) and that the amendment did not change the oxidation state of Cu. In SS, the relative proportions of Cu(OH)₂, CuO, and CuCO₃ were 64.69%, 5.25%, and 30.06%, respectively. The CC treatment had the highest proportion of CuO at 18.78% (Table 5), while the highest proportion of Cu(OH)₂ was 64.94% in the FF treatment. Cu(OH)₂ accounted for the largest proportion in each amendment, indicating that hydroxyl groups (-OH) on the amendment surfaces and hydroxide ions (OH⁻) in the solution play important roles in Cu

(II) adsorption. Cu(II) was chemisorbed onto the amendment surfaces, promoting the formation of Cu(OH)₂.

Effect of amendments on soil pH

The four amendments used in this study have a large specific surface area and are alkaline, which can increase the pH of the system and promote the formation of potentially toxic metal precipitates (Cui et al., 2016). As shown in Fig. 3, compared to the original contaminated soil, the soil pH increased with increasing dosages of the different amendments. The highest pH of 8.52 was observed with the addition of 10% FF, followed by the addition of WW, which reached a pH of 8.30 at a 10% dosage. The pH for CC and SS varied less, reaching 8.17 and 8.07 at a 10% addition, respectively.

The addition of amendments, especially alkaline amendments, will enhance soil pH. Alkaline environments may cause soil compaction and inhibit microbial activity, as well as plant growth and development. Existing studies indicate that alkaline stress exerts a greater negative impact on soil crop yields than saline stress (Liu et al., 2024). The appropriate application of amendments can improve soil pH and physical conditions while providing essential nutrients such as calcium (Ca), potassium (K), and magnesium (Mg) to promote plant growth (Rinklebe and Shaheen, 2015). In practical applications, it is essential to balance the agronomic benefits with the potential impacts of amendments.

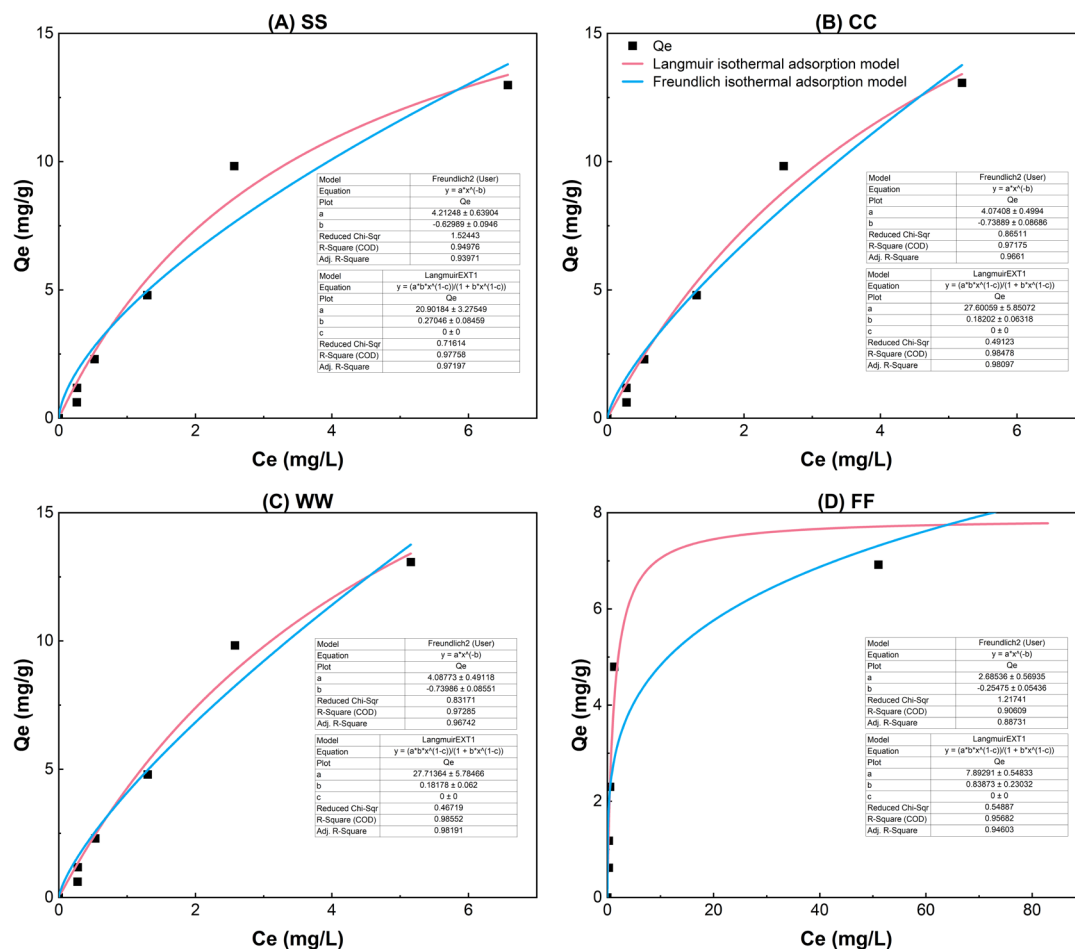
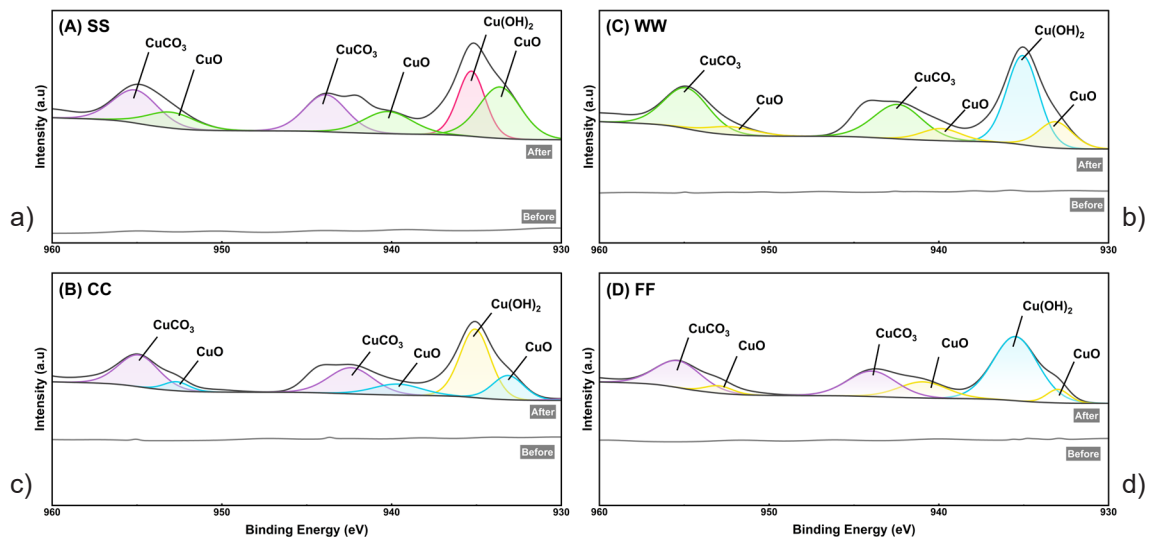


Fig 1. Adsorption isotherms of Cu by four amendments (SS: steel slag; CC: carbonated waste concrete fines; WW: waste concrete fines; FF: fly ash)

Table 4: Langmuir and Freundlich adsorption fitting parameters (R²: correlation coefficients of nonlinearly fitted curves)

	langmuir			Freundlich		
	C _m	K _L	R ²	K _F	n	R ²
SS	20.90	0.27	0.97	4.21	0.63	0.94
CC	27.60	0.18	0.98	4.07	0.74	0.97
WW	27.71	0.18	0.98	4.09	0.74	0.97
FF	7.89	0.84	0.95	2.69	0.25	0.89

**Fig 2.** XPS curves of Cu2p after adsorption of Cu by different amendments ((A) SS: steel slag; (B) CC: carbonated waste concrete fines; (C) WW: waste concrete fines; (D) FF: fly ash).

Effect of amendments on the distribution of soil Cu chemical forms

The changes in the chemical forms of soil Cu after 28 days of treatment with different doses of different amendments are illustrated in Fig. 4. In the control treatment, Cu was predominantly found in the weak acid extractable state (46.76%), with the distribution pattern of the four Cu forms as follows: weak acid-extractable state (99.88 mg/kg) > oxidizable state (70.87 mg/kg) > reducible state (32.03 mg/kg) > residual state (10.79 mg/kg). The addition of amendments resulted in a significant ($p < 0.05$) decrease in Cu content in the weak acid-extractable state and an increase in Cu content in the oxidizable state across all treatments. The treatment with 10% WW recorded the lowest Cu content in the weak acid-extractable state at 25.13 mg/kg (11.73%), while the treatment with 5% WW had the highest Cu content in the oxidizable state at 160.31 mg/kg (69.34%). Additionally, the treatment

Table 5: XPS quantitative results of surface elements after adsorption of Cu by the amendments

Amendment	Cu(OH) ₂	CuCO ₃	CuO
SS	64.69	30.06	5.25
WW	52.73	30.93	16.33
CC	51.76	29.45	18.78
FF	64.94	28.25	6.81

with 10% FF exhibited the highest Cu content in the reducible state at 39.34 mg/kg (20.41%). All four amendments are rich in calcium, iron and aluminum, which play important roles in the stabilization of PTMs (Rehman et al., 2019; Shu and Sasaki, 2022). The effects of different amendments vary with the amount added. At a 3% amendment addition, the best stabilization was achieved with FF, which showed the lowest Cu content of 27.90 mg/kg in the weak acid-extractable state. As the addition increased to 5% and 10%, WW provided the best stabilization, with Cu contents of 29.36 mg/kg and 25.13 mg/kg in the weak acid-extractable state, respectively.

Overall, the changes in Cu forms 28 days after the addition of amendments primarily involved a transition from the weak acid-extractable state to the oxidizable state, with some treatments showing an increase in Cu content in the reducible state. This indicates a gradual transformation of Cu from active states to potentially active and inactive states. However, there was no significant difference in residual-state Cu among the treatments. Notably, with increasing amendment additions, the Cu content in the residual state did not show a significant increase across the different treatments, indicating that changes in the amount of amendment added had little effect on the transformation of Cu forms.

Conclusion

Waste concrete fines and carbonated waste concrete fines demonstrate effective stabilization of Cu in contaminated soil. Based on the Langmuir model, the maximum adsorption

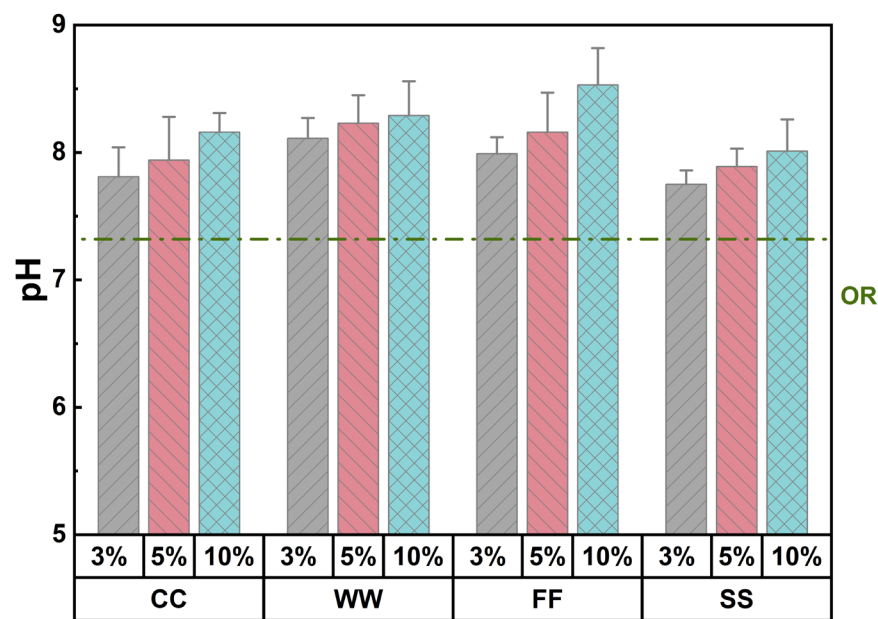


Fig 3. Effect of different amendments on soil pH (SS: steel slag; CC: carbonated waste concrete fines; WW: waste concrete fines; FF: fly ash) (legend: different passivator additions)

capacities for Cu were determined to be 20.90 mg/g for SS, 27.60 mg/g for CC, and 27.71 mg/g for WW, whereas FF exhibited a significantly lower capacity of only 7.89 mg/g. The stabilization efficiency follows the order: carbonated waste concrete ≈ waste concrete > steel slag > fly ash.

Cu adsorbed onto the surfaces of these four amendments predominantly exists in the form of Cu(II), with no alteration in its valence state observed. The hydroxyl groups (-OH) present on the amendment surfaces, along with hydroxide ions (OH⁻)

in the solution, play a critical role in the adsorption of Cu(II).

The addition of alkaline amendments elevates soil pH, although controlling their dosage can mitigate substantial impacts on pH levels. This process promotes the transformation of Cu from a weakly acid-leachable state to an oxidizable state, thereby gradually converting it from a mobile to a more stable form.

The secondary use of waste concrete as a soil amendment appears feasible for Cu stabilization. However, the

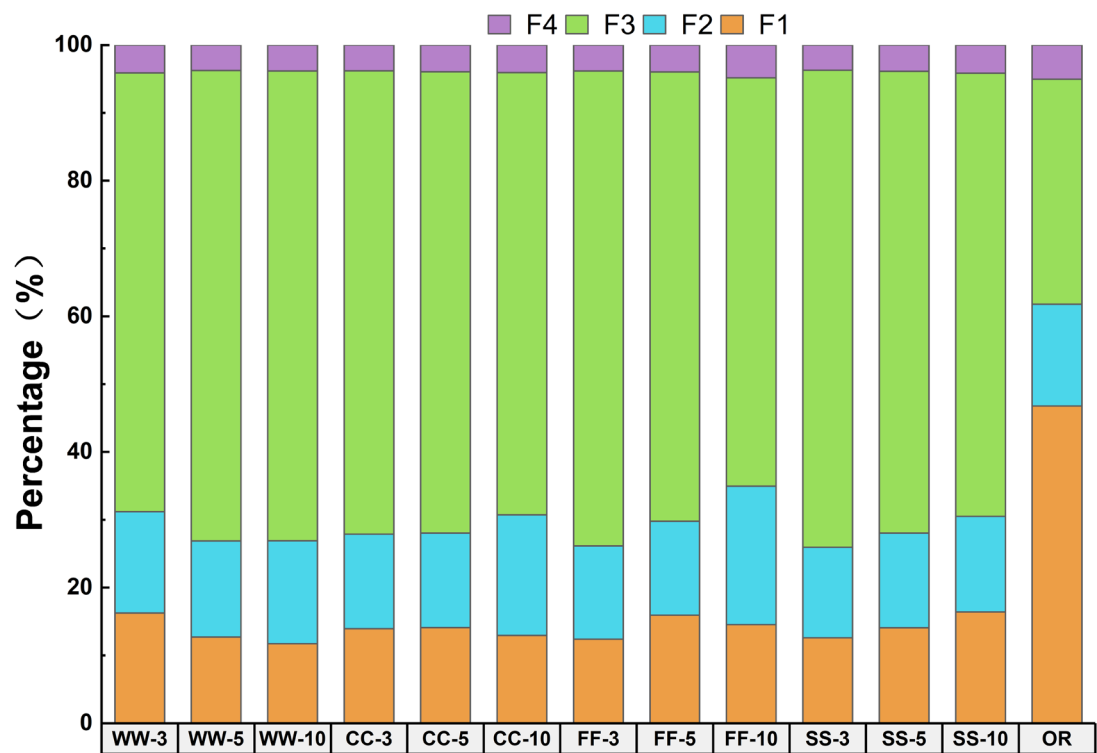


Fig 4. Effect of different amendments on the chemical form of soil Cu (SS: steel slag; CC: carbonated waste concrete fines; WW: waste concrete fines; FF: fly ash. 3: 3% addition; 5: 5% addition; 10: 10% addition)

contaminated soil used in this study was artificially prepared. In actual contaminated soils, the stabilization of Cu may be more complex, requiring further investigation into the behavior of waste concrete. Additionally, despite its short-term effectiveness, the long-term stability of immobilized Cu and the potential uptake of potentially toxic metals by plants require further experimental investigation.

Credit authorship contribution statement

Rixiu Zhou: Conceptualization, methodology, validation, formal analysis, data curation, investigation, writing - original draft, resources. **Quan Zhou:** Investigation, resources, project administration. **Chaozhen Xie:** Validation, data curation, investigation. **Zhenzhou Zhang:** Investigation, resources. **Furong Wu:** Investigation, resources. **Qiming Li:** Validation, investigation. **Fangze Shang:** Investigation. **Yifan Hu:** Investigation. **Zhengjie Zhu:** Project administration. **Dianpeng Li:** Project administration, funding acquisition. **Shuqing An:** Project administration, funding acquisition.

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Reference

- Arias, M., Pérez-Novo, C., Osorio, F., López, E. & Soto, B. (2005). Adsorption and desorption of copper and zinc in the surface layer of acid soils. *Journal of Colloid and Interface Science* 288(1), pp. 21-29. DOI:10.1016/j.jcis.2005.02.053
- Cui, H., Wu, Q., Zhang, X., Su, B., Yi, Q., Zhang, S. & Zhou, J. (2016). Immobilization of Cu and Cd in Contaminated Soil by Coal Fly Ash. *Soils* 48(5), pp. 971-977. DOI:10.13758/j.cnki.tr.2016.05.019
- Dai, J.L., Zhang, M., Hu, Q.H., Huang, Y.Z., Wang, R.Q. & Zhu, Y.G. (2009). Adsorption and desorption of iodine by various Chinese soils: II. Iodide and iodate. *GEODERMA* 153(1-2), pp. 130-135. DOI:10.1016/j.geoderma.2009.07.020.
- Ho, H.-J., Iizuka, A. & Shibata, E. (2021). Chemical recycling and use of various types of concrete waste: A review. *Journal of Cleaner Production* 284, 124785. DOI:10.1016/j.jclepro.2020.124785.
- Kong, F., Ying, Y. & Lu, S. (2023). Heavy metal pollution risk of desulfurized steel slag as a soil amendment in cycling use of solid wastes. *JOURNAL OF ENVIRONMENTAL SCIENCES* 127, pp. 349-360. DOI:10.1016/j.jes.2022.05.041
- Li, Q., Ma, Y., Chen, J., Cai, Y., Lu, Q., Yu, Q., Duan, X., Zhao, D. & An, S. (2023). The negative effect of the high pH of waste concrete in constructed wetlands on COD and N removal. *Journal of Water Process Engineering* 51, 103356. DOI:10.1016/j.jwpe.2022.103356
- Liu, B., Huang, L., Jiang, X., Liu, Y., Huang, G., Yang, C., Liang, Y., Cai, J., Zhu, G. & Kong, Q. (2024). Quantitative evaluation and mechanism analysis of soil chemical factors affecting rice yield in saline-sodic paddy fields. *Science of The Total Environment* 929, 172584. DOI:10.1016/j.scitotenv.2024.172584
- Liu, L., Li, W., Song, W. & Guo, M. (2018). Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Science of The Total Environment* 633, 206-219. DOI: 10.1016/j.scitotenv.2018.03.161
- Lu, X.-M., Lu, P.-Z., Chen, J.-J., Zhang, H. & Fu, J. (2015). Effect of passivator on Cu form transformation in pig manure aerobic composting and application in soil. *Environmental Science and Pollution Research* 22(19), pp. 14727-14737. DOI:10.1007/s11356-015-4680-7
- Ma, M., Ha, Z., Xu, X., Lv, C., Li, C., Du, D. & Chi, R. (2023). Simultaneous immobilization of multiple heavy metals in polluted soils amended with mechanical activation waste slag. *Science Of The Total Environment* 894. DOI:10.1016/j.scitotenv.2023.164730
- Meier, S., Curaqueo, G., Khan, N., Bolan, N., Cea, M., Eugenia, G.M., Cornejo, P., Ok, Y.S. & Borie, F. (2017). Chicken-manure-derived biochar reduced bioavailability of copper in a contaminated soil. *Journal of Soils and Sediments* 17(3), pp. 741-750. DOI:10.1007/s11368-015-1256-6
- Moliszewska, E.B., Bida, I., Matik, K.R., Hovorukha, V. et al. (2025). Analysis of variations in heavy metal levels and soil microorganism counts resulting from shelling incidents in Ukraine. *Archives of Environmental Protection*, 51(1), pp. 83-91. DOI:10.24425/aep.2025.153752
- Nguyen, T.-B., Sherpa, K., Bui, X.-T., Nguyen, V.-T., Vo, T.-D.-H., Ho, H.-T.-T., Chen, C.-W. & Dong, C.-D. (2023). Biochar for soil remediation: A comprehensive review of current research on pollutant removal. *Environmental Pollution* 337. DOI:10.1016/j.envpol.2023.1224571
- Qian, Z., Zeng, J., Zhang, L., Lei, X. & Li, Y. (2023). Cu(II) adsorption characteristics by deep-sea sediment from the South China Sea. *Acta Scientiae Circumstantiae* 43(09), pp. 152-163. DOI:10.13671/j.hjkxxb.2023.0006
- Rehman, M., Liu, L., Wang, Q., Saleem, M.H., Bashir, S., Ullah, S. & Peng, D. (2019). Copper environmental toxicology, recent advances, and future outlook: a review. *Environmental Science and Pollution Research* 26(18), pp. 18003-18016. DOI:10.1007/s11356-019-05073-6
- Rinklebe, J. & Shaheen, S.M. (2015). Miscellaneous additives can enhance plant uptake and affect geochemical fractions of copper in a heavily polluted riparian grassland soil. *Ecotoxicology and Environmental Safety* 119, pp. 58-65. DOI:10.1016/j.ecoenv.2015.04.005
- Shu, K. & Sasaki, K. (2022). Occurrence of steel converter slag and its high value-added conversion for environmental restoration in China: A review. *Journal Of Cleaner Production* 373. DOI:10.1016/j.jclepro.2022.133876
- Zhang, Y., Lu, X., Deng, S., Zhu, T. & Yu, B. (2024). Bibliometric and visual analysis of heavy metal health risk assessment: Development, hotspots and trends. *Archives of Environmental Protection*, 50(1). DOI:10.24425/aep.2024.149432
- Zhou, D.M., Deng, C.F., Alshawabkeh, A.N. & Cang, L. (2005a). Effects of catholyte conditioning on electrokinetic extraction of copper from mine tailings. *Environment International* 31(6), pp. 885-890. DOI:10.1016/j.envint.2005.05.034
- Zhou, D.M., Hao, X.Z., Wang, Y.J., Dong, Y.H. & Cang, L. (2005b). Copper and Zn uptake by radish and pakchoi as affected by application of livestock and poultry manures. *Chemosphere* 59(2), pp. 167-175. DOI:10.1016/j.chemosphere.2004.11.008
- Zou, C., Jiang, Y. & Huang, H. (2022). Distribution, Exposure and Health Risk Assessment of Heavy Metal Cadmium: A Review. *Asian Journal of Ecotoxicology* 17(6), pp. 225-243. DOI:10.7524/AJE.1673-5897.2021062300.