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A Review on the Leaching Behavior and pH Dynamics of Nickel and Copper Contaminated Sandy Soils Stabilized with Cement and Fly Ash.

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ABSTRACT

The review aimed for Nickel- and copper-contaminated soils, particularly sandy ones, are a continuing environmental and health concern due to their highly permeable nature and poor water-holding capacity. This review examined the leaching success and pH behavior of nickel- and copper-contaminated sandy soils stabilized separately using cement and fly ash. Cement stabilization demonstrated a significantly higher soil pH, which contributed to the formation of metal hydroxides, significantly reducing the mobility of both nickel and copper. Despite the low alkalinity of fly ash stabilization, it stabilizes the metals either by adsorption or pozzolanic reactions to reduce their solubility. Leaching behavior varies depending on the type and quantity of binder used, the duration of treatment, the natural soil characteristics, and environmental considerations. Studies have shown that cement and fly ash performed better in terms of stabilization for both binders, with cement appearing to raise the pH more and achieve a higher stabilization rate than fly ash. However, the research indicates a limited number of long-term field studies and an incomplete understanding of stabilization pathways. The research also highlights potential future developments, which could also assist in binder selection, dosage determination, and subsequent application of stabilizers to improve and promote environmentally sustainable practices. In summary, this study provides a foundation for a comprehensive understanding of the mechanisms and influencing factors that regulate the stabilization of sandy soils contaminated with nickel and copper, contributing to more successful contamination remediation experiments.

1. Introduction

Soil pollution is a growing environmental problem caused primarily by human interventions, including the overuse of chemical fertilizers and pesticides, improper disposal of domestic and industrial wastes, and the deposition of untreated wastewater onto land [1]. Soil pollution poses significant risks to human, animal, and plant health, as well as to the quality of surface and groundwater. The most persistent and significant soil contaminants are heavy metals, solid waste, and radioactive elements. These contaminants cause toxicity and long-term degradation of soil quality and function, specifically, the accumulation of contaminant toxicity [2]. Heavy metals, particularly nickel and copper, have increased in soil over the past decade due to industrialization, mining, and urbanization.

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Heavy metals are defined as environmental contaminants that are non-biodegradable and can bioaccumulate in living organisms. Heavy metals can be toxic even at specific concentrations and conditions. Heavy metals can affect soil microbial activity and plant growth, while reducing water quality, potentially having serious implications for agricultural sustainability and environmental stability [3]. The Environmental Protection Agency (EPA) identifies lead (Pb), mercury (Hg), arsenic (As), nickel (Ni), and copper (Cu) as some of the most toxic heavy metals to terrestrial and aquatic systems [4]. Sandy soils are characterized by high porosity, low organic matter, and a low cation exchange capacity, making them particularly susceptible to heavy metal contamination. All three properties increase contaminant mobility and limit the soil's buffering capacity, making remediation options more challenging [5]. Therefore, it is essential to select appropriate remediation options for sandy soils to reduce metal discharge to groundwater and thus reduce environmental risks. Solidification/stabilization (S/S) has been shown to be an acceptable and effective method for remediating contaminated soils by stabilizing heavy metals [6]. This method involves the use of calcium-based binders (such as cement and lime) or industrial by-products (such as fly ash) to reduce contaminant mobility, improve soil mechanical properties, and control pH [7]. Cement and fly ash have achieved impressive results due to their chemical ability to bind metal ions and generate alkaline conditions, leading to the precipitation of metal hydroxides [8]. This research aims to integrate the results of recent laboratory studies that investigated the potential of cement and fly ash for stabilizing sandy soils contaminated with nickel and copper [9]. The research was based on a comparative evaluation of leaching behavior and pH variations as indicators of stabilization performance, as well as the mechanisms and factors affecting stabilization, and potential gaps in current knowledge to better inform future research and enhance the sustainability of remediation practices [10].

2. Sources of Nickel and Copper and their Environmental Impact on Soil

2.1. Sources of Nickel and Copper Pollution

Nickel (Ni) and copper (Cu) are naturally occurring in the Earth's crust, but human activities have disproportionately raised soil levels of copper and nickel, which have increased significantly. Major sources of nickel and copper contamination in soil include industrial discharges. Effluents from smelting, electroplating, and metal finishing can contain high concentrations of nickel and copper [11]. Mining activities such as surface mining, mine tailings dumping, ore processing, and the mining process release heavy metals into the surrounding soil. Furthermore, agricultural inputs, phosphate fertilizers, pesticides, and sludge can add trace amounts of nickel and copper to agricultural soils. Municipal and industrial wastes, landfill leachate, and sewage irrigation have been shown to be major contributors to persistent soil pollution. Fossil fuel combustion, coal-fired power plants, and vehicle exhaust all contribute to the deposition of nickel and copper in soil through atmospheric deposition [12].Cumulatively, anthropogenic metal emissions into soil manifest themselves through the gradual accumulation of metals in the surface and subsurface layers of the soil. For this reason, the latter layer is the most important in terms of metal accumulation, particularly in industrial and urban contexts[13].

2.2. Environmental Behavior of Nickel and Copper in Soil

The mobility and retention of nickel and copper in soil environments may vary depending on soil pH, organic matter, redox potential, and cation exchange capacity[14]. Both metals have low biodegradability; however, they adsorb well to clay minerals and organic colloids[15].However, under acidic or dilute conditions, their mobility may increase significantly, leading to leaching into groundwater sources. Nickel (Ni): Nickel is most often found in soil as Ni^{2+}, which is moderately mobile and can be leached into acidic, sandy, or silty soils. Nickel can also compete with essential nutrients, such as magnesium and iron, disrupting plant energy metabolism. Copper (Cu): Copper typically forms stable complexes with organic matter or clay minerals, and the average mobility of copper in the terrestrial environment is relatively low. However, copper mobility can be increased under certain environmental conditions, including low pH and high chloride concentrations, where copper is more susceptible to leaching. Excess copper has been shown to interact with various types of microbes, including the enzymatic activities of microorganisms, as well as plant species.

2.3. Environmental and Health Risks

Environmental and public health risks associated with nickel and copper contamination have been identified[16].In soil degradation, these two metals can affect microorganisms, enzymes, and nutrient cycling, potentially impacting soil fertility. Plant toxicity. Bioaccumulation of nickel and copper affects plant tissues, inhibiting growth, photosynthesis, and root systems. High concentrations of nickel and copper can lead to necrosis and yellowing. Groundwater contamination: High concentrations of nickel and copper are prevalent in permeable soils such as sand and can permeate aquifers, impacting drinking water sources. Human impacts. Long-term exposure to nickel is associated with dermatitis and respiratory diseases and may be carcinogenic. Copper toxicity can result in liver and kidney failure, gastrointestinal irritation, and neurological syndromes. Because these metals are non-gradual and bioaccumulative, they must be contained and treated to reduce long-term, sustainable threats to humans and the environment.

3. Characteristics of Sandy Soils and Their Susceptibility to Heavy Metal Contamination

3.1. Physical and Chemical Properties of Sandy Soils

Sandy soils have a coarse texture composed of various particles, with diameters typically ranging between 0.05 and 2.0 mm. The coarse texture of sandy soils is characterized by a variety of important physical and chemical properties, the first of which is high permeability, where water and dissolved materials, including contaminants, can quickly flow over the soil surface, increasing the risk of leaching [17].The second characteristic is low water-holding capacity, as sandy soils retain very little water, limiting chemical interactions between soil components and contaminants. Another characteristic is low organic matter content, as organic matter is an important binding agent for heavy metals, and low organic matter content limits the soil's ability to stabilize contaminants [18]. Finally, low cation exchange capacity (CEC), as sandy soils limit the availability of cationic heavy metals, such as Ni^{2+} and Cu^{2+}, due to the limited negatively charged sites on soil particles, and poor buffering capacity, as sandy soils are less able to withstand changes in pH, thus increasing their sensitivity to acidification and metal transport [19].

3.2. Behavior of Heavy Metals in Sandy Soils

Given the above characteristics, sandy soils are particularly susceptible to heavy metal contamination and transport. When heavy metals enter the soil through surface application, atmospheric deposition, or subsurface infiltration, their retention is reduced and their potential to remain in the soil solution increases, increasing their bioavailability[20]. These metals migrate to deeper soil layers or groundwater, especially during rainfall or irrigation. Absorption is limited, especially when the pH is low or the organic content is low. Studies have shown that heavy metals, including nickel and copper, leach more readily into sandy soils than into fine-textured soils such as silt or clay, due to weaker sorption interactions and faster leaching rates.

3.3. Remediation Challenges

Remediation of contaminated sandy soils presents unique challenges due to their low retention capacity, and stabilizing agents may not react homogeneously due to the rapid drainage and loose agglomeration characteristics of sandy soils. Rapid removal prior to stabilization is essential, as there is a high risk of contaminant migration prior to chemical stabilization. Without natural binding agents such as clay minerals and humic substances, the potential for stabilization is limited. These challenges underscore the importance of carefully designing stabilization strategies, such as using cement and fly ash to enhance metal stabilization and altering the soil chemical environment to reduce metal mobility [21].

4. Stabilization of Contaminated Sandy Soils Using Cement and Fly Ash

4.1. Soil Stabilization as a Remediation Technique

Stabilization/solidification (S/S) is a commonly used technique for remediating contaminated soils, reducing contaminant mobility and improving their geotechnical properties [22]. This approach involves agents that physically and chemically interact with waste materials to bind and stabilize the contaminants in the soil matrix. For example, cement and fly ash are binders that have shown great potential for use in remediating sandy soils contaminated with heavy metals [23]. These materials, at least partially, physically bind the contaminated materials into a three-dimensional structure, with an increase in pH and the dissolved metals becoming less mobile or insoluble.

4.2. Stabilization with Cement

Cement is a binder containing a large amount of calcium that undergoes hydration reactions in the presence of water. Cement will react with water to produce calcium silicate hydrate (C-S-H) and calcium hydroxide [$Ca(OH)_2$] [24]. These reactions produce products that help stabilize metals, such as nickel (Ni) and copper (Cu), through three mechanisms. First, raising the pH. The release of $Ca(OH)_2$ will raise the soil pH to alkaline levels (>10), favoring the precipitation of more stable metal hydroxides, for example, $Ni(OH)_2$ and $Cu(OH)_2$ [25]. Second chemical bonding Metal ions can be chemically incorporated into the C-S-H phases through ion exchange or surface adsorption. Third, physical encapsulation: Cement gels can bind soil particles and contaminants and limit their exposure to extractive agents [26]. Research has indicated that the effectiveness of cement increases with its quantity and curing time. Increasing cement content may lead to increased soil fragility and carbon emissions, which is a significant factor in determining environmental sustainability.

4.3. Stabilization with Fly Ash

Fly ash is a suitable pozzolanic material containing amorphous silica and alumina in its chemical composition [27]. Fly ash can be pozzolanic, producing gels of C-S-H and similar compounds, in the presence of calcium hydroxide and moisture [28]. In fly ash-treated soils, typical (cementitious) stabilization mechanisms are typically observed as follows: 1) pH adjustment. While fly ash does not raise the pH as much as cement, it contains residual lime or alkali, which raises the pH to some extent [29]. 2) Adsorption and ion exchange. Fly ash has a large surface area and is chemically reactive, with a known potential for metal and ion exchange, providing opportunities for adsorption. 3) Formation of stable phases. Pozzolanic reactions, which produce less soluble forms of mobile metal ions that bind to the fly ash matrix, are responsible for long-term stabilization. The pozzolanic effectiveness of fly ash varies with chemical composition (Class F vs. Class C), fineness, and dosage. It should not be compared to cement in terms of pH or initial strength, but it is a sustainable and inexpensive solution for mineral stabilization, especially in the presence of many industrial by-products such as fly ash [30].

5. Nickel and Copper Leaching Behavior in Treated Soils

5.1. The Importance of Leaching Behavior in Risk Assessment

Extraction behavior indicates the potential for contaminants, especially heavy metals, to move from the soil matrix to the surrounding environment via water movement. This behavior is critical in assessing the long-term effectiveness of stabilization techniques, especially in sandy soils, where permeability is high and water retention is low [31]. High capacity increases the risk of groundwater contamination. In the context of this review, the extraction behavior of nickel (Ni) and copper (Cu) is a key performance indicator for assessing the effectiveness of soil stabilization using cement and fly ash.

5.2. Leaching in Cement-Stabilized Soils

Extraction in Cement-Stabilized Soils

Cement reduces the extractability of nickel and copper metals through multiple processes in geological formations, sandy soils, and soils in general. The introduction of cement hydration products, specifically calcium hydroxide ($Ca(OH)_2$), raises the soil pH, promoting the precipitation of metal hydroxides[32]. Extraction behaviors include: Nickel (Ni): Under high pH conditions caused by cement, nickel (Ni2+) can exist as $Ni(OH)_2$ and precipitate as an insoluble complex. Nickel solubility is known to decrease significantly above pH 9, resulting in reduced extraction rates. Copper (Cu): Extraction behaviors. Copper (Cu) also behaves in a similar manner, precipitating under alkaline conditions as $Cu(OH)_2$ and basic copper(II) carbonate. Unlike nickel, copper appears to be better absorbed into soil particles, making it less mobile than nickel. Some researchers have shown that more than 90% of the pre-extraction nickel and copper concentrations are recovered and enhanced by cement stabilization at 10% to 20% of the dry soil weight. Long-term TCLP and SPLP-treated soils have been shown to contain no hazardous waste and are safe to use. The composition of the added binders improves metal retention through higher pH[33]. The density of the hydration products increases further with increasing binder content. Longer curing periods have been shown to enhance cementitious systems by promoting hydration, creating durable cementitious frameworks, and preventing metal dissolution. Soil moisture and compaction also play an important role, as appropriate compaction and moisture conditions improve binder distribution and stabilization uniformity[34].

5.3. Extraction in Fly Ash-Stabilized Soils

Although fly ash is less alkaline than cement, it mitigates heavy metal leaching through adsorption and pozzolanic interaction mechanisms [35]. Its high surface area and porous texture, as well as its diverse chemical composition, allow it to adsorb and retain metal ions. Nickel (Ni), with a Ni^{2+} behavior, can adsorb onto fly ash and may form some pozzolanic gels. However, its leaching potential is higher in fly ash-treated soils than in cement-stabilized soils due to the lower pH. Copper (Cu) also has a higher adsorption affinity than nickel and is easier to stabilize. Stabilization efficiency is significantly influenced by the type of fly ash used (Class F vs. Class C) and the concentration of available reactive aluminosilicates. Available studies indicate a reduction in nickel and copper recovery of 40%–80% and 60%–90%, respectively, using 10%–30% fly ash. The increased effectiveness of fly ash is attributed to slower pozzolanic reactions, which enhance bond strength and reduce porosity over time. Low pH: As with cement, fly ash is unlikely to consistently raise pH to levels above which hydroxides precipitate, especially in highly acidic soils [36].

6. pH Dynamics in Stabilized Soils

6.1The Role of pH in Heavy Metal Immobilization

The mobility, solubility, and bioavailability of heavy metals, including nickel (Ni) and copper (Cu), are of concern for soil and agriculture [37]. In general, heavy metals are mobile and bioavailable under acidic conditions and tend to precipitate as hydroxides or carbonates in alkaline environments. Therefore, controlling and maintaining alkaline pH levels in the treated soil matrix is critical for successful stabilization. Both cement and fly ash affect soil pH, but to varying degrees [38]. In addition, several factors, including binder dosage, duration of soil treatment and exposure to the environment, and the buffer capacity of the soil, influence the rate and dynamics of pH change over time.

6.2. pH Dynamics in Cement-Stabilized Soils

Cement hydration generates calcium hydroxide ($Ca(OH)_2$), which immediately raises the soil pH to above 10.5 [39]. This high alkalinity significantly aids nickel and copper stabilization for the following reasons. First, it increases precipitation, as nickel and copper hydroxides (such as $Ni(OH)_2$ and $Cu(OH)_2$) form at high pH and are nearly insoluble. Second, it reduces solubility. The solubility of most metals decreases significantly when pH exceeds 9 [40]. The presence of reactive silica and alumina also enhances the stabilization process by catalyzing pozzolanic reactions. The observed pH changes show a significant increase in pH within the first few days of treatment. This elevated pH level is maintained for a long time, partly dependent on soil carbonation and precipitation. A possible scenario for a slow pH decrease over time is the result of: carbon dioxide ingress leading to the carbonation of $Ca(OH)_2$ to $CaCO_3$, leaching of calcium and hydroxide ions, acid rain, or general environmental exposure. However, cement-treated soils can maintain low alkaline pH levels that protect the cementitious minerals over time.

6.3. pH Dynamics in Fly Ash-Stabilized Soils

Unlike cement, fly ash does not directly produce significant amounts of $Ca(OH)_2$. However, depending on its chemical composition, particularly Class C fly ash, which contains free lime, it may contribute to a moderate pH increase, typically in the range of 8.0–10.0 [41]. pH-influencing mechanisms occur when alkali oxides (such as CaO, K_2O, and Na_2O) in fly ash raise the pH moderately. Pozzolanic reactions between fly ash and the existing $Ca(OH)_2$ ions (if present) consume hydroxide ions over time [42]. This may lead to a gradual stabilization of pH rather than a sudden increase. Adsorption of H^+ ions to the surface of ash particles may contribute to subtle changes in pH. The observed behavior of this effect is that pH increases more slowly than in cement-treated soils. In the absence of a strong alkaline source, fly ash may not consistently maintain pH levels high enough to ensure complete precipitation of all mineral species. Long-term pH trends may stabilize or decline slightly, depending on filtration conditions and environmental exposure [43].

7. Key Parameters Affecting Stabilization Efficiency

The effectiveness of stabilizing sandy soils contaminated with heavy metals using cement or fly ash depends on a combination of physical, chemical, and environmental factors[44]. Understanding these parameters is critical to optimizing the treatment process and predicting long-term performance.

7.1 Binder Type

Choosing the right binder is essential for the success of the stabilization process. As mentioned in previous sections, cement provides rapid strength and high alkalinity, which promotes immediate stabilization through precipitation and chemical bonding [45]. Fly ash also contributes to long-term stabilization through pozzolanic reactions and adsorption, although its performance depends largely on chemical composition and reactivity [46].The choice between cement and fly ash should be based on the following factors: the presence of specific contaminants (e.g., nickel versus copper), the desired stabilization timeline (short-term versus long-term), cost, and environmental considerations.

7.2. Binder Dosage

Binder dosage directly affects the extent of chemical reactions, pH elevation, and the formation of stabilization products. In general, higher binder content results in more effective stabilization and reduced leachability.[47] However, excessive cement dosage can lead to increased brittleness, higher costs, and increased carbon emissions. For fly ash, higher dosages may be required compared to cement to achieve similar stabilization results, especially in the absence of other calcium sources. Optimal dosages vary by site but typically range between 5% and 20% of the soil dry weight [48].

7.3. Curing Time

Curing time allows hydration (in cement) and pozzolanic (in fly ash) reactions to progress. These processes are time-dependent and significantly affect pH stability, the formation of secondary binding phases, and reduced porosity and permeability[49]. Longer curing periods typically result in improved filtration resistance, stronger soil binding matrices, and increased pH stability. Typical laboratory studies evaluate curing times as 7, 14, and 28 days, with particularly notable improvements occurring between 14 and 28 days [50].

7.4. Soil Properties

Soil properties affect both contaminant interactions and the stabilization response. In sandy soils, key properties include texture and particle size. Coarse grains lead to poor adhesion between the soil and the stabilization products, requiring careful binder selection and precise compaction. Moisture content is also important, as sufficient moisture is necessary to activate cement hydration and pozzolanic reactions [51]. Excessively dry and wet conditions can impair the stabilization process. Organic matter is low in sandy soils, limiting the natural mineral adsorption capacity, making chemical stabilization even more important. Acidic soils with an initial pH require more alkaline binders to neutralize the minerals and promote their deposition.

7.5. Compositional Properties

Different minerals exhibit distinct chemical behaviors in response to stabilization. Nickel (Ni) is more mobile in acidic conditions and less adsorbed to soil particles, requiring a higher pH for effective stabilization [52]. Copper (Cu) tends to form stronger complexes with organic materials and is more easily absorbed, even in mild alkaline conditions [53].

7.6. Environmental Conditions

External factors affect the success of long-term stabilization. These include carbonation, where $Ca(OH)_2$ can react with atmospheric $Ca(OH)_2$ to produce $CaCO_3$, which can lead to a decrease in pH over time. Also, rainfall and leaching, where sandy soils have higher water permeability, can contribute to pH changes and slow mineral remobilization. High temperature is also an external factor, as high temperatures can accelerate hydration, as well as hydration and pozzolanic reactions. However, there is an increased need to protect against excessive desiccation and cracking. All of these factors must be considered over the long term and monitored during field work.[54].

8. Limitations of Current Research

Despite significant progress in the development and evaluation of methods for stabilizing heavy metal-contaminated soils, several limitations remain in current research, particularly regarding the use of cement and fly ash as single binders in sandy soil environments [55]. Recognizing these gaps is essential to improve future studies and guide practical applications.

8.1. Limited Field Validation

Currently, field studies are mostly conducted in the laboratory, which is not applicable to all realistic conditions. Factors such as seasonality, rainfall, and microbial processes, as well as soil composition, can significantly influence field stabilization performance. Laboratory conditions are likely to overestimate stabilization effectiveness due to idealized treatment environments and standardized extraction tests. Furthermore, there is a lack of field testing, making it impossible to evaluate study results or estimate long-term stabilization and extraction processes under variable conditions[56].

8.2. Variability in Fly Ash Composition

Fly ash is an industrial by-product consisting of fine ash collected by electrostatic precipitators. Its chemical composition varies significantly depending on the coal source, combustion process, and collection method. Varying amounts of calcium, silica, alumina, and some minor minerals affect the pozzolanic activity and acid-neutralizing ability of fly ash [57]. Most studies do not mention or distinguish the fly ash class used (Class F or Class C), limiting the reproducibility and wider applicability of results. Furthermore, these variations exacerbate the difficulties encountered in regulating fly ash stabilization protocols and the consequent difficulties in obtaining regulatory approvals.

8.3. Short-Term Evaluation

Short curing periods—typically between 7 and 28 days—are the subject of numerous studies. However, this does not reflect the long-term stability of the systems [58]. The responses of fly ash-treated soils persist for weeks or even months. Over a long period, carbonates, acid intrusion, or wet-dry cycles may reduce the leaching resistance and durability of treated soils. It is difficult to assess the sustainability of mineral stability under natural stresses without long-term monitoring periods, which may range from six months to several years.

9. Future Research Directions

Although the stabilization of nickel (Ni) and copper (Cu) in contaminated sandy soils using cement and fly ash has shown promising results in laboratory studies, several gaps and uncertainties remain [59]. Addressing these gaps through future research is essential to improve the reliability, sustainability, and applicability of these remediation technologies under realistic conditions.

9.1. Field Studies and Long-Term Monitoring

Much of current knowledge is based on short-term, small-scale laboratory experiments under controlled conditions. Future studies should conduct field applications to validate laboratory results under varying environmental conditions and monitor long-term performance, particularly pH stability, leaching behavior, and binder degradation over time. They should also assess the impact of climatic factors (such as rainfall, temperature fluctuations, and freeze-thaw cycles) on stabilization effectiveness.

9.2. Comprehensive Evaluation of Binder Performance

Further studies are required to independently verify and compare the effectiveness of fly ash and cement across different soil types and contamination patterns. This includes studying various dosages, curing periods, and combinations of binders, soils, and minerals, and assessing the impact of changing binder compositions especially industrial by-products such as fly ash on stabilization results. The use of alternative or modified binders (such as nano-reinforced materials, geopolymers, or biochar) can improve performance and sustainability.

9.3. Risk-based policies and guidelines

As research advances, it is essential to establish risk-based criteria for assessing the success of soil stabilization [60].

9.4. Understanding the Mechanism Through Advanced Analytical Tools

To better understand how nickel and copper are stabilized, future studies should employ advanced characterization techniques such as X-ray diffraction (XRD) to identify new mineral phases formed during stabilization, using scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) to monitor microstructural changes and elemental distribution (Figure 1).

Update regulatory frameworks to include performance standards for stabilized soil. Encourage the reuse of industrial by-products, such as fly ash, in environmental remediation, while respecting safety and efficacy standards.

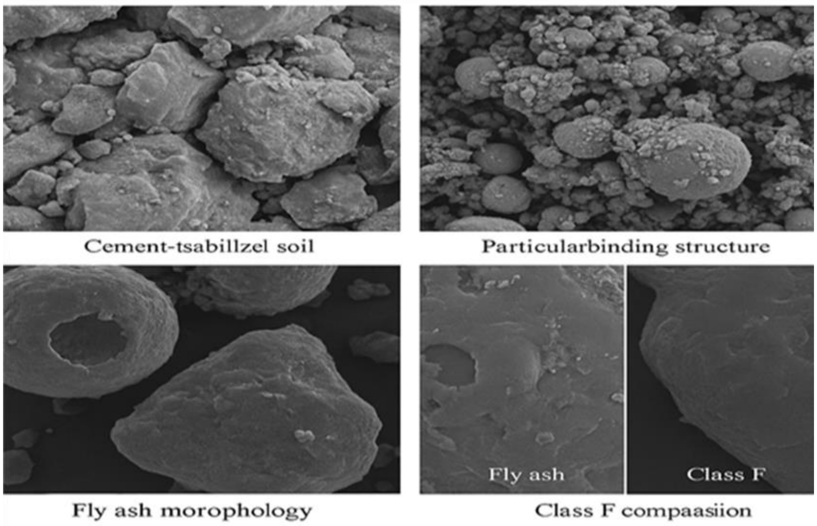

Figure 1. Scanning electron microscope images showing different microstructures related to cement and fly ash stabilization in sandy soil.

10. Conclusion

The high mobility and bioavailability of heavy metals in sandy soils under unfavorable conditions poses significant environmental and health risks, especially when soil contamination inevitably comes into contact with human populations. Sandy soils suffer from a significant drawback in remediation due to their low cation exchange capacity, severe water infiltration and filtration problems, and poor buffering capacity. This review investigated the accumulation and extraction behavior of the typical metals Ni and Cu, along with pH dynamics, in a type of sandy soil contamination stabilization mediated by two well-researched binders: cement or fly ash. In the cement reaction, a significant and immediate increase in pH occurred, leading primarily to the precipitation of hydroxides, while the metal extractability was significantly reduced. On the other hand, low-mineral alkali fly ash (10 mg/kg) has been shown to be more sustainable through adsorption mechanisms and pozzolanic interactions, making it a more economically viable alternative. Furthermore, in some situations, the key factors affecting stabilization efficiency include binder type and quantity, duration of treatment, soil properties, and whether or not the soil is exposed to weather conditions. The use of cement or fly ash alone has been shown to be effective in reducing heavy metal mobility and increasing soil chemical stability. However, limitations related to steel still need to be addressed, such as variability in binder composition, lack of long-term data, and limited mechanical analysis. Future directions should focus on field validation and characterization of advanced materials, and integrating stabilization with other treatment methods. Life-cycle assessments and appropriate regulatory guidelines for these stabilizers should also be developed to ensure their wider adoption and, consequently, their environmental safety. Thus, while cement and fly ash offer effective solutions for stabilizing heavy metals (nickel and copper) in sandy soils, achieving long-term effectiveness and environmental sustainability requires multidisciplinary efforts, technological innovation, and policy support.

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Figure 1. Scanning electron microscope images showing differer ash stabilization in sandy soil.

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