Stabilization/Solidification Remediation Method for Contaminated Soil: A Review

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Abstract. Stabilization/Solidification (S/S) is typically a process that involves a mixing of waste with binders to reduce the volume of contaminant leachability by means of physical and chemical characteristics to convert waste in the environment that goes to landfill or others possibly channels. Stabilization is attempts to reduce the solubility or chemical reactivity of the waste by changing the physical and chemical properties. While, solidification attempt to convert the waste into easily handled solids with low hazardous level. These two processes are often discussed together since they have a similar purpose of improvement than containment of potential pollutants in treated wastes. The primary objective of this review is to investigate the materials used as a binder in Stabilization/Solidification (S/S) method as well as the ability of these binders to remediate the contaminated soils especially by heavy metals.

Keywords: Soft soil, stabilization/solidification, contaminated soils.

1. Introduction

Heavy metal contaminations in soil are causing a serious threat to the environment and human health. However, there are several technologies that have been developed to treat and remediate the contaminated soil. Remediation technologies can be classified according to immobilization or extraction (action that is applied to metals), in-situ or ex-situ (location that is applied to metals) and other types of technologies [1]. The treatments of heavy metal contaminated soils are limited to two main strategies which is immobilization and extraction. Immobilization approaches aim at stabilizing the metals by minimizing the leaching characteristics of the soil matrix and change the metals to less soluble, toxic or bioavailable form in the soil to reduce the risks of human health and the environment [2]. While, extraction approaches are referred to a process that separates the metals from the soil's composition, reduce the concentration of metals as well as reduce the volume of the entire contaminated medium. However, between these two strategies, immobilization approaches is identified to have advantages in terms of cost-effective and environmentally friendly.

Currently, there are several remediation methods that have been implemented using immobilization approaches. One of the promising methods is Stabilization/Solidification method. Hunce et., al. [3] defines the Stabilization/Solidification (S/S) method as a technique that aims in immobilizing contaminaints by converting them into a less soluble form and encapsulating them with the creation of durable matrix. Other research that were done by Lasheen et., al. [4] stated that heavy metal wastes normally needs S/S method processes to reduce contaminant leaching prior to landfill disposal. Another research by Yao et., al. [5] mentioned that the Stabilization/Solidification (S/S) method is commonly used to reduce the mobilization of contaminants within a hardened mass (solidification) and chemical conversion.
of contaminants into less soluble form (stabilization). In the same way, Voglar and Lestan [6] stated that the S/S method has emerged as an efficient technique for the treatment of sites that are contaminated with potentially toxic metals. Therefore, this study were conducted to review the current knowledge on the materials used as a binders in the Stabilization/Solidification (S/S) remediation method focusing on the soil contaminated by heavy metals.

2. Stabilization/Solidification Remediation method
Cement-based S/S technology has been shown to be effective in immobilizing the heavy metals even without additional additives [7]. Du et., al. [8] has studied the leaching behavior of Pb contaminants by using OPC as a binder. This research concluded that at pH 2.0, this strongly acidic condition has resulted in substantial lowered leachate pH and significantly increased the amount of Pb leached. Contradictory to the condition, when OPC was added in S/S sample from 12% to 18%, it resulted in a decreased amount of Pb leached. In another study, Li et., al. [9] concluded that Pb concentration has been leached out from the solidified specimens using OPC as a binder at 109, 83 and 71 mg respectively with cement ratio of 0.2, 0.3 and 0.4. Another research by Wang et., al. [10] has showed an excellent capacity of OPC in remediating the contaminated soil at a 17 year-old site. This research found that the Toxicity Characteristic Leaching Procedure (TCLP) test sample containing Cu, Ni, Zn, Pb and Cd has satisfied the drinking water standard.

Malviya and Chaudhary [11] has also used the OPC to remediate soil that is contaminated by Pb, Zn, Cu, Fe and Mn. As a result, they argued that sample containing OPC at pH ≥ 12 leached less Pb. Then, it was observed that the concentrations of Zn, Cu, Fe and Mn were also decreased in alkaline conditions. This study concluded that the leachability of heavy metals studied are very pH dependent. Similar observation were reported by Voglar and Lestan [6] which showed that concentrations of Cd, Pb, Zn and Ni decreased in alkaline conditions on TCLP extraction and met the regulatory limit for heavy metals in soils.

Furthermore, a part from OPC, there is an interesting study using Calcium Aluminate cement (CAC). Voglar and Lestan [12] studied the use of CAC and pozzolanic cement (PC) as a binder in the S/S sample. The result indicates that there are significant reductions in soil leachability of Cd, Pb, Zn, Cu, Ni and As into deionized water below the limit of quantification. Similarly, Voglar and Lestan [13] stated that there are higher mechanical strength usage of up to 7.65 Nmm$^{-2}$ when using CAC in S/S soil samples. They also argue that S/S with CAC effectively reduces the leachability of Zn, Pb, Cu, As, Cd and Ni. On the other hand, Navarro-Blasco et., al. [14] studied the sorbent capacities of CAC for toxic metals and found that the total uptake of Pb, Zn and Cu could be achieved of up to 3 wt %.

However, there were some researchers who were interested in substituting the cement content with other additives such as fly ash, lime and pozzolan materials. Jing et., al. [15] have studied the effects of Pb leachability in S/S method using OPC, lime and fly ash. As a result, samples containing 10% of lime showed a significant reduction of 43 mg/L Pb concentration compared to samples containing 10% OPC alone with 699 mg/L Pb concentration at 28 curing days. In the same study, the researcher mixed lime and fly ash and found it to have a better result as the reduction of Pb concentration was at it highest at 8 mg/L at 28 curing days. The usage of fly ash was also highlighted by Moon et., al. [16], Anastasiadou et., al. [17] and Xi et., al. [18]. The results indicated that by adding fly ash into the S/S samples, the strength could be enhanced but they argue that the strength of sample was mainly derived from cement. However, by partially replacing the cement with fly ash, it
showed a significant reduction on the leachability. Additionally, concentrations of heavy metals were reduced to below the regulatory limit for TCLP test compared to sample with cement standalone.

Nonetheless, there were also other researchers who tried mixing the OPC with waste materials which are available free of charge. The main objective of using these waste materials was to investigate the ability in the soil remediation process and if it could help in preserving the environment towards a more sustainable circumstance. Yin et., al. [19] have used the admixture of OPC with Rice Husk ash (RHA) to remediate the Pb contaminated soil. The result shows that leachability of Pb from crushed block were reduced due to the incorporation of RHA into the binder system where the Pb concentration was reduced from 3.70 to 1.06 mg/L (deionized water), 0.66 to 0.08 mg/L (acetic acid) and 3.22 to 1.88 mg/l (sulfuric/nitric acid). Another study by Jain et., al. [20] showed the effects of Cr (VI) on solidification and hydration behavior of Ordinary Portland cement (OPC) and rice husk ash (RHA) blended (10%, 20%, and 30%) cement. The result indicates that the addition of RHA accelerates final settings as compared to control samples (OPC), while retardation in setting time has been observed when there is an increase in rice husk ash concentration (10%–30%). Additionally, the TCLP test shows that the retention capacity of OPC and RHA blended samples were in the range of 92% to 99% and the leached Cr (VI) concentration was under the allowable limit (5 mg/l) of U.S. Environmental Protecting Agency (EPA). Table 1 summarizes the overview of soil remediation by S/S method.

**Table 1.** Soil remediation by S/S method over 10 years from 2004 to 2014.

| Binder                     | Heavy metals studied | Findings                                                                 | Location | References |
|----------------------------|----------------------|--------------------------------------------------------------------------|----------|------------|
| OPC, lime and fly ash      | Pb                   | TCLP indicated that Pb final pH divide into acid, neutral and alkaline condition. | USA      | [15]       |
|                            |                      | GANC of S/S materials leached out all Pb concentration                   |          |            |
|                            |                      | In MEP, Pb was leached out in average concentration at 4.8 mg/L.         |          |            |
| Ordinary Portland cement (OPC) | Pb, Zn, Cu, Fe, Mn | Diffusion coefficient of all metals studied was above 11.5 indicating low mobility in cement matrix. | India    | [11]       |
|                            |                      | Sample containing OPC attained the required strength after 28 days of curing. |          |            |
| Quicklime, fly ash         | Pb                   | Test result in leaching indicated that S/S treatment was effective in immobilizing Pb and can be accepted according to leachability index (LX) | USA      | [16]       |
| OPC and Rice Husk ash (RHA) | Pb                  | Results indicates that usage of OPC incorporated with RHA to remediate Pb concentration in S/S method is more favourable in reducing the leachability the usage the OPC standalone | Malaysia | [19]       |
| OPC                        | Cd, Pb, Cu, Ni, As   | Through TCLP, concentration of Cd, Pb, Zn and Ni generally decreased, concentration of As remained unchanged while concentration of Cu increased | Slovenia | [6]        |
| OPC, CAC and Pozzolanic cement (PC) | Cd, Pb, Zn, Cu, Ni, As | TCLP testing reduced soil leachability of Cd, Pb, Cu, Ni and As into deionized water below the limit and produce high value in mechanical strength up to 12 Nmm\(^{-2}\) | Slovenia [12] |
| OPC and Rice Husk ash (RHA) | Cr | Solidification studies show that the compressive strength of controls and rice husk ash blended samples increases with increase in the curing period and maximum strength was observed with 20% RHA blended samples | India [20] |
| Fly ash (FA), bottom ash (BA) and OPC | Cr, Fe, Ni, Cu, Cd, Ba | Cement based S/S exhibited a UCS of 0.55 to 16.12 MPa - UCS was decreased as the percentage of cement reduced - UCS of S/S decreased with partial additional of FA and BA | Greece [17] |
| Calcium Aluminate cement (CAC) and Sulfate Resistant Portland cement (SRC) | Zn, Pb, Cu, As, Cd, Ni | CAC produced S/S soil higher in mechanical strength up to 7.65 Nmm\(^{-2}\) - Result of TCLP indicate that S/S with CAC reduced leachability more than SRC | Slovenia [13] |
| Calcium Alite cement (CAC) | Pb, Zn, Cu | CAC showed good sorbent capacities for the toxic metals where metals were fully retained when added below 3% (w/w) by cement | Spain [14] |
| OPC | Pb | Result shows that the acidic leachant (pH 2.0) altered the leaching behavior of the soil in semi dynamic leaching test | China [8] |
| OPC | Pb | Lead was leach out from 109, 83 and 71 mg to 37, 30 and 25 mg respectively in semi dynamic leaching test | China [9] |
| OPC | Cu, Ni, Zn, Pb, Cd | Result indicates that S/S treatment at 17 year service time satisfied the TCLP standard level where Ni was the most stable with around 40% remained in soil | UK [10] |
| OPC, lime, montmorillonite, diatomite, sepiolite, and fly ash | Pb | Result demonstrate that the additives with mass ratio cement: fly ash: quicklime were found to be the most effective ratio. - Pb contaminated level of 10,000 mg/kg could be successful remediated | China [18] |

### 3. Conclusion

Soil contamination especially by hazardous heavy metals is pointed as a main contributor to environmental problems throughout the world. To ensure that these problems can be reduced and finally be solved, a systematic prevention and remediation methods should be taken. It is evident from this review that S/S remediation methods using various types of binders attempted of addressing these problems. S/S method using OPC are the most frequently studied for the remediation of heavy metals in soil. However, this review have revealed that S/S method using OPC incorporated with other potential additive such as fly ash, bottom ash and lime showed satisfactory results as well as help on reducing the remediation cost. This review also found that the use of recycle material from agricultural waste such as Rice Hush...
Ash (RHA) capable to improve the quality of soil treatment as well as contributed towards a sustainability remediation method.

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