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ARTICLE

Release behavior of soluble salts in MSWI bottom ash used as road basement materials under continuous rainfall conditions

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Abstract

The bottom ash is increasingly used as a substitute aggregate material in road construction in China, and road salting is the major salt source in groundwater. Continuous rainfall releases soluble salts from the bottom ash subgrade into the surrounding soil and groundwater, resulting in potential hazards. Different methods were employed to simulate and collect runoff water during rainfall events, including batch leaching test, dynamic leaching test and constant head test, to assess environmental impact of bottom ash as road basement materials under continuous rainfall conditions. This study simulated the seepage of bottom ash backfill roads under different rainfall intensities, rainfall times, and rainfall pH values. A comprehensive sampling and laboratory testing program was undertaken to characterize the environmental impact of soluble salts from bottom ash. The obtained results reveal that the leaching concentrations of Cl^- and SO_4^{2-} exceed the limit specified in the class V standard of surface water, which are 2.06–2.17 times and 1.08–1.25 times, respectively. By examining the long-term environmental influence under the condition of continuous rainfall, the leaching of Cl^- mainly occurs in the early leaching stage, and the maximum leaching concentration reaches 19,700 mg/L. The release concentration of Cl^- begins to be lower than the class V standard of surface water when continuous rainfall approaches the total rainfall for 13 months. The cumulative release of Cl^- in the bottom ash is 2.8–5.4 mg/g. Both rainfall intensity and rain pH affect the release of Cl^-. The obtained results derived from the constant head tests indicate that stagnant water caused by rainfall deteriorates the release of soluble salt into the groundwater in only 1 day, especially at the early stage of 12 h. This work provides some basic information about how to minimize damage to the surrounding environment caused by the leaching of salt in bottom ash.

Keywords Municipal solid waste · Incineration bottom ash · Salts · Leaching · Continuous rainfall

Introduction

It was reported that the production of municipal solid waste (MSW) in China ranked first in the world in 2020, accounting for 29% of the world annual MSW production. Incineration is one of the most effective utilization methods due to its characteristics of energy recovery, mass and volume reduction (approximately 70% and 90%, respectively), and pollutant minimization [1]. Municipal solid waste incineration (MSWI) has become dominant in China. According to the standard for pollution control on MSWI (GB 18485-2001) [2], the bottom ash from the incineration of MSW is identified as normal solid waste. The physical composition, particle size distribution, chemical composition, and hardness of MSWI bottom ash are similar to those of some natural aggregates [3, 4]. Many researchers have investigated whether MSWI bottom ash can be used as building materials and subgrade filling materials [5–7]. Currently, the recycling of MSWI bottom ash as a secondary aggregate material in roadway construction has been carried out in Europe and the US and is slowly gaining attention in China [5, 8]. Several European countries and regions have methodological and regulatory developments aimed at encouraging the acceptance and reuse of those materials in construction applications.

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However, the chemical composition of MSWI bottom ash is more complex than that of natural materials, which contain metal oxides, hydroxides and carbonates, sulfates, etc., especially soluble salts, which are mainly chlorine salts and sulfate [9]. When bottom ash is used as an aggregate for road and parking construction, continuous rainfall enables the pollutants in bottom ash, such as soluble salts, to be released into the surrounding soil and groundwater [10]. Moreover, potential environmental pollution is considered to be the main limiting barrier that could restrict the valorization opportunities of bottom ash [11, 12]. Therefore, an in-depth investigation of the environmental impact and leaching performance of bottom ash under continuous rainfall is necessary for bottom ash recycling.

Some studies have demonstrated specific elements such as Cr, Cu, Pb, Se, and Zn in cement composites prepared by MSWI bottom ash, but most heavy metal contents are within the corresponding regulated range [13–15]. Izquierdo et al. [16] observed that the highest cumulative release amounts of salts were Na, Ca, K, Cl^-, and SO_4^{2-} in bottom ash. The leaching behavior of soluble salts is influenced by various factors, including pH, liquid-to-solid (*L*/*S*) ratio, ash properties, weathering and aging, leaching methods, contact time, and investigation scale. The static batch test is straightforward, and the column leaching test data are more reliable because the seepage-based data in the column test are collected from the flow mode that is similar to field conditions [17, 18]. Due to the lack of a study on the possible toxicity of salt leaching during MSWI bottom ash backfilling, particularly under the conditions of continuous rainfall, the following investigations were conducted.

This study aimed to characterize the migration and leaching behaviors of soluble salts derived from bottom ash when used in the road base under continuous rainfall conditions. Batch static leaching tests were conducted to quantitatively estimate the potential leaching levels of Cl^- and SO_4^{2-} in bottom ash. The relevance of rainfall intensity and rainfall acidity as factors regulating the release characteristics of the Cl^- component in bottom ash were investigated by a soil column leaching test under continuous rainfall. Furthermore, a constant head test was carried out to comprehensively analyze the release characteristics of soluble salts in bottom ash as a road base under the condition of surface ponding. Based on the above work, the environmental impact and leaching performance of bottom ash can be well studied, which would be valuable for bottom ash recycling.

Materials and methods

Sampling of bottom ash

The MSWI bottom ash was obtained from the Shanghai MSW incineration plant. This plant adopted the technology of an inclined forward tilting reciprocating grate and a natural circulation angle tube boiler to burn domestic waste, and the bottom ash generated after incineration was cooled by water and discharged into the storage pit. First, a 200 kg bottom ash sample was obtained from 8 different sampling points of the bottom ash storage pile at the end of the standard follow-up treatment at the incinerator. Then, the bottom ash was spread out to make its thickness as thin as possible and mixed evenly, after which the covered area was subdivided into four parts. To calibrate the samples, pretreatments of the bottom ash, including the sifting and removal of ferrous and nonferrous elements, were carried out on site. The samples were stored in a sample bag for further analysis. Considering that the particle size range of natural aggregates commonly used in road sites is 0–10 mm, the bottom ash of 0–5 mm contains a large amount of Cl^- component (accumulating more than 20% of the total Cl^- content), and the mass of metal, ceramic, and glass fragments accounts for a relatively small proportion of the total bottom ash [19]. Therefore, the bottom ash of 0–10 mm was selected for the batch static leaching test. In addition, bottom ash with a size of 0–5 mm was used as the test sample. X-ray fluorescence (XRF) was used to measure the chemical composition of major elements in the samples, and the results are presented in Table 1. The particle size reduction of bottom ash is necessary for leaching experiments to be reproducible. Therefore, the small (< 5 mm) size fractions were selected for their higher contaminant leaching relative to the bulk material, which may represent a worst-case scenario.

Table 1 Chemical composition of MSWI bottom ash

Chemical composition	SiO_2	CaO	Al_2O_3	Fe_2O_3	P_2O_5	MgO	Na_2O	SO_3
Bottom ash (%, in weight)	31.2	28.21	8.71	8.01	5.65	4.35	3.91	2.76
Chemical composition	Cl	K_2O	TiO_2	ZnO	BaO	CuO	Cr_2O_3	LOI
Bottom ash (%, in weight)	1.90	1.57	1.26	0.721	0.281	0.248	0.104	7.71

MSWI municipal solid waste incineration, *LOI* Loss on ignition

Batch static leaching test

To analyze the basic toxicity and leaching risk of MSWI bottom ash, batch static leaching tests were performed according to the modified standards of the leaching toxicity-horizontal vibration method (HJ 557-2010) [20] and sulfuric acid and acetic acid buffer solution method (HJ/T 300-2007) [21] protocol. Herein, two leaching solvents, deionized water and acetic acid buffer solution were applied. Deionized water was used to simulate the surface water. Acetic acid buffer solution was prepared according to the HJ/T 300-2007 [21] standard to simulate MSW landfill conditions. In addition, to initially quantitatively estimate the leaching risk of MSWI bottom ash at different acid rain intensities, the samples were subjected to leaching using deionized water with pH values of 3, 5, and 7, based on HJ 557-2010 [20]. The analytical procedure was as follows: 100 g of dry bottom ash was weighed and placed in a 2 L extraction bottle. According to the volumetric water content of the sample, the volume of the required leaching solvent was calculated with a liquid/solid ratio of 10:1 (L/kg), and distilled water was added to mix it thoroughly with the sample. To fix it vertically on the horizontal oscillating device, the oscillation frequency was adjusted to 110 ± 10 times/min, and the amplitude was 40 mm. After shaking at room temperature for 8 h, the extraction bottles were placed still for 16 h. Using vacuum pumps and filters, the leachate was collected for measurement. Finally, the concentrations of Cl^- and SO_4^{2-} in the leaching solution were quantitatively detected using an inductively coupled plasma–mass spectrometer (ICP−MS) based on the standard of HJ 84-2016 [22].

Continuous rainfall simulation test

According to the Technical Specification for Construction of Highway Subgrades (JTG F10-2006) in China [23], the compaction degree of a third- and fourth-grade highway embankment base should be larger than 85%. Therefore, the minimum compaction was adopted for the bottom ash filling testing column. Meanwhile, according to the natural rainfall conditions in Shanghai, with an average annual rainfall of 1123.7 mm and an average pH value of acid rain of 5, the rain intensities in this test were set as 0.1 mm/min, 0.3 mm/min, and 0.5 mm/min, and the acid rain intensity was set as pH 3, 5 and 7 in the tests.

In order to simulate the bottom ash road base under continuous rainfall conditions, a column device was used as shown in Fig. 1. The top of the column was connected to a leaching nozzle with a flowmeter, and the nozzle was connected to a peristaltic pump, which controlled the natural rain intensity and accurately controlled the flow rate. Meanwhile, the porous filter plate under the bottom ash layer at the bottom of the column can prevent the leached collection pipe from being blocked. The water outlet was designed to be conical to facilitate the collection of the leaching solution, and a speed regulating valve was set at the upper part of the water outlet to control the speed of the leaching solution. The columns consisted of the following parts: (1) a 30 mm bottom quartz sand layer (size 2–6 mm), covered with filter paper to facilitate leaching; (2) a bottom ash layer of 1000 mm; (3) a 30 mm upper quartz sand layer (size 2–6 mm) covered with filter paper to adequately distribute rainwater infiltration throughout the columns; and (4) spared space of 100 mm for water overload. Prior to each experiment, the flow rate of the pump was carefully adjusted to produce the best conditions. The leachate was collected from the outlet of the column bottom at regular intervals and filtered, and the soluble chlorine salt was determined by ICP−MS.

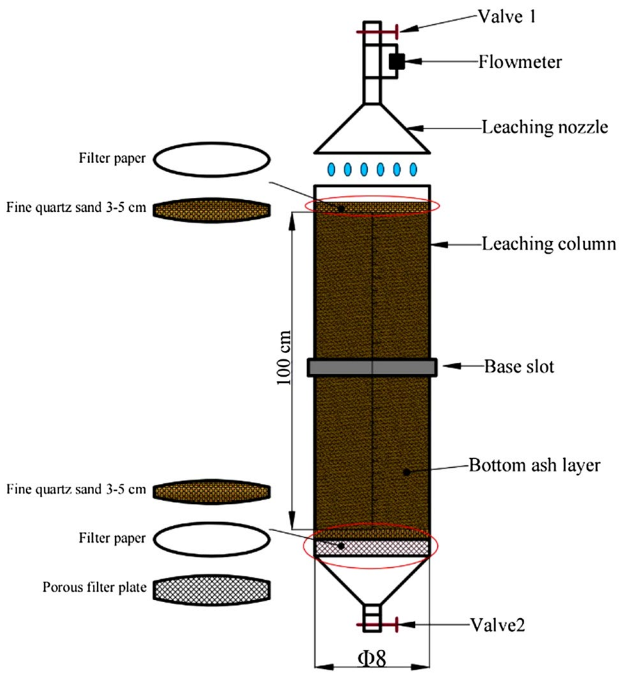
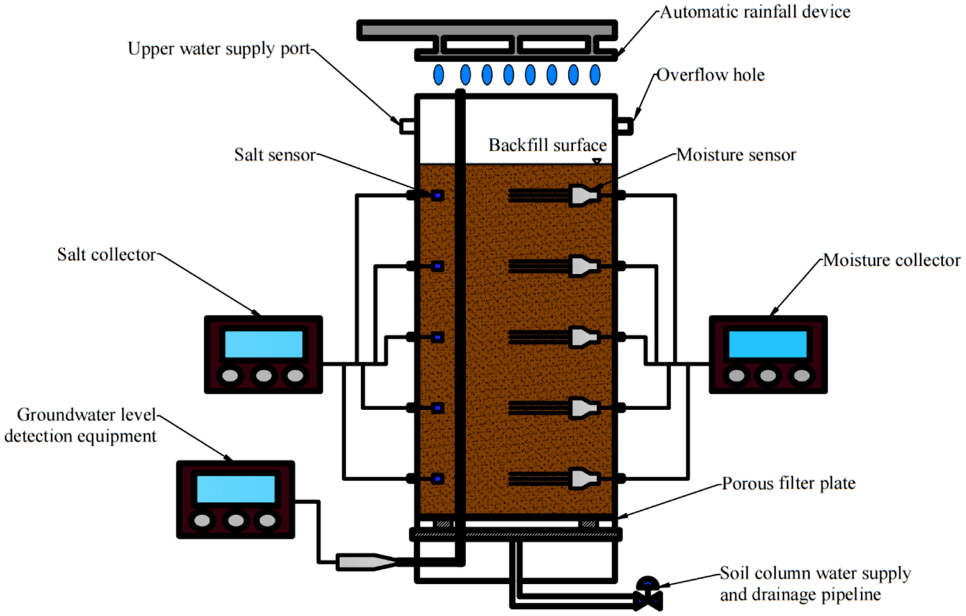


Fig. 1 Simulation column of road filled with bottom ash under continuous rainfall

Constant head test

A self-manufactured Big bottom ash column is shown in Fig. 2. It was employed to investigate the migration behavior of soluble salt in the simulated road basement backfilled with bottom ash. In the self-manufactured disturbed bottom ash column, the sidewall was arranged with measurement holes from top to bottom, which were equipped with salt and moisture sensors and collectors. Then, the data could be collected in real time by moisture and salt collectors. The bottom ash was stratified into the permeate column by layers

Fig. 2 Self-manufactured Big bottom ash column



and compacted to a height of 60 cm. An aqueous solution with pH 5 was prepared with nitric acid solution and placed in a large water tank (200 L) for standby use. The water head height of the design constant head test was 10 cm to control the external water continuous permeate conditions. Along with the infiltration of water in the main column, the soluble salt and moisture distribution in different layers of the bottom ash column could be constantly measured.

Results and discussion

Leaching risk of Cl^- and SO_4^{2-} in bottom ash by batch static leaching tests

The basic toxicity of Cl^- and SO_4^{2-} in bottom ash is shown in Fig. 3. The concentration limits of Cl^- and SO_4^{2-} in class V surface water pollutants in the standard limits of environmental quality standards for surface water (GB 3838-2002) [24] are both 250 mg/L. It was noted that the leaching contents of Cl^- and SO_4^{2-} surpassed the concentration limit of class V surface water when the preparation solution was acetic acid buffer solution, especially the SO_4^{2-} leaching concentration value, which reached 2.4 times the limit. In addition, when the preparation solution was composed of deionized water and nitric acid solution, the leaching concentrations of Cl^- and SO_4^{2-} from the 0–10 mm bottom ash exceeded the limits, which were 514–524 mg/L and 271–312 mg/L, respectively. The SO_4^{2-} and Cl^- leaching concentrations grew slowly as the pH value declined under acidic conditions, while the Cl^- leaching concentrations decreased when the acid strength reached pH 2. Comparing the two batch leaching experimental methods, the prepared solution dominated by organic acid can promote the leaching of SO_4^{2-} in bottom ash, which may be because the trace elements represented by Cu, Zn, Pb, and As in the bottom ash are more easily leached under the condition of organic acid, resulting in a large amount of SO_4^{2-} incidental leaching, while nitric acid is an inorganic acid, which has difficulty bringing out heavy metals, less leaching, and more soluble Cl^- components. The results show that when the bottom ash is leached by a solution of inorganic acid, the stronger the acidity of the preparation solution is and the greater the harm of SO_4^{2-} and Cl^- in the bottom ash is to the surrounding environment. In addition, the leaching concentration of Cl^- in bottom ash is much higher than that of other salts, such as SO_4^{2-}. Therefore, in the next section of the leaching experiment, we focused on the Cl^- release concentration from the bottom ash subgrade.

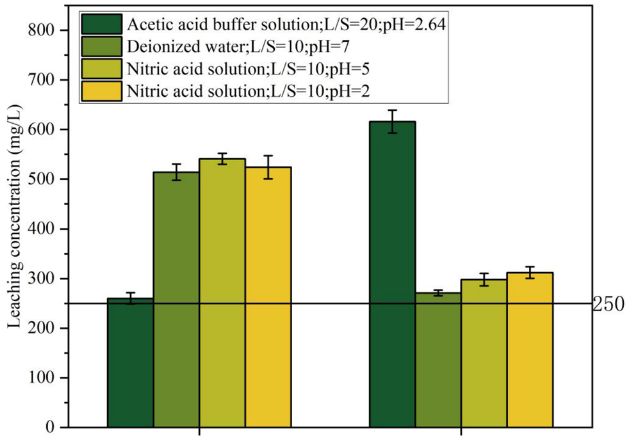


Fig. 3 Leaching concentrations of Cl^- and SO_4^{2-} in bottom ash

Release of Cl⁻ in bottom ash subgrade under continuous rainfall

In this section, the target pollutant Cl⁻ was selected and analyzed because soluble salts in bottom ash may cause strength and durability problems in roads, and the potential toxicity of Cl⁻ is the most serious in the previous section. Figure 4 illustrates the results of the Cl⁻ concentration released from bottom ash with different acid rain intensities. The maximum Cl⁻ leaching concentration reached 13,400 mg/L, which was approximately 80 times the concentration limit of Cl⁻ in class V surface water [24]. The obtained results were similar to the time-varying curves of the Cl⁻ concentration and total hardness of MSW leachate with increasing accumulated rainfall. For the bottom ash samples tested, the leachability of Cl was weakly affected by pH [25]. The contact time between the bottom ash subgrade and rainfall is within 100 days, and the slope of the Cl⁻ release concentration in the bottom ash subgrade with contact time is 174.5–134.4. After that, the slope begins to decrease slowly and tends to zero after 800 days of continuous rainfall. The cumulative Cl⁻ release mass clearly changed during the testing, reaching 3.23–4.17 mg/g (Fig. 5a). Within 200 consecutive days of continuous rainfall, the soluble salts in the bottom ash are mainly a diffusion- and reaction-controlled process. Most soluble chlorides (such as rock salt) and physically adsorbed chlorides (especially aqueous metal chlorides) are dissolved and can be classified as diffusion-controlled leaching. After large-scale diffusion, the release of the Cl⁻ component depends on the weathering stage and the solubilities/decomposition reactions of bottom ash [9]. Therefore, the contact time between the bottom ash roadbed and rainfall is within 200 days, and the leaching of Cl⁻ in the bottom ash is diffusion-controlled leaching. The time-varying curves of the Cl⁻ cumulative leaching rate in Fig. 5b show a similar trend of increase–stability. The pH has some bearing on the leaching rate at which Cl⁻ is being leached from the studied bottom ash samples. The greater the pH value within the typical rainfall pH range, the more cumulative Cl⁻ can leach from the bottom ash. The results indicate that under the continuous rainfall condition of strong acidic acid rain (pH 3 and 5), the Cl⁻ release capacity in bottom ash is stronger than that in normal rainfall within 200 days, and this trend is most pronounced after about 100 consecutive days of rainfall. This may be due to the low pH value of the preparation solution, which promotes the solubilities/decomposition reactions of the weathering phases and incineration slag in the bottom ash.

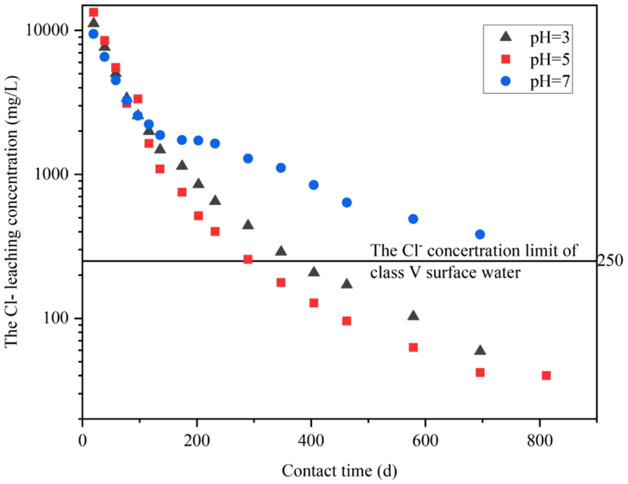


Fig. 4 The Cl⁻ release concentration in bottom ash at different acid rain intensities

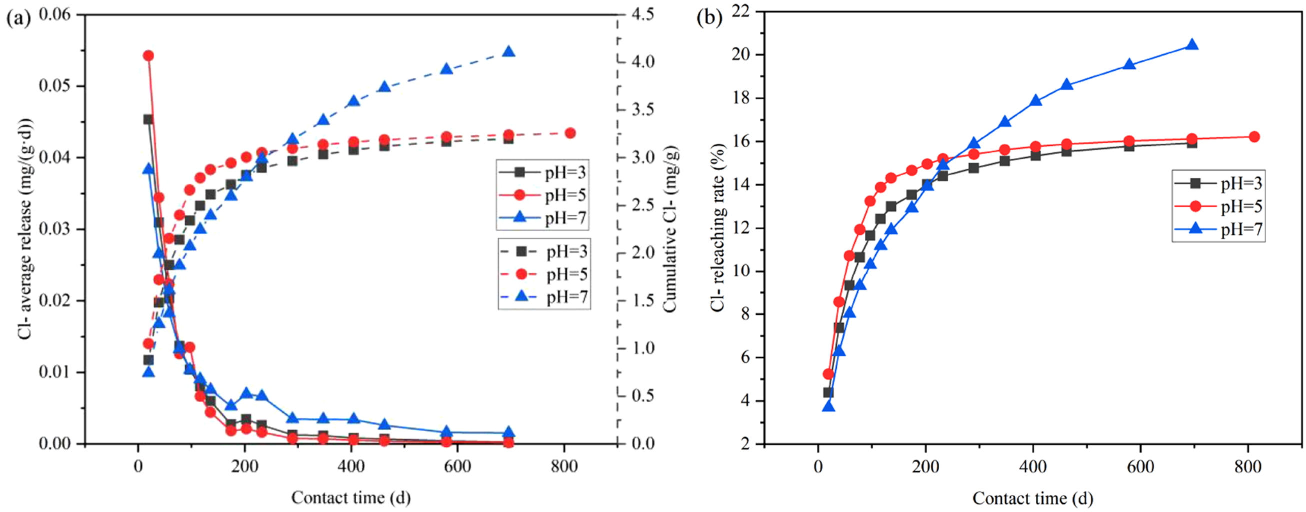


Fig. 5 **a** The cumulative Cl⁻ release mass (mg/g) and **b** the Cl⁻ cumulative leaching rate in bottom ash at different acid rain intensities

Figure 6 shows the variation curve of the release concentration of Cl$^-$ in the bottom ash subgrade under different rainfall intensities. With the increase in the contact time between the bottom ash subgrade and rainfall, the Cl$^-$ leaching concentration in the bottom ash subgrade first decreases rapidly and then becomes a constant, which is consistent with previous literatures [10, 26]. Since the release rate is slow when the rainfall intensity is 1 mm/min and the leaching cycle takes too long, only the measurement data of the first 5 months are provided. Compared with the concentration limits of class V surface water in the Environmental Quality Standard for Surface Water [24], in the whole detection cycle, the Cl$^-$ leaching concentration in the exudate of the three groups far exceeded the standard limit. Under the condition of heavy rainfall (> 0.3 mm/min), the release Cl$^-$ concentration in the bottom ash subgrade decreases more obviously, while the release concentration of Cl$^-$ is still higher than 7000 mg/L within 5 months under the condition of normal rainfall (= 0.1 mm/min). This is because, during normal rainfall, the longer the retention time of rainfall in the bottom ash, that is, the longer the interaction time of water molecules in the bottom ash, the surface layer of the bottom ash particles contains many readily leachable components, which are easily washed out by water in an aqueous environment [27, 28].

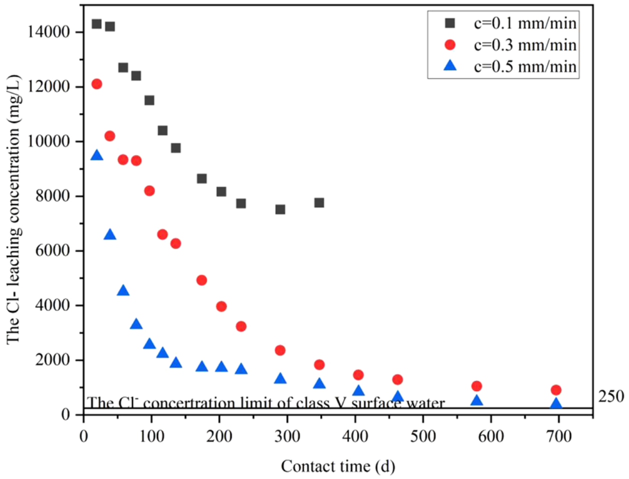


Fig. 6 The Cl$^-$ release concentration in bottom ash at different rainfall intensities

Figure 7 shows the cumulative mass and cumulative leaching rate of Cl$^-$ release from the bottom ash subgrade under different rainfall intensities. The results revealed that under the condition of heavy rainfall (> 0.3 mm/min), the cumulative mass of Cl$^-$ release in the bottom ash subgrade is relatively small, at 2.73 mg/g. The reasons are as follows: under the normal rainfall intensity of $C = 0.1$ mm/min, the soluble salts in the bottom ash subgrade can contact the rainwater for a longer time. In other words, water molecules have more time to penetrate the microcracks and pores on the bottom ash surface to expand the cracks and form water channels on the bottom ash surface. Moreover, the water channel on the surface of the bottom ash particles and the capillary bridge connecting the bottom ash particles contribute to the leaching of the soluble, resulting in more compositions being dissolved and released by the soluble salts in the bottom ash subgrade under normal rainfall (< 0.3 mm/min) than during heavy rainfall. The presence of water channels on the surface of bottom ash particles and the capillary water bridge connecting bottom ash particles facilitate the leaching of soluble components of the bottom ash [13, 29]. Therefore, we can

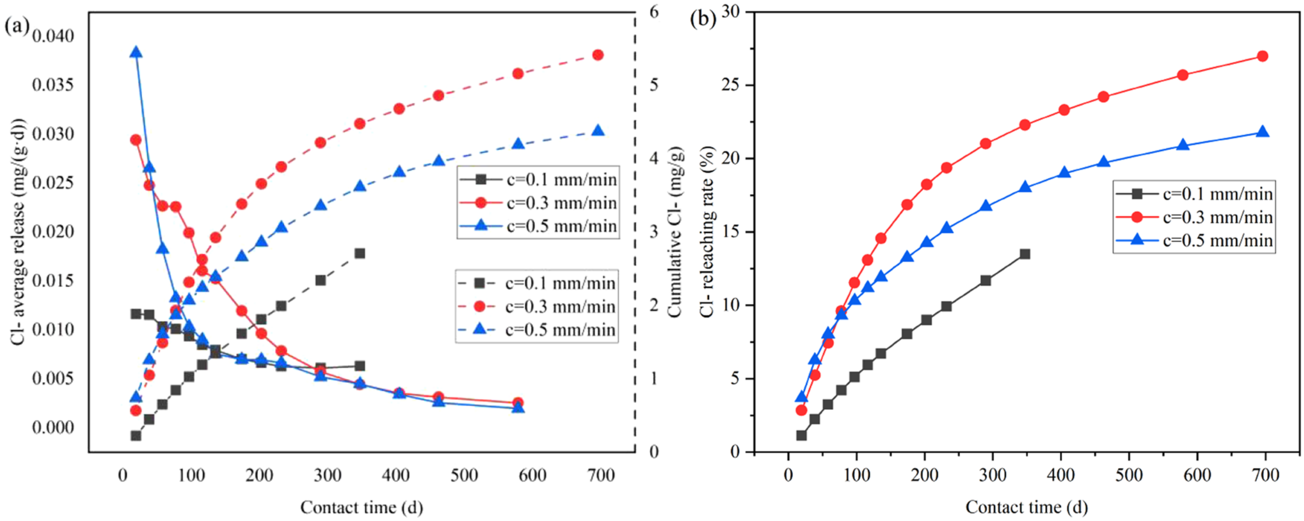


Fig. 7 **a** The cumulative Cl$^-$ release mass (mg/g) and **b** the cumulative Cl$^-$ release rate in bottom ash under different rainfall intensities

draw a preliminary conclusion that long-term normal rainfall (< 0.3 mm/min) will cause greater harm to the surrounding environment. Under long-term normal rainfall conditions, bottom ash can maintain a high Cl^- release concentration for a long time, causing serious pollution to groundwater.

Release characteristics of the total soluble salts in the Big bottom ash column

The Big bottom ash column was designed to simulate the migration behavior of soluble salts in a practical road structure backfilled with 0–5 mm bottom ash under the condition of accumulated water caused by rainfall. To better observe the movement law of the total soluble salts, a 10 cm constant head was employed above the backfilled bottom ash. A solution with pH 5 was prepared to conduct the tests. The concentration variation of the total soluble salts at different column depths was monitored continuously.

Figure 8 shows the volumetric water contents at different depths in the disturbed bottom ash column with contact time. The volumetric water content of the bottom ash closest to the top of the bottom ash column (the first measuring point) changes most significantly in a short time, with a water migration rate of 0.402 mm/min. In addition, the data of high moisture content before 18 h indicate that it is supersaturated. Previous studies have shown that under the condition of constant head flow, the water transfer in the bottom ash is mainly influenced by the matrix potential and gravity potential [30]. In the process of constant head leaching, a large amount of ponding seeps into the bottom ash and migrates under the action of gravity. However, because the matrix suction in the bottom ash is equivalent to the reverse force, the water in the bottom ash does not flow out completely, and part of the water in the bottom ash moves upward through the matrix suction. Therefore, when the volumetric water content of each layer in the bottom ash reaches equilibrium, the water content volume fraction of each layer is different and does not change with the bottom ash height of the soil column, and each layer is stable at 55%–60%.

The distribution curve of the soluble salt content over time in different depth layers of the bottom ash subgrade is shown in Fig. 9. In addition, the soluble salt content in the bottom ash is reflected by the electrical conductivity (EC) value. The results show that the EC value of the bottom ash in the depth layer of each measuring hole decreases significantly within 10 h. With increasing experimental time, a large amount of water infiltrates into the bottom ash, which greatly reduces the soluble salt of the bottom ash at different depths, in good agreement with a previous study [31]. It also illustrated the internal soluble salt leaching process of bottom ash with liquid migrating down. Furthermore, seepage migration is the main driving force of soluble salt migration, indicating that soluble salts migrate with pore water as the bearing medium. In other words, salt seeped down slowly with water migration [32]. The change trend of the soluble salt content of the bottom ash in each depth layer decreases rapidly at the initial stage and then oscillates back and forth slightly until the EC value is close to 0.04–0.07, which indicates that the internal seepage of the bottom ash subgrade is mainly affected by seepage migration, but the salt in the bottom ash is still affected by certain matrix suction, and a small part of the soluble salt still moves upward with membrane water. After 25 h of testing, the soluble salt content in the bottom ash remained stable, and most of the soluble salts that could be released were discharged. Unlike the situation in "Release of Cl^- in bottom ash subgrade under continuous

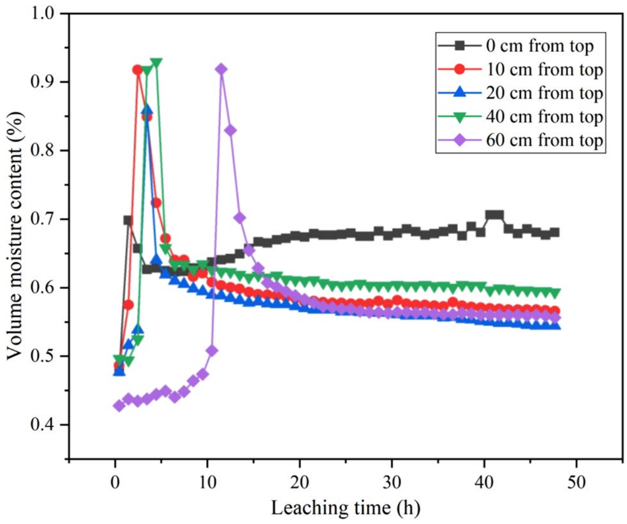


Fig. 8 The change curve of water volume fraction of 0–5 mm bottom ash in each depth layer with time

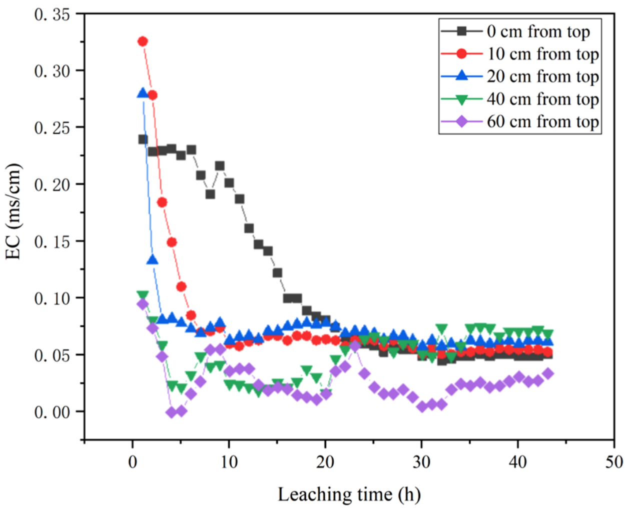


Fig. 9 The change curve of EC value of bottom ash in each depth layer with time. *EC* Electrical conductivity

rainfall", where most Cl⁻ is discharged after 400 days of continuous rainfall under continuous rainfall conditions, soluble salts are rapidly released within 10 h with a rainfall product of 10 mm. After 25 h, most of the transferable soluble salts are basically completely discharged.

In general, there is a negative correlation between the water volume fraction and the total salt content over time. The average infiltration rate of water reaches a maximum within the initial 5 h, resulting in the rapid release of soluble salt components. As shown in Fig. 10, the bottom ash closest to the top of the bottom ash column (the first measuring point) quickly enters the supersaturation state. Because salt migration along with water is the main form of salt migration, the surface layer of the bottom ash particles contains many readily leachable components, which are easily washed out by water in an aqueous environment [27, 28]. Therefore, a large amount of leachable Cl⁻ flowed downward. In the intermediate layer of bottom ash, the seepage rate of water slows down, and the bottom ash is in an unsaturated state. The water molecules had more time to penetrate tiny cracks and pores on the bottom ash surface, enlarging the cracks to form water channels on the bottom ash surface with time. The presence of water channels on the surface of bottom ash and the capillary water bridge connecting bottom ash particles facilitate the leaching of soluble components. In the final stable state, the order of total salt content and water content in each depth layer is not equal, and the salinity gradient between bottom ash layers at different depths also plays a certain role. Under similar conditions, the water content and salt content contained in the bottom ash road base will positively promote each other, making a large amount of soluble salt penetrate into the groundwater, causing certain harm to the groundwater.

Conclusions

This is a novel work that utilizes batch leaching tests, dynamic leaching tests, and constant head tests to simulate the effects of rainfall intensity, duration of rainfall, and rainfall pH values on the leaching behavior of soluble salts in bottom ash roadbeds. The migration characteristics and environmental impact of soluble salt during MSWI bottom ash backfilling and reutilization were studied in detail. The potential leaching toxicity of Cl⁻ and SO_4^{2-} in MSWI bottom ash was analyzed by batch leaching experiments. The Cl⁻ and SO_4^{2-} leaching concentrations are higher than the class V surface water pollutant concentration limit, which reached 514 mg/L and 312 mg/L, respectively. In addition, an experimental setup simulating continuous rainfall was used to investigate the influence of rainfall and acid rain acidity with different intensities on the release behavior of Cl⁻. The results suggest a strong correlation between the release behavior of Cl⁻ and rainfall variations. The acid rain conditions will accelerate the release of dissolved salt from bottom ash to surface water. The contact time between the bottom ash subgrade and rainfall is within 200 days, and the release of Cl⁻ from the bottom ash was strong under acid rain (pH 3, 5), where the average Cl⁻ release was 0.043–0.021 mg/(g day). However, the longer the duration of rainfall, the greater the environmental impact of bottom ash under pH 7 conditions is. The cumulative release rate of Cl⁻ in bottom ash can reach 20%, and the Cl⁻ leaching concentration can still reach 327–1050 mg/L. Regarding the impact of rainfall intensity on the release behavior of Cl⁻ in bottom ash, research has found that long-term normal rainfall (< 0.3 mm/min) will cause greater harm to the surrounding environment. During rainfall for up to 400 days,

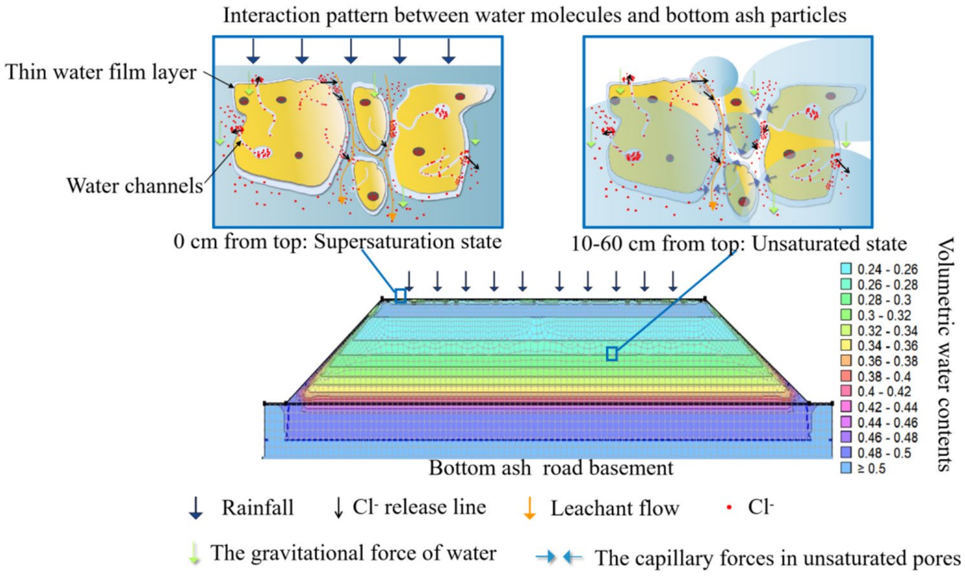


Fig. 10 Schematic diagrams showing mechanism of Cl⁻ release during rainfall simulations

the concentration of Cl^- released in the bottom ash can still reach 3870 mg/L, which is 15.5 times the standard limit. It is obvious that continuous rainfall could cause a serious long-term impact on the application of bottom ash in the process of road backfilling. In addition, if rainfall causes water accumulation, which lasts for more than 12 h, most of the soluble salts will quickly flow into the groundwater, causing serious pollution to the groundwater. The above findings provide the migration and leaching characteristics of soluble salts derived from bottom ash when used in roadbeds under continuous rainfall conditions. Special attention should, therefore, be paid to the environmental impact of soluble salt released into groundwater when using bottom ash roadbeds in areas with normal rainfall intensities and long rainfall durations and in areas prone to waterlogging from rainfall. A proper treatment could be proposed to prevent the release of harmful salt ions into groundwater, thus promoting the further development of MSWI and bottom ash utilization.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Conflict of interest The authors of this manuscript have no conflicts of interest related to the content of the study. Yanjun Hu is the Editorial Board member of *Waste Disposal & Sustainable Energy*.

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