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Effective Use of Inorganic Binders for Stabilization/Solidification of Contaminated Soil: An Overview

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Abstract. Heavy metal pollution of soils is one of the most significant environmental issues since it has the potential to seriously harm the ecosystem and human health. Stabilization/Solidification (S/S) technology is capable of use in engineering procedures due to its ease and cost-effectiveness. In the S/S procedure, an additive is mixed with the contaminated soil to physically or chemically fix the hazardous compounds in a stable state and restrict their migration in the soil. The remediation efficiency of the S/S technique has been achieved by the use of various inorganic binders like cement, lime, fly ash, GGBS, red mud, and other industrial by-products. The current study critically reviews the performance of various inorganic materials as binders to treat contaminated soil using the S/S technique. The efficiency of each binder is assessed in terms of commonly used mechanical and leaching parameters which include the unconfined compressive strength test and TCLP procedure. It was observed that the UCS value increased with the addition of binders, thus solidifying the contaminated soil. Also, the leachability of various heavy metals in soil was found to be within acceptable limits with inorganic binder amendment. This research aids in the understanding of the feasibility of various inorganic binders for heavy metal remediation in soils.

Keywords: unconfined compressive strength; heavy metals; stabilization/Solidification.

1 Introduction

Ex-situ and in-situ remediation techniques have been developed over time to clean up and restore soils contaminated with heavy metals. These techniques include soil washing, stabilization/solidification, electro kinetic extraction, and phytoremediation [1]. In the field, the performance and expense of these techniques vary considerably. Stabilization/solidification is one of the most widely used soil treatment techniques for removing inorganic heavy metals. In this method, the soil's toxic constituents are chemically and physically fixed by lowering their mobility in order to reduce the environmental threat and ensure agreement with existing safety requirements. In addition, stabilized soils may achieve sufficient shear strength for use in construction applications such as engineering fill or pavement material. Furthermore, according to the United States Environmental Protection Agency (USEPA), S/S is the best demonstrated available technology (BDAT) for treating hazardous metals [2], [3].

A great deal of work has already been done on stabilization/solidification techniques all over the world, and many researchers have been experimenting with the use of inorganic binders to obtain stabilized soil that can be used in the future without endangering the environment. An assortment of inorganic binders, including traditional materials such as cement and lime, supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, limestone calcined clay cement (LC3), binders with high phosphate content and iron-containing binders, have been examined for the purpose. These inorganic binders have been found to be effective in achieving the desired result. However, each binder is selectively efficient in immobilizing different heavy metals through particular mechanisms. For instance, W. Li et al. [4] found in their study that CaO and cement were more effective at lowering the leachability of lead and zinc-contaminated soils than MgO, but that MgO was more effective at lowering the leachability of cadmium and manganese contaminated soils than cement. Therefore, in order to achieve satisfactory stabilization/solidification of heavy metal-contaminated soils, it is essential to have a solid understanding of the efficacy of various inorganic binders and the mechanism by which they work.

This article compares various inorganic materials used as binders to immobilize heavy metals in contaminated soil. It describes the benefits and drawbacks of various binders and helps one choose the most appropriate inorganic additive for the stabilization/solidification process.

2 Use of conventional binders

Traditional and most popular binders with excellent stabilization/solidification results include quicklime and ordinary Portland cement. When added to soil, commercial quicklime raises the pH more than any other available additive and at a lower cost. With this additive, remediation might also take less time than with others. These benefits have prompted a number of in-situ and ex-situ studies on the use of lime for the stabilization of heavy metal-contaminated soil. According to a study by Dermatas & Meng [5], quicklime treatment significantly decreased the leachabilities of lead, arsenic, and trivalent chromium in soils while simultaneously increasing their strength.

Another typical binder used in S/S remediation projects is ordinary Portland cement [6], [7]. Cement is a good binder because of its high strength, low permeability, and relatively long lifespan. Cement-based stabilization/solidification has been widely used in the world for about 50 years [8], [9]. Cement makes the inorganic pollutants stable by trapping them in a solid cementitious matrix. Even without the addition of any admixtures, the cement-based S/S technology has been demonstrated to be effective in immobilizing contaminants such as heavy metals. In certain circumstances, however, such as when it is utilized in the presence of organic materials or significant quantities of soluble sulfates, it may only demonstrate a moderate degree of effectiveness. Also, it has been shown that zinc and lead both have a retardant effect on the cement hydration of cement-based S/S treated industrial wastes and heavy metal soils [10], [11]. This could lead to a reduction in strength as well as an increase in the leachability of heavy metals [12]. In addition, the production of cement and lime contributes significantly to the emission of greenhouse gases into the atmosphere as a result of the calcination of limestone and the utilization of fossil fuels [4], [13]. The drawbacks of using traditional materials have led to the search for alternative materials in order to preserve the natural integrity of the environment.

3 Use of low carbon materials

Researchers have been inspired to find alternatives to cement, such as industrial wastes, which are more sustainable and effective stabilizers for a variety of reasons, including cost savings, reduced environmental impact, and improved engineering properties in S/S products.

As binders for the remediation of contaminated soils, various by-products of combustion are being investigated. Some of these byproducts include coal ash, ash from municipal solid waste incinerators, and ash from sewage sludge. Moon & Dermatas [14] used fly ash, lime, and sulfate salts to immobilize lead (Pb), trivalent chromium (Cr^{3+}), and hexavalent chromium (Cr^{6+}) in synthetically contaminated clayey sand soils. Artificial pozzolans found in fly ash, when combined with lime, cause a significant increase in soil strength through cementation. But, when sulfates were present in conjunction with this quicklime-fly ash treatment, an excessive amount of the pozzolanic product ettringite formed, leading to a degradation of the stabilized matrix. Another byproduct of combustion, known as incinerated sewage sludge ash (ISSA), was mixed with OPC and used to treat lead-contaminated soil by J. Li & Poon [15]. The findings demonstrated that the addition of ISSA brought about a reduction in the UCS value of the stabilized soil; however, the overall leachability of lead was shown to be controlled by adsorption and precipitation mechanisms in the S/S soil. Other studies on the use of pozzolanic ash include the work of Moon & Dermatas, H. Q. Liu et al and Zha et al [10], [16], [17]

Ground granulated blast-furnace slag (GGBS), a by-product of the steel industry, is another potential binder to use in place of cement (or lime) when dealing with difficult soils. Because of its high lime content, GGBS can be used to produce calcium silicate hydrate (CSH) gel. It improves strength, reduces permeability, increases durability, and decreases the heat of hydration compared to using just cement. In addition to these benefits, GGBS also has much lower energy consumption and CO_2 emission than cement or lime. In order to modify soil contaminated with different concentrations of heavy metals, GGBS has been used both alone and in combination with other additives. Reza & Movahedrad [18] adopted GGBS alone and GGBS activated with cement (C-GGBS) and MgO (M-GGBS) in the stabilization/solidification (S/S) of zinc (Zn) contaminated clayey soil. It was concluded that activated slag with cement and MgO had higher strength and lower leachability than GGBS alone. Zhang et al. [19] conducted mechanical and environmental tests to compare the performance and mechanisms of CaO-GGBS, MgO-GGBS, and ordinary Portland cement (OPC) for the treatment of Zn-contaminated clay slurry. The results showed that MgO-based GGBS outperformed CaO-activated slag. The microstructural studies revealed that a retarder, calcium zinc hydroxide, was formed during the immobilization process when the CaO-GGBS binder was added, preventing GGBS hydration and resulting in lower strength and higher Zn leachability.

Another low-carbon and low-cost cementitious material, limestone calcined clay cement (LC^3), is being investigated for its potential in S/S of contaminated soils [20]–

[23]. LC^3 is typically a ternary mixture of 30% Calcium carbonate, 15% Lime stone, and 5% gypsum with 50% cement clinker. After a 14-day curing period, the addition of LC^3 causes the soil's pH to change from acidic to alkaline, allowing the adsorption of heavy metals to form various insoluble metal hydroxides.

4 Use of phosphate and iron based materials

It is observed that the use of SMCs tends to slow down the formation of hydration products, reducing the effectiveness of such binders and giving rise to innovative materials containing phosphate and iron that are capable of easily immobilizing heavy metals. Single superphosphate and calcium oxide (SPC) content and curing time were studied by Xia et al [24] for their effects on the pH, leachability, and strength properties of lead, zinc, and cadmium-contaminated soils. It was inferred that in addition to reducing the leachability of Pb, Zn, and Cd, stabilization also increased the pH and unconfined compressive strength (UCS) of the soil. Wang et al. [25] combined industrial waste products (red mud, phosphogypsum, and Portland cement; RPPC) to stabilize/solidify (S/S) multi-metal contaminated soil in their study. All binders were able to produce soil with a strength that met the uniaxial compressive strength requirement of 350 kPa for S/S waste in landfills. According to microstructural analysis, adsorption occurs primarily through the formation of hydration products like ilmenite, ettringite, anhydrite, and hydrated calcium silicate. In another study, soil samples spiked with zinc and lead were used to test the efficacy of a new binder, KMP, made from oxalic acid-activated phosphate rock, monopotassium phosphate, and reactive magnesia binder [26]. Immobilization of Zn and Pb with the KMP binder occurred primarily through the formation of hopeite, scholzite, zinc hydroxide, and fluoropyromorphite in the soils.

5 Conclusion

It is necessary to remediate soil that has been contaminated by heavy metals in order to reduce the risks associated with the contamination, make the land resource available for agricultural production, improve food security, and reduce the number of problems associated with land tenure. In this article, the benefits of utilizing the stabilization/solidification technique for the removal of inorganic contaminants in soil are analyzed and discussed. It has been observed that the stabilization/solidification process is quick, simple, and applicable to a wide variety of inorganic pollutants and that it has costs that are relatively low. This method does not completely remove the contaminants, but it does reduce their mobility and solubility, which in turn limits the amount of toxic pollutants that can move into water and onto plants. Various inorganic materials have been used for this purpose and have proven to be effective in field applications as well. Traditional binders such as cement and lime have been widely used, but due to limitations and environmental side effects, alternatives such as SCMs and phosphate, iron-based materials have been developed and proven effective for stabilizing contaminated soil and producing comparable results to cement. Although a wide variety of inorganic materials have been investigated, it has been found that the efficiency and mechanisms by which the adsorption of heavy metals takes place vary greatly depending on the material. Therefore, making the right choice of binder is essential in order to achieve satisfactory performance from the stabilization/solidification technique when applied in the field.

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