A review of the mechanical and leaching performance of stabilised/solidified contaminated soils

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Abstract

Stabilisation/solidification (S/S) technology, which basically involves chemical fixation and immobilisation of contaminants, mainly metals, in the matrix of cementitious binders, is widely used for treatment of contaminated soils. This paper presents a critical review of the performance of commonly used blended binder systems in S/S technology. The binders considered are Portland cement, and cement-fly ash, cement-slag, lime-slag and lime-fly ash blends. This work compares and evaluates the performance of contaminated soils treated by the binders in terms of commonly used mechanical and leaching properties, including unconfined compressive strength (UCS), bulk density, hydraulic conductivity and leachability. The long-term performance of S/S treated soils is also reviewed. It was observed that the inclusion of slag in a binder blend gave superior performance compared to fly-ash. Generally, the leachability of common contaminants in soil can be reduced to acceptable levels with about 20 - 35% dosage of the different binders. The UCS was observed to be optimum around the optimum water content for compaction. The hydraulic conductivity generally fluctuated around 10^{-9} m/s over time. Long-term performance of treated soils showed consistent effectiveness over a period of 5 - 14 years with the occurrence of fluctuations in mechanical and leaching behaviour owing to the complex nature and variability of S/S treated soils.

This is an author-created version of an accepted manuscript (post-print). A definitive version was subsequently published in the journal, *Environmental Reviews*. The full citation can be obtained using the article DOI: http://dx.doi.org/10.1139/er-2013-0004

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Abstract

Stabilisation/solidification (S/S) technology, which basically involves chemical fixation and immobilisation of contaminants, mainly metals, in the matrix of cementitious binders, is widely used for treatment of contaminated soils. This paper presents a critical review of the performance of commonly used blended binder systems in S/S technology. The binders considered are Portland cement, and cement-fly ash, cement-slag, lime-slag and lime-fly ash blends. This work compares and evaluates the performance of contaminated soils treated by the binders in terms of commonly used mechanical and leaching properties, including unconfined compressive strength (UCS), bulk density, hydraulic conductivity and leachability. The long-term performance of S/S treated soils is also reviewed. It was observed that the inclusion of slag in a binder blend gave superior performance compared to fly-ash. Generally, the leachability of common contaminants in soil can be reduced to acceptable levels with about 20 - 35% dosage of the different binders.

The UCS was observed to be optimum around the optimum water content for compaction. The hydraulic conductivity generally fluctuated around 10^{-9} m/s over time. Long-term performance of treated soils showed consistent effectiveness over a period of 5 - 14 years with the occurrence of fluctuations in mechanical and leaching behaviour owing to the complex nature and variability of S/S treated soils.

Keywords: cement, compressive strength, fly ash, leachability, hydraulic conductivity, slag.

1. Introduction

Stabilisation/solidification (S/S), which usually employs the addition of cementitious binders to contaminated soils in order to immobilise the contaminants present, has emerged as a cost effective and efficient remedial measure for contaminated soils (Al-Tabbaa and Perera 2005a). S/S treatment entails chemical fixation and physical encapsulation of contaminants. The process is aimed at minimising the rate of contaminant migration into the environment or reducing the toxicity. Contaminant migration is restricted by vastly decreasing the surface area exposed to leaching and/or by isolating the wastes/soils within an impervious capsule.

The combined process of stabilisation and solidification usually results in increasing the strength, and decreasing the leachability, compressibility and hydraulic conductivity of the treated material. However, decrease in leachability is the most important factor, since from an environmental point of view; S/S does not make sense when there is no decrease in leachability (Kogbara et al. 2011). S/S is most suitable for the immobilisation of metals, and to a lesser extent for organic contaminants because of the detrimental effects on the hydration and structural formation of the materials (Young 1972). Due to the high pH of cement, the metals are retained in the form of insoluble hydroxide or carbonate salts within the hardened structure. Details on terminology, history, design criteria, binders and contaminant stabilisation mechanisms can be found elsewhere (Wiles 1987; Conner 1990; Glasser 1997; Conner 1998; Conner and Hoeffner 1998; LaGrega et al. 2001; Bone et al. 2004; Shi and Spence 2004; Spence and Shi 2005; Paria and Yuet 2006; Du et al. 2010).

Although there are many reviews on S/S technology, very few have considered in depth, or brought together, the mechanical and leaching performance of contaminated soils treated by different cementitious binders from different studies. Hence, this paper seeks to fill that gap in the literature by providing a critical review of the mechanical and leaching performance of commonly used blended binder systems in S/S technology. Moreover, this work combines information on the key factors that influence S/S treatment of contaminated soils, which are ordinarily the subjects of entire books. This would be invaluable to remediation experts and environmental professionals as it would help in making informed decisions on the application of one binder or another.

2. Overview of S/S binders and stabilisation mechanisms

S/S binders can be divided into two groups, primary stabilising agents and secondary stabilising agents. Primary stabilising agents are those stabilising agents that can be used alone to bring about the stabilising action required. Portland cement (CEMI) and lime are the most common. While secondary stabilising agents includes pozzolanic materials (i.e. materials that react with lime or cement in the presence of water to produce a cementitious compound) like pulverized fuel ash (PFA) also known as fly-ash and ground granulated blast furnace slag (GGBS) (LaGrega et al. 2001), that are not very effective on their own but can be usefully used in conjunction with lime or cement (Bone et al. 2004). The above mentioned binders are the most commonly used although there are several other binder materials for S/S works including natural bentonite clays, organophilic clays, bitumen, cement kiln dust, silica fume and some proprietary binders like Geodur, EnvirOceM, etc. Details on the basic principles of S/S binders, research and applications have been reviewed in state of practice reports (Al-Tabbaa and Perera 2005a, b; Al-Tabbaa and Perera 2005c).

Generally, binders are mixed with wastes or soils containing contaminants with the aim of stabilising and/or solidifying the contaminants by way of immobilising them within the binders. Many contaminated soils are characterised by the concomitant presence of organic and inorganic contaminants. Immobilisation of inorganic contaminants in soils involves both stabilisation and solidification, while that of organics mainly involves solidification only, as chemical bond(s) may not be formed (Wiles 1987). The following mechanisms have been identified as fixation mechanisms involved in the interaction of inorganic contaminants with soils and/or binders. They are: pH-dependent precipitation, redox-controlled precipitation of insoluble compounds, sorption potential and incorporation into crystalline components of the cement matrix (Bone et al. 2004). On the other hand, although organic contaminants are not essentially stabilised, cement-based systems operating at ambient temperatures and pressures in aqueous environments are involved in a few organic reactions. These include: hydrolysis, oxidation, reduction and the formation of organic salts (Conner 1990). Further, organic matter such as humus can retard the hydration of cement due to the action of fulvic and carbonic acids. This can also have a negative influence on characteristics of the cement matrix (de Korte and Brouwers 2009a).

As mentioned earlier, CEMI, PFA, GGBS and lime are the most commonly used binders, either singly or in blended binder systems in the literature. Hence, this paper will focus on studies that have deployed binder blends involving the above-named binder materials for treatment of contaminated soils. It appears that the most common combinations of the above materials in the literature are blends of CEMI-PFA, CEMI-GGBS, lime-PFA and lime-GGBS. CEMI is normally used alone and it is the most commonly used binder for S/S of contaminated soils and have been applied to a greater variety of wastes than any other binder has. Therefore, the section(s) on performance of S/S treated soils will deal with the deployment of the different blended binder systems mentioned above in previous S/S works.

3. Test methods for S/S treated soils

S/S treatment of a contaminated soil is usually designed to satisfy some criteria, which are mainly leachability and strength, depending on the end use of the treated material. In addition to leachability and strength, a range of other properties that could be specified depending on the end use include hydraulic conductivity, bulk density, porosity, compaction, freeze-thaw durability, compressibility, California bearing ratio (CBR), Moisture Condition Value (MCV), etc. Clearly, the leachability of the stabilised/solidified (S/S) soil is the most important design parameter. Two leaching tests in common use are the batch leaching test, BS EN 12457 (BSI 2002), and the tank leaching test, NEN 7375 (Environment Agency 2004). The batch leaching is considered a worst-case scenario since the material is crushed prior to testing hence maximising the leaching potential of contaminants, while the tank-leaching test assesses the leaching potential due to diffusion processes which is likely to be a more realistic scenario in practice. The acid and base neutralisation capacity (ANC/BNC), DD CEN/TS15364 (BSI 2006), and analysis of contaminants in the leachate to assess their availability at pH values of interest is sometimes used.

Hydraulic conductivity, sometimes used interchangeably with permeability, indicates the rate at which water can flow through a material, which is a key variable in environmental behaviour. S/S materials often rely on a reduction of the ingress and egress of water in and out of a monolithic mass of material to reduce leaching potential. Determining the likely permeability of the treated material is therefore especially important in regards to determining the potential for the transport of leachate bearing contaminants to move through the treated material into underlying strata and eventually into groundwater. Thus, hydraulic conductivity is closely related to leachability. The UCS is used as a measure of the ability of a monolithic S/S material to resist mechanical stresses. It relates to the progress of hydration reactions in the product, and durability of a monolithic S/S material, and is therefore a key variable. Bulk density is the mass per unit volume of the material. It can be used together with moisture content and specific gravity to calculate S/S material porosity and degree of saturation. Bulk density can also be used together with mass change factor to calculate volume increase due to S/S treatment (Perera et al. 2005b). It can also be used to determine the volume of wastes to be treated, shipped off site, or returned to the site (Lin et al. 1996).

The properties described above have been reported to be the most commonly used for performance tests. The relevance of other tests, including those above, in the assessment of the effectiveness of S/S processes has been reviewed (Bone et al. 2004; Perera et al. 2005b). Table 1 summarises some available regulatory limits for the most commonly used performance tests. Leaching thresholds are provided for only five metals, Cd, Cu, Pb, Ni and Zn, which are amongst those commonly found in contaminated soils, alongside total petroleum hydrocarbons (TPH) (Kabata-Pendias and Mukherjee 2007). The above-mentioned metals and TPH are the major contaminants of interest in this work.

Table 1. Regulatory limits for mechanical and leaching behaviour

Adapted from (**Kogbara and Al-Tabbaa 2011**)

Performance criteria	**UCS**	**Hydraulic conductivity**	**Cd**	**Ni**	**Zn**	**Cu**	**Pb**
Environment Canada WTC: Proposed UCS before immersion for controlled utilisation (kPa)	440	N/A	N/A	N/A	N/A	N/A	N/A
UK Environment Agency: 28 d UCS limit for disposal of S/S treated wastes in landfills (kPa)	1,000	N/A	N/A	N/A	N/A	N/A	N/A
UK and USEPA hydraulic conductivity limit for in-ground treatment and landfill disposal, respectively (m/s)	N/A	$< 10^{-9}$	N/A	N/A	N/A	N/A	N/A
Environment Canada WTC: Proposed permeability limit for landfill disposal scenarios (m/s)	N/A	$< 10^{-8}$	N/A	N/A	N/A	N/A	N/A
Environmental Quality Standard for inland surface waters (mg/l)	N/A	N/A	0.0045	0.02	N/A	N/A	7.2
Hazardous waste landfill WAC for granular leachability (mg/kg)	N/A	N/A	5	40	200	100	50
Stable non-reactive hazardous waste in non-hazardous landfill WAC (granular leaching) (mg/kg)	N/A	N/A	1	10	50	50	10
Inert waste landfill WAC for granular leaching (mg/kg)	N/A	N/A	0.04	0.4	4	2	0.5

4 Performance parameters of S/S treated soils

4.1 Overview

This section reviews the deployment of the different blended binder systems considered in this work in previous S/S works. As mentioned in section 2, the binders considered are CEMI, CEMI-PFA, CEMI-GGBS, lime-PFA and lime-GGBS blends. The performance of soils treated by the cement and lime-based binders is evaluated in terms of selected performance parameters, which include UCS, leachability, hydraulic conductivity and bulk density. Consequently, sub-sections 4.2.1 – 4.2.5 deals with all four performance parameters for each of the above-mentioned binders. In addition, the variation of these performance parameters in the long-term are also considered. Furthermore, sub-section 4.2.6 provides a comparison of the different binders in terms of the afore-mentioned performance parameters.

Generally, majority of previous studies deploying the afore-mentioned cement and lime-based binders focused on UCS and leachability. This is because both performance parameters are necessary for successful stabilisation and solidification. Few studies include hydraulic conductivity and bulk density among the performance parameters used for evaluating S/S treated soils. Hence, the tables on performance parameters in section 4.2 contain more information on UCS and leachability compared to hydraulic conductivity and bulk density. Furthermore, CEMI has been widely used in S/S treatment of contaminated soils and other hazardous wastes than any other binder (Spence and Shi 2005). As sequel, extensive discussion on the performance properties of S/S treated soils is made in the section on CEMI, and reference to such made while discussing the same properties in the sections on the other binders.

4.2.1 CEMI S/S treated contaminated soils

The details of the soil and binder characteristics, and mix composition and curing age from ten studies, which dealt with S/S treatment of contaminated soil using CEMI, are summarised in Table 2a. Table 2b shows the performance characteristics of the S/S treated soils detailed in Table 2a in terms of the four parameters of interest in this work, namely, UCS, bulk density, hydraulic conductivity and leachability.

After soil particles and contaminants have been wetted by cement grout, the addition of more binder increases the binding force of the particles; hence, UCS increases with binder dosage (Tables 2a and 2b). It is well known that in CEMI, the formation of calcium silicate hydrates (C-S-H) is principally responsible for strength development, and more C-S-H is formed as the binder dosage increases. Most studies on S/S of contaminated soil normally focus on strength and other performance parameters at a standard curing age of 28 days. However, cement hydration reactions continue beyond the standard curing age. These provide the reasons why UCS increases with increase in binder dosage and curing age (Bone et al. 2004; Paria and Yuet 2006). However, although UCS increases with curing age, over a long time as cement hydration approaches completion, the UCS reaches a plateau. This was observed in a study in Table 2b (Al-Tabbaa and Evans 2000; Al-Tabbaa and Boes 2002) where the UCS after 5 years was slightly less than the UCS at 28 months.

Furthermore, the strength level achieved by a stabilised soil depends on the water content of the soil-cement mixture as it is for concrete mixtures. However, there is a dearth of literature on the variation of UCS with water content in CEMI S/S contaminated soil, although there are a few studies on that for uncontaminated soils. It has been reported that the 28-day UCS and other mechanical properties of CEMI-treated contaminated sandy soil was optimum around the optimum moisture content (OMC) for compaction of the S/S treated soil during sample preparation (Kogbara et al. 2010). Moreover, the UCS varies with the soil type, nature, and amounts of contaminants present. A comparison of the soil and binder characteristics and the UCS of three studies in Tables 2a and 2b (Lin et al. 1996; Yilmaz et al. 2003; Kogbara et al. 2010), which employed 20% binder dosage illustrates this. The UCS values in the last two studies (Yilmaz et al. 2003; Kogbara et al. 2010) were close at 2.52 and 2.24 MPa, respectively, while that of the other study (Lin et al. 1996) (8.74 MPa) was markedly different. With sands and gravel, the UCS is higher than with silt and clay. This is due to the effect of particle size, which is also visible in concrete mixtures. However, the presence of fresh hydrocarbon pollution leads to lower UCS values (Al-Sanad and Ismael 1997) as observed in the third study above (Kogbara et al. 2010) which had more gravel content. All the same, it can be deduced from the above that the 1 MPa UCS criterion in Table 1 can be met with 20% CEMI dosage for different soil types and contamination scenarios. The data in Table 2b even suggests that around 10% CEMI dosage could achieve that.

Contaminated soils generally achieve higher strengths after S/S treatment. Without the binder, the soils will usually have lower strength, as they cannot cope with internal tensile forces. However, contaminants in the soil may interfere with the cement hydration process and lead to a more complicated strength development than in uncontaminated cemented soils. The type of metal, the metal concentration, and the cement content are major factors that affect cement hydration and strength (Chen et al. 2010). The interferences of a few contaminants on cement hydration and in turn strength (Trussell and Spence 1994; Tremblay et al. 2002; Bone et al. 2004; Paria and Yuet 2006) are summarised as follows:

- Cd, Cr and Zn have been associated with increased formation of ettringite, which under some circumstances causes expansion and cracking of cement.
- Pb retards cement hydration by precipitating onto the surface of the Ca and Al silicates as insoluble Pb sulphates and carbonates forming impermeable coating, hence high concentrations may cause a weak S/S product.
- Zn effectively prevents appreciable hydration of cement, possibly because of a chemical, rather than physical mechanism.
- Oil and grease and other organic compounds are also known to decrease strength in cement mixtures. This is because hydrocarbons tend to coat cement particles, which delays their hydration and setting time.

In contrast to the above, a different trend in the UCS of CEMI S/S contaminated soil has been reported (Lin et al. 1996). The 7-day UCS of an oil-spiked soil (4% oil content) containing Pb (see Table 2a) was found to be higher than that of the same soil not spiked with oil. The possibility of the presence of Pb leading to a stronger structure in clay-fly ash mixtures has been reported (van Jarsveld and van Deventer 1999). Therefore, it is possible that in the presence of certain concentrations of metals, relatively low levels of hydrocarbon contamination would not cause detrimental effects on the UCS. In other words, although Pb and oil individually reduce the UCS, depending on the concentration, together they may cause an increase in UCS.

Table 2a. Soil and binder characteristics of CEMI S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Lin et al. 1996)	100% sand	Pb: 1,366 TPH: 40,000	13 16.7 20 23.1	0.14	7
(Day et al. 1997)	Relatively dense sand and gravel (other details not specified) pH – 7.75	Cd: 130	35 45	0.21	28
(Al-Tabbaa and Evans 2000)* and (Al-Tabbaa and Boes 2002)*	Made-ground consisting mainly of clayey sand and sandy clay	Cd: 8.7 Cu: 1,264 Pb: 2,801 Ni: 105 Zn: 1,589 Coal tar: 1,400 Mineral oil: 566 Toluene extract: 1,700	9.3 8.5% CEMI, 0.8% bentonite	0.05	Testing at day: 56 784 (2.3 yrs) 1826 (5 yrs)
(Sanchez et al. 2000)	Sandy loam 68% sand, 26% silt, 6% clay	Pb - 49,935	30 33	0.22 0.29	28
(Sanchez et al. 2002)	Purely Sand	As: 3,050 Cd: 3,100 Cu: 2,920 Pb: 2,700 Zn: 3,220	40	0.13	28
(Yilmaz et al. 2003)	Silt, 27% sand, 18% clay, 55% silt	Cd: 970 Cu: 3,640 Pb: 4,380 Zn: 3,760 Cr: 1,410	10 20	0.15	28

Table 2a (continued). Soil and binder characteristics of CEMI S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Shawabkeh 2005)	Model soil 50% sand, 50% clay	Cd 3,000 9,000 18,000	50	0.30	14
(Moon et al. 2010)	55.7% sand, 33.8% silt, 10.3% clay Organic matter content – 0.6% pH – 8.31	Zn 4,973	5 – 30 at 5% intervals	0.50	7 28
(Voglar and Lestan 2010)	Soils from 40 sampling points in Cinkarna brownfield, Slovenia (other details not specified)	Cd: 146 ± 68 Cu: 1,111 ± 1,997 Pb: 26,400 ± 20,140 Ni: 46 ± 16 Zn: 9,979 ± 11,910	15	0.25 to 0.45	28
(Kogbara et al. 2010)*; (Kogbara 2011)* and (Kogbara et al. 2012)*	Clayey silty sandy gravel 65% gravel, 29% sand, 2.8% sand, 3.2% silt Spiked with a mixture of metals and hydrocarbons pH of spiked contaminated soil - 9.83 Organic matter content – 0.22%	Cd: 3467 ± 153 Cu: 3,167 ± 231 Pb: 3,733 ± 208 Ni: 3,567 ± 153 Zn: 4,233 ± 289 TPH: 6312 ± 1482	5 – 20 at 5% intervals	0.13 to 0.19	28 84

W/S: water-to-solids ratio TPH: Total petroleum hydrocarbons *these studies were carried out on the same soil over time

Table 2b. Performance characteristics of CEMI S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	**Final leachate pH**	**Comments on leaching behaviour**
(Lin et al. 1996)	4.78 (13% dosage) 7.47 (16.7% dosage) 8.74 (20% dosage) 10.0 (23.1% dosage)	2.11 2.11 2.11 2.11	2.6 x 10^{-9}	TCLP	Not specified	- All samples passed the TCLP Pb leaching criteria of 5 mg/l. - Four (4) wt% TPH had little effect on Pb leachability. - TPH leachability not studied.
(Day et al. 1997)	4.70 (35% dosage) 5.20 (45% dosage)	Not determined	Not determined	TCLP	Not specified	0.8 and 8.8 mg/kg of Cd leached in 35 and 45% dosage mixes, respectively.
(Sanchez et al. 2000)	Not determined	Not determined	Not determined	ANC	2 – 13	- Pb leaching as a function of pH exhibited characteristic amphoteric behaviour with solubility minima at pH 9. - leachability of treated soils less than that of untreated soil by an order of magnitude within the pH range, 9 – 11. - For pH 5 – 8 and >12, Pb solubility was similar in treated and untreated soils.
(Al-Tabbaa and Evans 2000) and (Al-Tabbaa and Boes 2002)	1.30 (56-d) 3.25 (784-d) 2.97 (1826-d)	Not determined	0.70 x 10^{-9} 0.15 x 10^{-9} 0.31 x 10^{-9}	TCLP NRA leaching test*	10.6 (56-d) 7.5 (784-d) 1826-d not determined	- NRA leaching test after 1,826 days showed: 4.9 mg/kg of Cu, <0.05 mg/kg of Zn, 1.2 mg/kg of Ni and 0.16 mg/kg of mineral oil. Cd and Pb were below detection levels. - TCLP and data from earlier curing ages not determined.

Table 2b (continued). Performance characteristics of CEMI S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Sanchez et al. 2002)	Not determined	Not determined	Not determined	Modified ANC L/S = 5	4 – 12.5	- Metal release was influenced by changes in pH and speciation. Pb and As illustrated the impact of re-speciation due to carbonation. - At pH > 11, Cd solubility increased with pH, and for pH < 11, it decreased with increasing pH. - For pH > 9, Pb solubility increased with increase in pH.
(Yilmaz et al. 2003)	1.15 (10% dosage) 2.52 (20% dosage)	Not determined	Not determined	TCLP Batch leaching L/S = 10	6.1 – 6.8 in TCLP 8.1 – 9.5 in batch leaching	- In all cases, there was > 90% retention of metals in the solidified mass. - 10% binder dosage was inadequate to reduce the leaching of Cd to acceptable levels.
(Shawabkeh 2005)	11	Not determined	Not determined	TCLP	Not specified	- Amount of Cd leached varied with the initial concentration. - 240, 700 and 1,300 mg/kg were leached in increasing order of the initial amount of Cd.

Table 2b (continued). Performance characteristics of CEMI S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	**Final leachate pH**	**Comments on leaching behaviour**
(Moon et al. 2010)	Not determined	Not determined	Not determined	TCLP	5.5 6.5 7.1 8.0 9.8 10.9 pH increased with binder dosage	- No significant difference in leachability of samples cured for 7 and 28-days. - 892 mg/kg Zn was leached out of untreated soil with pH of 4.5. - 440 mg/kg was leached out in the 5% dosage mix, while 4 mg/kg was leached in 5 – 15% dosage mixes. - No leachable Zn was detected at 25 and 30% dosages.
(Voglar and Lestan 2010)	2.15	Not determined	Not determined	TCLP Batch leaching Tank test	Not specified	- The batch and TCLP leaching tests showed that Cd, Pb, Ni and Zn leachability were significantly reduced or below detection limit. - Cu leachability increased after S/S treatment in the batch leaching test but decreased after S/S treatment in the TCLP test. - The predominant release mechanism in the tank test was surface wash-off.
(Kogbara et al. 2010); (Kogbara 2011) and (Kogbara et al. 2012)	*28 (84)-day*† 0.33 (0.4) (5% dosage) 1.68 (2.0) (10% dosage) 1.83 (15% dosage)** 2.24 (20% dosage)**	*28 (84)-day* 1.79 (1.79) 1.81 (1.91) 1.87** 1.74**	*28 (84)-day* 9.7 (17) x 10^{-9} 9.5 (14) x 10^{-9} 4.5 x 10^{-9}** 3.5 x 10^{-9}**	- ANC at 0, 1 and 2 meq/g HNO_3 addition - Tank leaching	6.2 – 12.8	- Water content showed no significant effect on leachability - 20% dosage satisfied most leaching criteria, except for Pb. - predominant leaching mechanism: surface wash-off

ANC: Acid neutralisation capacity (BSI 2006) TCLP: Toxicity characteristic leaching procedure (USEPA 1986) ND: Not determined L/S: Liquid-to-solid ratio

*National Rivers Authority leaching test (Lewin et al. 1994), similar to the batch leaching test (BSI 2002) †Values at optimum moisture content ** 84-day data not available

Similarly, there was no observable effect on the bulk density of the oil-spiked soil with increase in binder dosage (Lin et al. 1996) (Table 2b), as was the case with the same soil without oil contamination. However, a different trend was observed in a soil with much lower (1%) oil content. Bulk density increased with binder dosage between 5% and 15% dosage (Kogbara et al. 2012) (Table 2b). Thus, oil contamination may impede increase in bulk density with increasing binder dosage depending on the oil concentration. Nevertheless, the bulk density of cement-stabilised contaminated soils generally increases with increase in binder dosage as the cement grout easily wets the particles and contaminants. Hence, the more the binder is added, the more void spaces are filled, leading to increase in bulk density with increasing binder dosage. Moreover, the bulk density depends on the particle size distribution of the soil, and the specific density of cement, which is higher than that of soil. Therefore, the bulk density of the mixture will increase with cement content.

The hydraulic conductivity of most S/S treated soils generally fluctuates around 10^{-9} m/s over time (Table 2b). There are not many studies that report hydraulic conductivity results alongside UCS and leachability, since as mentioned earlier, successful S/S treatment is usually assessed by both parameters. Hydraulic conductivity values around 10^{-9} m/s are considered sufficient for recycling of the stabilised contaminated soil, for instance, as a sub-base course in road pavement (Lin et al. 1996). There seem to be conflicting findings as regards hydraulic conductivity changes over time. In one study, the hydraulic conductivity of CEMI-treated soils increased between 28 and 84 days (Kogbara et al. 2012) (Table 2b). While in another, the hydraulic conductivity of cored made-ground samples decreased between 2 and 28 months, and increased between 28 months and 5 years (Al-Tabbaa and Evans 2000; Al-Tabbaa and Boes 2002) (Table 2b). This varied response of the hydraulic conductivity over time has been attributed to a combination of the following factors. The continued hydration of the cementitious constituents causes the hydraulic conductivity to decrease. Further, the long-term interaction between the contaminants and the soil–grout matrix superseding the effect of the continued hydration of the cementitious material, causing an increase in the hydraulic conductivity (Al-Tabbaa and Evans 2000; Al-Tabbaa and Boes 2002). Overall, there appears to be increase in hydraulic conductivity of S/S treated materials over time though not in a manner that is detrimental to recycling them for other uses.

CEMI has been widely used for the treatment of metals in soils as summarised in Table 2. The studies selected focus on the earlier-mentioned most common metals in soils (Table 2a). The studies on leaching behaviour indicate that the amount of contaminant leached from an S/S treated soil depends on the initial concentration present (Table 2b). There is no generally accepted binder dosage limit for the reduction of average levels of contaminant concentrations found in soils. Different studies used different binder dosages and water contents for S/S treatment, depending on the nature and level of the contamination, and the judgement of the S/S treatment designer. Moreover, different leaching tests are also used in the assessment of leaching behaviour, with the results being scenario-specific. Most of previous studies evaluated leachability using the Toxicity Characteristic Leaching Procedure (TCLP) (USEPA 1986). The test was originally designed to simulate leaching from wastes co-disposed with municipal solid wastes in a landfill. However, it has been used for assessment of leaching from contaminated soils, which has little or no relationship with the test's original plan. Especially, as there is increasing inclination towards re-use of stabilised contaminated soil as filler for construction purposes rather than disposal to landfill (Shawabkeh 2005; Voglar and Lestan 2010).

In spite of the above, it can be deduced from the leaching studies (Table 2) that between 15% to 20% binder dosage would be required to reduce the leachability of average metal concentrations found in soils to acceptable levels. There seems to be no significant effect of water content on the leachability of contaminants within the water content range that allows for workability of the soil-cement mixture (Kogbara et al. 2012). In some cases, depending on the pH attained, the leachability of Cu was higher in treated soils than untreated soils (Table 2b) (Voglar and Lestan 2010). Similarly, Pb leachability was found to be the same in both treated and untreated soils at pHs between 5 and 8 and greater than 12 (Sanchez et al. 2000). Similarly, the solubility of Cd and Pb had a minimum around pH 11 and 9, respectively. The leachability of both metals increased with increasing pH beyond the afore-stated pH values (Sanchez et al. 2002) (Table 2b). Hence, it has been suggested that CEMI may not be suitable for soils with high Pb concentrations, depending on the management scenario for the treated contaminated soil. For instance, Pb leachability in S/S treated soil with ≥ 10% CEMI dosage was found to exceed the limit for stable non-reactive hazardous and inert waste landfills (Kogbara et al. 2012). These observations are due to the well-known solubility behaviour of metals as a function of pH (Figure 1). The solubility of these metals decreases with pH up to a value of about 10 or more. Above this pH, the metal solubility increases with pH as the metal cations form complex soluble anions with excess hydroxide anions (Shi and Spence 2004).

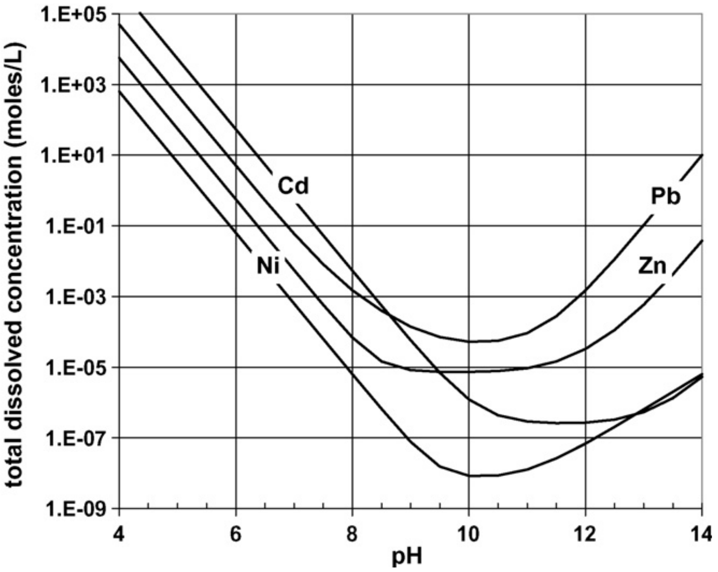


Figure 1. Cd, Pb, Ni and Zn hydroxide solubility at 25°C in dilute solution as a function of pH (Stegemann and Zhou 2009)

It is well known that release of metals from S/S materials is influenced by changes in pH and metal speciation. It has been shown that Cd illustrated the impact of reduced pH without re-speciation, resulting in increased release at lower pHs, while Pb illustrated the impact of re-speciation due to carbonation, resulting in reduced release as a function of pH (Sanchez et al. 2002). Thus, stabilisation of Pb within the S/S matrix occurs by re-speciation with cement constituents. Its release during leaching is governed by solubilisation phenomenon at the interface between the matrix and the leaching solution. This solubilisation phenomenon is controlled by the release of hydroxides, mainly from calcium hydroxide (Sanchez et al. 2000). Similarly, X-ray powder diffraction (XPRD) results have shown that Zn-substituted ettringite and $Zn_6Al_2(OH)_{16}CO_3.4H_2O$ were possible phases responsible for Zn immobilisation in cement-treated soils (Moon et al. 2010).

Very few studies have considered the long-term leaching behaviour of cement-treated contaminated soils. Since cement hydration continues after 28 days, there may be changes in release rates of contaminants from the treated material beyond this time and this must be considered when evaluating leaching data (Bone et al. 2004). Furthermore, acidic influences in the environment, for instance, carbonation by CO_2 uptake, and natural leachants like rainwater or landfill leachate with slightly acidic pH, will progressively lower the pH of S/S soils over time leading to release of contaminants. As a result, there are concerns regarding the long-term effectiveness of S/S treatment due to uncertainties in a number of areas like test methods, observed deficiencies in the process application, observed lack of chemical binding in crushed samples of treated wastes, and uncertainties of performance arising from anticipated behavioural degradation of the material over time (Perera et al. 2005a). Consequently, recent studies have also considered combining S/S and biodegradation in order to achieve some form of (organic) contaminant attenuation over time (Kogbara 2013).

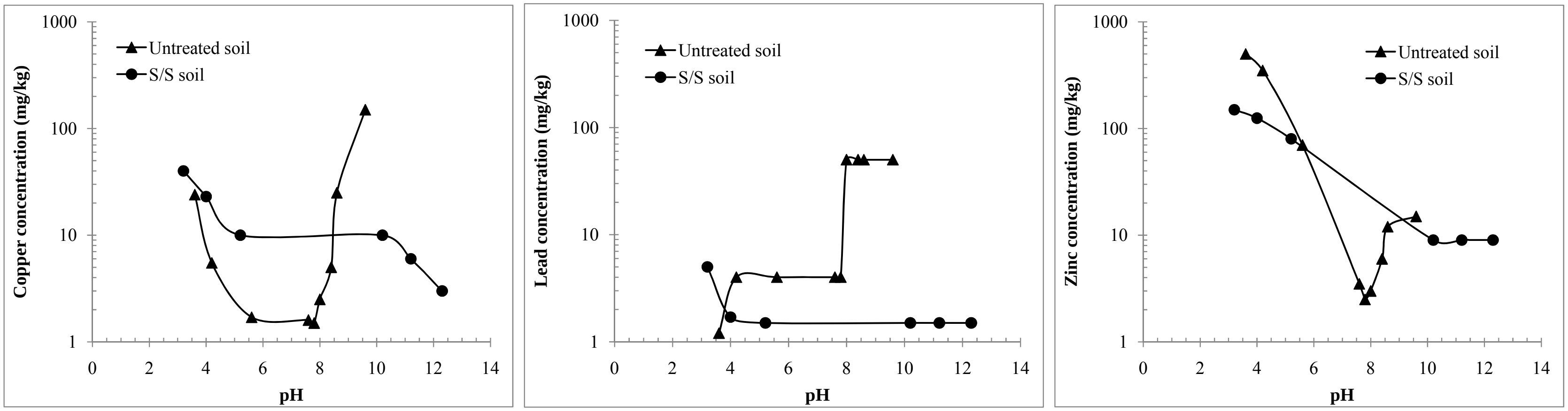
The long-term leaching behaviour of an S/S treated soil was considered in a fairly recent study (Antemir et al. 2010). The study evaluated the field performance of a 4-year old S/S treated contaminated soil at the former Astra military explosives Fireworks site in SE England. A hotspot of metals contamination, containing up to 96,000 mg/kg Cu, 81,000 mg/kg Zn and 750 mg/kg Pb was treated with 20 wt% dosage of EnvirOceM^{TM}, a superfine sulphate-resisting Portland cement at a 0.2 – 0.3 water/cement ratio. The results are summarised in Table 3. The pH-dependent leaching of the metals in the untreated and 4-year old S/S soil is shown in Figure 2.

Table 3. Average concentrations of contaminants in untreated and S/S treated soils after remediation and 4 years later

Adapted from (**Antemir et al. 2010**)

Metal	Concentration in Untreated soil (mg/kg)					Concentration in S/S soil (mg/kg)				
	Deionised water extraction		TCLP		Total	Deionised water extraction		TCLP		Total
	Historical	4-year old	Historical	4-year old	4-year old	Historical	4-year old	Historical	4-year old	4-year old
Cu	0.5	3.9 ± 0.4	3,040	11 ± 0.4	543 ± 142	9.4	6.1 ± 0.2	220	18	228 ± 58
Pb	0.2	0.4 ± 0.1	3.6	2.8	138 ± 15	n.d.	n.d.	0.4	n.d.	85 ± 29
Zn	2	11.7 ± 2.6	7,820	180 ± 33	1,324 ± 144	0.3	0.1	0.4	n.d.	735 ± 79

Initial total concentration of contaminants in untreated soil: 96,000 mg/kg of Cu, 81,000 mg/kg of Zn and 750 mg/kg of Pb



(a)

(b)

(c)

Figure 2. pH-dependent leaching of (a) Cu (b) Pb and (c) Zn in untreated and S/S treated soil (Antemir et al. 2010)

The leachability of the metals remained at low levels after 4 years of S/S treatment. It was observed that the shape of the pH-dependent leaching curves changed dramatically upon S/S treatment, providing a strong indication of different chemical phenomena governing the release of contaminants from the treated material. However, irrespective of this, metal leaching was reduced by one to two orders of magnitude in comparison to the untreated soil, particularly in the alkaline pH range. Metal leaching data in the S/S soil, correlated with the major element concentrations (Ca, Al and Si) in solution, indicating either encapsulation or incorporation in the alumino-silicate hydration phases (Antemir et al. 2010). The observed long-term leaching behaviour of the treated soils was corroborated by recent studies on pH-dependent leaching behaviour of contaminants over an 84-day period (Kogbara et al. 2012). Such studies simulate long-term behaviour of S/S treated soils after they are subjected to acidic influences in the environment. Further work on pH-dependent leaching behaviour of S/S treated soils cured for longer periods is necessary to provide more information on the durability of the treated soils.

4.2.2 CEMI-PFA S/S treated contaminated soils

As in the case of CEMI S/S treated soils, the details of the soil and binder characteristics, of some studies, which dealt with contaminated soil treatment using CEMI-PFA, are summarised in Table 4a. Table 4b shows the performance characteristics of the treated soils detailed in Table 4a. There is a dearth of literature on the optimum ratio of CEMI-PFA mixes for maximum strength in stabilised contaminated soils. However, with uncontaminated soils it is documented that the optimum proportion of PFA in the mix would depend on the chemical, physical and mineralogical properties of the PFA used (Naik et al. 1991). Table 4a shows that despite uncertainties in the optimum mix ratio of CEMI and PFA for effective stabilisation, the choice of mix ratio was between equal proportions of CEMI and PFA (CEMI:PFA=1:1) and 1 part CEMI to 4 parts PFA (CEMI:PFA = 1:4) in majority of the studies. Such choices were made based on the experience of a previous study. There have not been concerted efforts to evaluate the optimum mix ratio before using the binder for S/S of contaminated soil due to the volume of experimental work required. The binder formulations chosen still resulted in acceptable mechanical and leaching properties. Thus, the optimum mix ratio is likely to fall within the afore-stated mix ratios. This is because, generally, without cement, most fly ashes shows very little self-hardening property with curing time due to low free CaO content (Kaniraj and Havanagi 1999) and significant quantities of cement would be required in a mix for optimal performance.

Similarly, there is a dearth of literature on the water content of compaction for maximum strength of CEMI-PFA stabilised contaminated soil. However, in one case, it was observed that the UCS of contaminated sandy gravel treated with the binder (CEMI:PFA=1:4) increased with increasing water content within the range OMC-2 to OMC+5 (Kogbara et al. 2013). This differed from the observation with uncontaminated soil where maximum UCS was obtained on the dry side of OMC for sandy soil stabilised with CEMI:PFA=1:5 binder (Arora and Aydilek 2005). However, it has been shown that generally, the best mechanical and leaching behaviour is obtained around the OMC for different binder systems (Kogbara 2011). Hence, it is for this reason that only OMC values are shown in studies where different water contents were employed in Table 4, for simplicity of the table.

The UCS of CEMI-PFA treated soils was generally less than 1 MPa at 28 days in virtually all the studies in Table 4b, although exact UCS values were not stated in a study (Akhter et al. 1990) where equal proportions of CEMI and PFA was used. This is because PFA addition does not result in high strength in this time frame and strength levels largely depend on the quantity of cement present (Kogbara et al. 2013). However, strength levels increased above the 1 MPa mark at 56 days and beyond but this depended on the nature of contamination in the soil. Soils with high hydrocarbon content had much lower values even after 3 months (Perera 2005; Perera and Al-Tabbaa 2005; Kogbara et al. 2013) (Table 4a and 4b). Especially, where the contaminants were artificially spiked on the soil and did not have sufficient time to interact with the soil. Strength levels were also found to increase with the binder dosage (Kogbara et al. 2013).

As regards long-term strength behaviour, which was considered by a study (Al-Tabbaa and Evans 2000; Al-Tabbaa and Boes 2002) in Table 4, this varied with the mix ratio, specifically the cement content of the two mixes studied. The mix with higher cement content (CEMI:PFA = 3:8) showed a relative increase over the 5-year period, while the strength behaviour of the other mix (CEMI:PFA=1:4) suggest that the strength is reaching a plateau at 5 years (Table 4b). This implies that numerous factors that affect the strength development of the mixes come into play over time, such as interaction with contaminants, and in situ curing conditions. The 5-year strength was between three and six times greater than that at 2 months, which is perhaps an indication of the continual in situ long-term hydration of cementitious materials in the presence of contamination (Al-Tabbaa and Boes 2002).

Table 4a. Soil and binder characteristics of CEMI-PFA S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Akhter et al. 1990)	Loess with 2% organic content (composition and natural pH details not specified)	12,200 each of As and Cr Leachable As: 8,400 Cr: 8,820	30 C:PFA = 1:1	0.29	28
(Al-Tabbaa and Evans 2000) and (Al-Tabbaa and Boes 2002)	Made-ground consisting mainly of clayey sand and sandy clay	Cd: 8.7 Cu: 1,264 Pb: 2,801 Ni: 105 Zn: 1,589 Coal tar: 1,400 Mineral oil: 566 Toluene extract: 1,700	12.5 Two mixes: C:PFA = 1:4 C:PFA = 3:8	0.15	28 56 784 (2.3 yrs) 1,826 (5 yrs)
(Chitambira 2004)	Model soil 49% gravel, 37% sand, 7% silt and 7% clay	Cd – 8.7 Cu – 1,264 Pb - 2,801 Ni – 105 Zn – 1,589 Mineral oil – 566	12.5 C:PFA = 3:8	0.15	28 90 180
(Antemir 2005)	Pepper steel factory site in Florida (soil type not specified)	Pb - 1,728 As – 23.2 Some PCB	16.7 C:PFA = 3:2	Not specified	5,113 (14 years)
(Perera and Al-Tabbaa 2005) and (Perera 2005)	Model soil 49% gravel, 37% sand, 7% silt and 7% clay	Cd – 8.7 Cu – 1,264 Pb - 2,801 Ni – 105 Zn – 1,589 Paraffin oil – 8,700	12.5 C:PFA = 3:8	0.15	28 60 90

Table 4a (continued). Soil and binder characteristics of CEMI-PFA S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Moon et al. 2010)	55.7% sand, 33.8% silt, 10.3% clay Organic matter content – 0.6% Natural pH – 8.31	Zn 4,973	20 Three mixes: C:PFA = 1:3 C:PFA = 1:1 C:PFA = 3:1	0.50	7 28
(Kogbara et al. 2013)	Clayey silty sandy gravel 65% gravel, 29% sand, 2.8% sand, 3.2% silt Spiked with a mixture of metals and hydrocarbons pH of spiked contaminated soil - 9.83 Organic matter content – 0.22%	Cd: 3467 ± 153 Cu: 3,167 ± 231 Pb: 3,733 ± 208 Ni: 3,567 ± 153 Zn: 4,233 ± 289 TPH: 6312 ± 1482	5, 10 and 20 C:PFA = 1:4	0.14 to 0.21 OMC: 0.16 for 5 & 10% dosage, 0.165 for 20% dosage	28 84

C: CEMI PCB: Polychlorobiphenyls TPH: total petroleum hydrocarbons OMC: Optimum moisture content

Table 4b. Performance characteristics of CEMI-PFA S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Akhter et al. 1990)	≥ 0.35* for all mixes	Not determined	Not determined	Modified TCLP L/S = 10	> 5.2 (exact pH not stated)	- 1,014 and 1,170 mg/kg of As and Cr, respectively leached out. - Binder not very effective given the high dosage used.
(Al-Tabbaa and Evans 1998), (Al-Tabbaa and Evans 2000) and (Al-Tabbaa and Boes 2002)	*C:PFA = 1:4* 0.36 (28-d) 1.00 (56-d) 3.15 (784-d) 2.37 (1,826-d) *C:PFA = 3:8* 0.51 (28-d) 1.30 (56-d) 3.50 (784-d) 5.41 (1,826-d)	1.58 for both mixes at 28 days. Data for other time points not available.	*C:PFA = 1:4* 0.72 x 10^{-9} 3.60 x 10^{-9} 0.90 x 10^{-9} 0.86 x 10^{-9} *C:PFA = 3:8* 1.31 x 10^{-9} 0.69 x 10^{-9} 0.78 x 10^{-9} 1.25 x 10^{-9}	TCLP	*C:PFA = 3:8* 10.1 (56-d) 7.2 (784-d) 7.4 (1,826-d) same details not provided for the *C:PFA = 1:4 mix*	- The leachate concentrations of Cu, Pb and Zn after 5 years increased by up to 3, 82 and 104 times, respectively, above their 2-month values. - Leachate pH decreased over time due to carbonation. - The reduction in pH over time caused increase in metal solubility.
(Chitambira 2004)	0.4 (28-d) 2.0 (90-d) 3.8 (180-d)	2.23 (28-d) 2.09 (90-d)	0.85 x 10^{-9} 0.95 x 10^{-9} 180-d value not determined	TCLP Batch leaching	~ 7.3 for TCLP ~ 11.7 for Batch leaching	- Metal retention improved with curing age, especially for Cu, Pb and Zn. - Oil leachability was lower in stronger mixes
(Antemir 2005)	2.22 Average of 5 cores Range: 0.11 – 4.69	Not determined	2.50 x 10^{-8} Range: 1 x 10^{-7} - 3.6 x 10^{-9}	TCLP Multiple Extraction Procedure (MEP)	Not specified	- As levels was below detection limits in both leaching tests. - Pb leachability decreased from 1728 to 4 mg/kg in TCLP.
(Perera and Al-Tabbaa 2005) and (Perera 2005)	0.4 (28-d) 0.7 (90-d) 2.0 (180-d)	1.45 (28-d) 1.40 (90-d)	Not determined	Batch leaching	~ 12	- Only leachability of Pb was investigated. - Pb leachability decreased with time from 140 to 50 mg/kg between 28 and 90 days

Table 4b (continued). Performance characteristics of CEMI-PFA S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Moon et al. 2010)	Not determined	Not determined	Not determined	TCLP	5.3 (1:3) 6.0 (1:1) 7.9 (3:1) Mix ratio in parenthesis	- Zn leachability decreased between 7 and 28 days. - 260, 50 and 50 mg/kg were leached out of C:PFA = 1:3, 1:1 and 3:1, respectively, at 28 days
(Kogbara et al. 2013)	*28-day OMC values* 0.09 (5%) 0.10 (10%) 0.45 (20%) *84-day* 0.30 (10%) 5% & 20% dosage data not available	*28-day OMC values* 1.68 (5%) 1.71 (10%) 1.64 (20%) *84-day* 1.82 (10%) 5% & 20% dosage data not available	*28-day OMC values* Not available 1.58 x 10^{-9} 4.69 x 10^{-9} *84-day* 4.97 x 10^{-9} 5% & 20% dosage data not available	- ANC at 0, 1 and 2 meq/g HNO$_3$ addition - Tank leaching	5.4 – 11.5	- Water content showed no significant effect on leachability - 10% and 20% binder dosage reduced the leachability of metals in the treated soil below that of the untreated soil, but 5% dosage did not. - The binder was quite effective for Pb immobilisation. - The binder was the least suitable for TPH immobilisation among those studied. Leachability increased significantly over time. - The predominant leaching mechanism was surface wash-off in the tank test.

C: CEMI OMC: Optimum moisture content TCLP: Toxicity characteristic leaching procedure (USEPA 1986) ANC: Acid neutralisation capacity (BSI 2006)

* Testing only carried out on mixes with UCS > 0.35 MPa, exact UCS values not provided

The bulk densities of the studies were different, even those that used the same binder dosage and water content (Al-Tabbaa and Evans 2000; Al-Tabbaa and Boes 2002; Chitambira 2004; Perera 2005; Perera and Al-Tabbaa 2005) were markedly different (Table 4b). The difference in bulk density was probably due to differences in the degree of compaction in the studies. The bulk density was observed to decrease between 28 and 90 days in some of the afore-mentioned studies, although other study (Kogbara et al. 2013) recorded an increase in bulk density within the said time-frame (Table 4b). The exact trend for bulk density even with increasing binder dosage (Kogbara et al. 2013) is unclear.

The hydraulic conductivity was generally around 10^{-9} m/s and was similar to those of soils stabilised with CEMI. Its evolution over time was compared between two mixes (Al-Tabbaa and Evans 2000; Al-Tabbaa and Boes 2002). The average hydraulic conductivity of both made ground mixes at 5 years were similar (Table 4b). There was a varied response of the hydraulic conductivity of the mixes over time as it increased between 28 and 56 days in one mix, while it decreased in another. However, it appears that the mix with greater PFA content (CEMI:PFA =1:4) had a more stable evolution over time (apparent decrease beyond 56 days) unlike the other mix whose evolution over time was unclear. Its (CEMI:PFA = 3:8) hydraulic conductivity decreased between 28 and 56 days and increased subsequently, although the 5-year value was quite similar to the 28-day value. The likely reasons for the varied response have been provided in section 4.2.1.

Although, combinations of CEMI and PFA have been used to treat metal sludges, very few studies have deployed the binder for treatment of metals in contaminated soils. A few studies have used PFA alone alongside combining it with lime – e.g. (Dermatas and Meng 2003). PFA addition was found to increase the immobilisation pH region for Pb and Cr. The findings of previous studies (Table 4) show that metal leachability decreases with curing age in contaminated soils treated by the binder. The binder dosage required for effective leachability reduction was between 10 and 20%. However, in a particular case, it was observed that even with 30% dosage, the binder was not very effective for stabilising As and Cr (Akhter et al. 1990). Equal proportions of CEMI and PFA in the mix was found to be more effective in Zn stabilisation than higher proportion of PFA in the mix (Moon et al. 2010) (Table 4b). The binder is also not suitable for TPH immobilisation as TPH leachability increased significantly over time probably due to the binder's low buffering capacity to pH changes (Kogbara et al. 2013).

4.2.3 CEMI-GGBS S/S contaminated soils

Table 5 shows the details of a few studies in which CEMI-GGBS blends were used to treat contaminated soils. Very few published studies have actually deployed CEMI-GGBS blends for treatment of contaminated soils, although it has been shown to be effective in ground improvement, and has been used for other hazardous waste streams. One study (de Korte and Brouwers 2009b) in which CEMI-GGBS was used in combination with lime for contaminated soil treatment is also shown in Table 5.

Bulk density was determined on only two of the studies in Table 5b. It looks like the bulk density increases with binder dosage although there is contradictory evidence between 10 and 20% binder dosage in one of the studies (Kogbara 2011) (Table 5b). All the same, it can be observed that the bulk density increases by only a little amount even with large increases in binder dosage.

Table 5a. Soil and binder characteristics of CEMI-GGBS S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Akhter et al. 1990)	Loess with 2% organic content (composition and natural pH details not specified)	As: 12,200 Cd: 10,000 Cr: 12,200 Pb: 10,900	9 17 30 C:GGBS = 1:1	0.37 0.34 0.29	28
(Allan and Kukacka 1995)	Alluvial with silty to gravelly sand (composition not specified) Natural pH – 8.4	Cr^{3+} : 200 and 1,000 Cr^{6+} : 200, 500 and 1,000	17 33 50 C:GGBS =1:4* C:GGBS =2:3* C:GGBS =3:2*	0.23 0.24 0.24	28
(de Korte and Brouwers 2009b)	Sandy soil, containing clay and poor in humus (natural pH not specified)	Cd – 20 Cr - 28 Cu – 27 Pb – 140 Ni – 22 Zn – 150 Mineral oil - 49	13.6 21.9 C:GGBS: lime = 2:7:1	0.21	28
(Kogbara 2011) and (Kogbara and Al-Tabbaa 2011)	Clayey silty sandy gravel 65% gravel, 29% sand, 2.8% sand, 3.2% silt Spiked with a mixture of metals and hydrocarbons pH of spiked contaminated soil - 9.83 Organic matter content – 0.22%	Cd: 3467 ± 153 Cu: 3,167 ± 231 Pb: 3,733 ± 208 Ni: 3,567 ± 153 Zn: 4,233 ± 289 TPH: 6312 ± 1482	5 10 20 C:GGBS = 1:9	0.13 - 0.20 OMC: 0.16 for 5%, 0.17 for 10% & 0.15 for 20% dosages.	28 84

C: CEMI *Chosen from among many different proportions of CEMI and GGBS since more testing focused on them.

Table 5b. Performance characteristics of CEMI-GGBS S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Akhter et al. 1990)	≥ 0.35 for all mixes	Not determined	Not determined	Modified TCLP L/S = 10	> 5.2 (exact pH not stated)	- 3,900, 9.6 and 0.4 mg/kg of Cd and 2,100, 5.6 and 3.6 mg/kg of Pb leached in 9, 17 and 30% binder contents, respectively. - The CEMI-GGBS blend was observed to be more effective for Pb than CEMI alone.
(Allan and Kukacka 1995)	*C:GGBS=1:4* 8.5 (17% dosage) 12.5 (33% dosage) 24 (50% dosage) *C:GGBS=2:3* 8 (17% dosage) 15 (33% dosage) 29 (50% dosage) *C:GGBS=3:2* 6 (17% dosage) 20 (33% dosage) 35 (50% dosage)	Not determined	*C:GGBS=1:4* 1.1×10^{-7} 9.0×10^{-8} 1.0×10^{-10} *C:GGBS=2:3* 4.0×10^{-7} 9.0×10^{-8} 7.0×10^{-11} *C:GGBS=3:2* 2.0×10^{-7} 7.0×10^{-11} 1.5×10^{-10}	TCLP Tank test	7.5 – 10.7 (17% dosage) 9.2 – 10.4 (33% dosage) 9.7 – 11.3 (50% dosage)	- Concentrations up to 1,000 mg/kg stabilised to give TCLP leachate concentration less than 5 mg/kg in all cases. - Leaching resistance improved with increasing GGBS content. - GGBS caused partial reduction of Cr^{6+} to Cr^{3+}. - Leachability of both Cr(III) and Cr(VI) decreased with increasing GGBS content.

Table 5b (continued). Performance characteristics of CEMI-GGBS S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(de Korte and Brouwers 2009b)	18.6 (13.6% dosage) 30.3 (21.9% dosage)	2.09 2.21	Not determined	Tank test	Not specified	- There was no significant difference in contaminant emission among the two binder dosages used. - 64d emission less than 1 mg/m^2 for all contaminants.
(Kogbara 2011) and (Kogbara and Al-Tabbaa 2011)	*28 (84)-day OMC values* 0.1 (0.13) (5% dosage) 0.5 (0.8) (10% dosage) 0.44 (20% dosage) - No 84-day data for the 20% binder dosage.	*28 (84)-day OMC values* 1.79 (1.92) 1.82 (1.93) 1.69 – No 84-day data for 20% binder dosage.	*28-day OMC values* - 1.09×10^{-8} 4.66×10^{-9} *84-day* 2.14×10^{-8} 28 & 84-day data for 5% dosage and 84-day for 20% dosage not available.	- ANC at 0, 1 and 2 meq/g HNO_3 addition - Tank leaching	5.8 – 11.2	- Water content showed no significant effect on leachability - Leachability of metals was reduced to meet relevant criteria with up to 20% dosage. - The binder was quite effective for Pb immobilisation. - pH-dependent leachability of the metals studied was found to decrease over time. - The predominant leaching mechanism was surface wash-off in the tank test.

C: CEMI OMC: Optimum moisture content TCLP: Toxicity characteristic leaching procedure (USEPA 1986) ANC: Acid neutralisation capacity (BSI 2006)

The UCS behaviour in Table 5b shows that the higher the replacement levels of GGBS in the blend, the lower the strength. This has been attributed to non-optimum gypsum contents particularly at replacement levels in excess of 50% (Cook et al. 1986). However, depending on the total binder dosage, the UCS may decrease with high slag content at higher binder dosages and increase with increasing slag content at lower dosages (Allan and Kukacka 1995). The optimum proportion of GGBS for maximum strength appears to lie between 50 - 60% of the total binder dosage (Allan and Kukacka 1995). Furthermore, the presence of high concentrations of contaminants, especially high hydrocarbon content in the soil leads to very low strength. Hence, the very large differences in strengths between two studies (de Korte and Brouwers 2009b; Kogbara and Al-Tabbaa 2011) (Table 5b) with similar binder dosages.

There are discrepancies between the two studies (Allan and Kukacka 1995; Kogbara and Al-Tabbaa 2011) in Table 5b containing hydraulic conductivity data on the binder. Hydraulic conductivities are higher in the first study (Allan and Kukacka 1995) by more than one order of magnitude, even though it used higher binder dosages. This may probably be due to difference in test facilities as a rigid wall permeameter was used in the first study and flexible wall permeameter used in the other study. This sometimes causes enormous difference in test results (Christopher et al. 2006). Nevertheless, the hydraulic conductivities obtained with flexible wall permeameters, which are recommended for low permeability soils (Christopher et al. 2006), was within acceptable limits (10^{-8} to 10^{-9} m/s, see Table 1).

The findings of the studies show that the binder could effectively reduce the leachability of most of the common metals in soils and was quite effective for Pb, which poses problems during immobilisation in CEMI. The binder also has the potential to partially reduce Cr^{6+} to Cr^{3+} when immobilising the contaminant. A few other studies have reported that GGBS activated by other alkaline materials showed good immobilisation of metals. In one study (Deja 2002), sodium carbonate was used as activator and the binder was doped with up to 2% of Cd, Cr, Pb and Zn, and tank-leaching tests showed immobilisation rates exceeding 99.9%. Another study (Qian et al. 2003) employed sodium silicate-sodium hydroxide solution as activator and the binder was doped with up to 2% Zn. It was observed that chemical fixation mechanisms like the formation of insoluble calcium zincate precipitate and the incorporation of Zn^{2+} into the C-S-H lattice was responsible for the effective immobilisation of Zn^{2+} in the binder matrix.

4.2.4 Lime-GGBS S/S contaminated soils

Most of previous studies utilising lime-GGBS binder for contaminated soil treatment have focussed on the use of lime, since as mentioned in section 2, it is a primary stabilising agent just like cement. Moreover, conventional stabilisation of contaminated soils has been based on lime rather than GGBS. Hence, there are few studies combining both binder materials for contaminated soil treatment. Table 6 summarises the details of some previous studies in this direction. Table 6a indicates that there is a paucity of specific literature on lime-GGBS mixes. The binder has been mostly used for stabilisation of uncontaminated soils (i.e. in ground improvement). With uncontaminated soils, it has been observed that higher UCS is achieved with more GGBS in the mix than with more lime. Previous works on uncontaminated soils suggest that the optimum mix for maximum strength is about one part lime to four parts GGBS (Kogbara 2011). However, the precise relationship between strength and binder components is complex due to interactive effects between the binder components.

Table 6a. Soil and binder characteristics of Lime-GGBS S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Akhter et al. 1990)	Loess with 2% organic content (composition and natural pH details not specified)	As: 12,200 Cd: 10,000 Cr: 12,200 Pb: 10,900	18 L:GGBS =1:35 18.5 L:GGBS =1:17 30 L:GGBS =1:34	0.37 0.37 0.34	28
(Dermatas 1994a; Dermatas 1994b)	Montmorillonite sand Kaolinite sand	Pb: 7,000	5, 10 and 15 Lime	OMC exact value not specified	90
(Yukselen and Alpaslan 2001)	19% sand, 56% Silt, and 20% clay 3% organic matter Natural pH – 2.73 Water content – 15.57%	Cu: 510 Pb:153 Leachable: Cu: 70 mg/l	3.85, 4.76 and 6.25 Lime	Not specified	Not specified
(Alpaslan and Yukselen 2002)	19% sand, 56% Silt, and 20% clay 3% organic matter Natural pH – 2.73 Water content – 15.57%	Pb: 7,700 Leachable Pb: 170 mg/l	1,1.3,2, 2.4,4.8,9.1 and 16.7 Lime	Not specified	Not specified
(Shah et al. 2003)	Loamy silt Natural moisture content – 10.5%	Fuel oil: 100,000 Leachable: 380 mg/l	5, 10 and 20 Lime	OMC value not specified	7
(Moon and Dermatas 2005)	Montmorillonite sand Kaolinite sand	Cr^{3+}: 4,000	10 Lime	Not specified	Not specified
(Schifano et al. 2005)	London clay, pH 11.40 Kaolinite sand, pH ~ 5.5	TPH London clay: 250 Kaolinite sand: 2,370	5, 10, 20 Lime	Not specified	Not specified

Table 6a (continued). Soil and binder characteristics of Lime-GGBS S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Korac et al. 2007)	NS Natural pH - 2	Total: Cu: 1,200 Pb: 700 Zn: 170 Leachable: Cu: 11.3 mg/l Pb: <1 mg/l Zn: 5.7 mg/l	6.25 Lime alone UFS alone L:UFS = 3:1	Not specified	Not specified
(Kogbara 2011) and (Kogbara et al. 2011)	Clayey silty sandy gravel 65% gravel, 29% sand, 2.8% sand, 3.2% silt Spiked with a mixture of metals and hydrocarbons pH of spiked contaminated soil - 9.83 Organic matter content – 0.22%	Cd: 3467 ± 153 Cu: 3,167 ± 231 Pb: 3,733 ± 208 Ni: 3,567 ± 153 Zn: 4,233 ± 289 TPH: 6312 ± 1482	5 10 20 L:GGBS = 1:4	0.13 – 0.20 OMC: 0.18 for 5%, 0.15 for 10% & 0.14 for 20% dosages.	28 84

L: Lime UFS – used foundry sand (by-product of iron and steel industry just like GGBS) OMC: Optimum moisture content

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Table 6b. Performance characteristics of Lime-GGBS S/S treated contaminated soils

Reference	**UCS (MPa)**	**Bulk density (Mg/m^3)**	**Hydraulic conductivity (m/s)**	**Leachability**		
				Major leaching test(s)	**Final leachate pH**	**Comments on leaching behaviour**
(Akhter et al. 1990)	≥ 0.35* for all mixes	Not determined	Not determined	Modified TCLP L/S = 10	> 5.2 (exact pH not stated)	- 1,640, 1,850 and 1.6 mg/kg of Cd leached from the 18, 18.5 and 30% dosage mixes, respectively. - 70, 40 and 6 mg/kg of Pb leached from 18, 18.5 and 30% dosage mixes, respectively. - The binder was quite less effective for Cd immobilisation at lower dosages.
(Dermatas 1994a; Dermatas 1994b)	Not determined	Not determined	$1x10^{-5}$ to 4 x 10^{-7} for mont-morillonite sand $1x10^{-5}$ to $2x10^{-5}$ for kaolinite	TCLP Tank test	5 – 12	- Effective binder dosage: ≥10%. - TCLP Pb leachability < 5 mg/l. Negligible Pb leaching in Tank test. - Pb leachability was influenced by clay mineral; pH controlled.
(Yukselen and Alpaslan 2001)	Not determined	Not determined	Not determined	TCLP	5 – 6 for 3.85 to 6.25% lime dosages.	- Effective binder dosage: 6.25%. - 94% reduction in Cu leachability. - Pb concentration in leachate too low.
(Alpaslan and Yukselen 2002)	Not determined	Not determined	Not determined	TCLP	12.5 – 13 for 4.8, 9.1 & 16.7% lime dosages. 5 – 6 for 1 to 2.4% lime dosages.	- Effective binder dosage: ≥ 4.8%. - 82 – 93% reduction in Pb leachability. - Precipitation as $Pb(OH)_2$ and encapsulation controlled leachability.

Table 6b (continued). Performance characteristics of Lime-GGBS S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Shah et al. 2003)	0.08 (5% dosage) 0.11 (10% dosage) 0.12 (20% dosage)	Not determined	Not determined	Flow through	Not specified	Treatment with 10% lime dosage caused 87% reduction in leachable oil concentration.
(Moon and Dermatas 2005)	Not determined	Not determined	Not determined	Tank test	Not specified	- 94% reduction in Cr^{3+} leachability. - Cr^{3+} leachability not influenced by clay mineral after lime treatment.
(Schifano et al. 2005)	Not determined	Not determined	Not determined	Batch leaching	NS	- 87% reduction in TPH concentration for London clay. - 80% TPH reduction for kaolinite sand. - TPH reduction was independent of binder dosage.

Table 6b (continued). Performance characteristics of Lime-GGBS S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	**Final leachate pH**	**Comments on leaching behaviour**
(Korac et al. 2007)	Not determined	Not determined	Not determined	Column test	12.5 lime-treated, 4 UFS-treated, 11 lime-UFS treated	- Lime treatment yielded 98% Cu and 72% Zn reduction, while lime-UFS treatment gave 78% Zn reduction, Cu leachability was below detection limit. - Leachability of Cu and Zn higher in UFS-treated soil than in untreated soil.
(Kogbara 2011) and (Kogbara et al. 2011)	*28 (84)-day OMC values* 0.04 (0.2) (5% dosage) 0.4 (0.8) (10% dosage) 0.8 (20% dosage)**	*28 (84)-day OMC values* 1.72 (1.74) 1.75 (1.79) 1.68**	*28-day OMC values* 1.22 x 10^{-8} 4.05 x 10^{-8} 5.42 x 10^{-8} *84-day*** 1.45 x 10^{-7} (5% dosage) 7.31 x 10^{-8} (10% dosage)	- ANC at 0, 1 and 2 meq/g HNO_3 addition - Tank leaching	5.8 – 12.2	- Water content showed no significant effect on leachability. - The binder showed the potential to reduce TPH leachability to some extent. - The binder had problems with Pb immobilisation due to its high pH regime, similar to CEMI. - Differences in leachability of contaminants over time were not statistically significant.

OMC: Optimum moisture content
TCLP: Toxicity characteristic leaching procedure (USEPA 1986)
ANC: Acid neutralisation capacity (BSI 2006)
*No 84-day data for 20% binder dosage
UFS – used foundry sand (by-product of iron and steel industry just like GGBS)
TPH: Total petroleum hydrocarbons
** Testing only carried out on mixes with UCS > 0.35 MPa, exact UCS values not provided

Table 6b shows that lime and lime-GGBS blend gives relatively low strength, especially when used for treatment of soils with large amounts of hydrocarbons (Shah et al. 2003; Kogbara et al. 2011). UCS, bulk density and hydraulic conductivity were not determined in majority of the studies in Table 6. Further, there is generally a paucity of data on the mechanical performance of lime or lime-GGBS treated contaminated soils. This is probably because the studies, which mostly utilised lime alone, focused on reducing granular leachability in soil and were not so concerned about mechanical performance of the treated soils.

It can be seen from two studies (Dermatas 1994a; Kogbara et al. 2011) (Table 6b) that considered the hydraulic conductivities of lime and lime-GGBS treated soils that the binder results in high hydraulic conductivity compared to cement-based binders. In one case (Kogbara et al. 2011), the hydraulic conductivity appears to increase with binder dosage and curing age. Such increased hydraulic conductivity is associated with the presence of lime. The reaction of lime with soil particles, especially clays, leads to agglomeration and flocculation of clay particles with a consequent reduction in the plasticity and an increase in shear strength of soils. This in turn leads to increase in permeability with lime addition (Kogbara 2011). However, there is little information on the effect of lime addition on sandy and gravelly soils that was studied in the above work. In a related study on ground improvement, it was observed that lime addition reduced the permeability of poorly graded river sand and increased that of sandy silty clay (El-Rawi and Awad 1981). Further, there existed a moulding water content at which the permeability of the lime-sand mixture reached a minimum. Thus, more work is required in this area to fully elucidate the effect of lime-GGBS binder on hydraulic conductivity in different soil types.

The major contaminants frequently treated by lime are Pb and Cu, and about 10% lime dosage would be effective in significantly reducing their leachability. Lead (Pb) was found to present problems during immobilisation with lime-GGBS (Kogbara 2011). Low binder dosage may satisfy certain leaching criteria but higher dosage may not, especially where the pH attained by higher binder dosages corresponded to the zone for increased Pb leachability (see Figure 1). However, it has been shown that the mechanism of Pb immobilisation in lime-stabilised soil is not only through precipitation as $Pb(OH)_2$ at alkaline pH but also encapsulation within the crystal structure of the cementitious compounds formed. Hence, significant reduction in Pb leachability could still be achieved at pH values greater than the pH (9.5–11) range, where $Pb(OH)_2$ is least soluble (Rha et al. 2000; Alpaslan and Yukselen 2002). The type of clay mineral present in the soil also controls Pb leachability (Dermatas 1994a; Dermatas 1994b). Lime has also shown potential for reducing TPH leachability to some extent, although the reduction was found to be independent of binder dosage (Schifano et al. 2005).

4.3.5 Lime-PFA S/S contaminated soils

Table 7 summarises the details of some contaminated soils treated by lime-PFA blends. It looks like lime-PFA blends have been deployed more for S/S treatment of contaminated soils than lime-GGBS blends. Most of the studies on lime-PFA binder deployed it for treatment of As, Cr and Pb contamination. Thus, although this review does not focus on As and Cr, they will be briefly discussed in this section. There are very few studies dealing with the other most common metals, Cd, Cu, Ni and Zn. One of such studies (Feigl et al. 2010) employed the binder for about 99% reduction of the leachability of very low levels of Cd (0.4 mg/l), Cu (1.5 mg/l) and Zn (89 mg/l), coupled with phytostabilisation.

Table 7a. Soil and binder characteristics of Lime-PFA S/S treated contaminated soils

Reference	Soil type and composition (including natural pH and other details if stated)	Initial amount of prime contaminants (mg/kg)	Binder dosage (%)	W/S ratio	Curing age (days)
(Akhter et al. 1990)	Loess with 2% organic content (composition and natural pH details not specified)	As: 12,200 Cr: 12,200	30 L:PFA = 1:5 34 L:PFA = 1:5	0.34 0.34	28
(Dermatas and Meng 2003)	Kaolinite sand (composed of clay and fine quartz sand)	Pb: 7,000 Total Cr: 1,945	35 L:PFA = 1:2.5	OMC value not specified	28
(Shah et al. 2003)	Loamy silt Natural moisture content – 10.5%	Fuel oil: 100,000 Leachable: 380 mg/l	20 L:PFA = 1:1 L:PFA = 3:1	OMC value not specified	7
(Dermatas et al. 2004)	Kaolinite sand (composed of clay and fine quartz sand) pH: 4 – 6.5	As: 124	35 L:PFA = 1:2.5	OMC value not specified	90
(Jing et al. 2006)	Soil from Cr-contaminated industrial waste site (details not specified)	Cr: 1,330	25 L:PFA = 1:4	OMC value not specified	28
(Moon and Dermatas 2006)	Kaolinite sand (composed of clay and fine quartz sand)	Pb: 7,000	35 L:PFA = 1:2.5	OMC value not specified	28

L: Lime OMC: Optimum moisture content

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Table 7b. Performance characteristics of Lime-PFA S/S treated contaminated soils

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Akhter et al. 1990)	≥ 0.35* for all mixes	Not determined	Not determined	Modified TCLP L/S = 10	> 5.2 (exact pH not stated)	- 4,020 mg/kg of As leached from the 30% dosage mix. - 5,300 mg/kg of Cr leached from the 34% dosage mix. - The binder showed poorer As & Cr leachability performance compared to others tested.
(Dermatas and Meng 2003)	6.66	Not determined	Not determined	TCLP	3 – 13 leachability evaluated over the above pH range.	- The binder reduced the leachability of Pb below the TCLP regulatory benchmark of 5 mg/l. Pb immobilisation was ensured if the treatment TCLP pH was kept between 8 and11. - Adsorption was predominant Pb immobilisation mechanism at pH > 9. The binder widens Pb immobilisation range from 5 to 13. - Total Cr leachability was reduced by 99.7% of the initial amount.
(Shah et al. 2003)	0.11 (L:PFA = 1:1) 0.12 (L:PFA = 3:1)	Not determined	Not determined	Flow through	Not specified	- Leachability was not evaluated for lime-PFA mixes as it was done for only selected mixes. A combination of lime:PFA:cement = 2:1:1 was found to give better leachability results (92% reduction) than lime alone.

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663 **Table 7b (continued). Performance characteristics of Lime-PFA S/S treated contaminated soils**

Reference	UCS (MPa)	Bulk density (Mg/m^3)	Hydraulic conductivity (m/s)	Leachability		
				Major leaching test(s)	Final leachate pH	Comments on leaching behaviour
(Dermatas et al. 2004)	Not determined	Not determined	Not determined	Semi-dynamic leaching test (ANS 1986)	10.5	- There was no significant effect on reduction of As emission even with 35% of the binder. - Precipitation as low soluble Ca-As compounds was the dominant release mechanism.
(Jing et al. 2006)	1.43	Not determined	Not determined	TCLP ANC	8.74	- Release of Cr(III) controlled by adsorption on Fe oxides at pH<10.5, and precipitation of $Ca_2CrO_5.6H_2O$ at pH > 10.5. - There was 60% reduction in TCLP Cr concentration from 104 mg/kg to 42 mg/kg.
(Moon and Dermatas 2006)	Not determined	Not determined	Not determined	Semi-dynamic leaching test (ANS 1986)		- The controlling mechanism of Pb immobilization appeared to be precipitation. The formation of Pb_2SiO_4 (a very insoluble compound) was observed. - The controlling leaching mechanism of Pb was diffusion.

664 * Testing only carried out on mixes with UCS > 0.35 MPa, exact UCS values not provided TCLP – Toxicity characteristic leaching procedure (USEPA 1986)

665 TPH: Total petroleum hydrocarbons

It has been suggested that a mix ratio of one part lime to two and half parts PFA (lime:PFA = 1:2.5) is the optimum dose for treatment of hexavalent Cr-contaminated soil (Kostarelos et al. 2006). This may reasonably apply to other metals since majority of the mix ratios in Table 7a contain no more than five parts PFA to one part lime. There are very few 'easily accessible' studies on the mechanical behavior of soils treated with the binder. This can be seen in Table 7b, as it contains no information on the bulk density and hydraulic conductivity of the treated soils. All the same, Table 7b shows a reasonable UCS level of 1.43 MPa at 28 days (Jing et al. 2006) with 20% dosage. A much higher value (6.66 MPa) (Dermatas and Meng 2003) was even obtained with the afore-mentioned optimum mix for Cr-leachability reduction. These compare favourably with the UCS values for CEMI-PFA mixes in Table 4b.

With respect to leachability reduction, it appears that the mix ratio of the binder constituents significantly affects the leaching results, especially for Cr. With comparable (~35%) dosages of the binder, it showed poorer (57%) TCLP Cr leachability reduction in one study (Akhter et al. 1990), which employed a mix ratio of lime:PFA = 1:5. This compares with the 60% reduction with a lime:PFA = 1:4 mix obtained elsewhere (Jing et al. 2006), albeit with a lesser (25%) binder dosage. While in another study (Dermatas and Meng 2003), a 99.7% TCLP Cr leachability was obtained with a lime:PFA = 2.5 mix ratio. However, this differences may also depend on the initial contaminant concentration as the contaminant concentrations in the two studies with similar binder dosages (Akhter et al. 1990; Dermatas and Meng 2003) was largely different.

Lime-PFA blends do not seem to be very good for As immobilisation as they showed no significant difference to untreated soils even at 35% dosage addition (Akhter et al. 1990; Dermatas et al. 2004). The binder even mobilised As concentrations to higher levels than in untreated soil (Feigl et al. 2010). Conversely, the binder is quite effective for Pb immobilisation as it even widens the immobilisation pH range. This is due to its fly ash content, which forms pozzolanic products that either adsorb Pb on to fresh surfaces or incorporate Pb by means of chemical inclusions. Additional pozzolanic product formation with increasing curing age further increases the amount of non-extractable Pb (Dermatas et al. 2006).

4.3.6 Comparisons between binders

This section synthesizes information in the previous sections to provide a comparison of the effectiveness of the five different binder systems in terms of the key mechanical and leaching properties considered. Table 8 summarises the comparisons between the binders and provides useful information to help in the choice of one binder over another, depending on the contaminated soil management scenario. Bulk density is not included in the table, as it is not considered to be of utmost importance in assessment of the effectiveness of S/S treated soils, compared to UCS and hydraulic conductivity. Hence, it was not determined in most of the studies in the tables on performance characteristics of S/S treated soils.

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Table 8. Comparisons of the performance characteristics of different binder systems

Binder system	Strength behaviour	Hydraulic conductivity behaviour	Leaching behaviour
CEMI	- 28-day UCS can range from 300 kPa for 5% binder dosage to around 11 MPa for 50% binder dosage. - As with all binders, the UCS depends on the type of soil and would be significantly reduced if treating soil with fresh hydrocarbon contamination. - Can easily meet the 1 MPa UCS criteria with around 10% binder dosage. Further, there is significant strength gain with time.	- Hydraulic conductivity values at 28 days are in the 10^{-8} to 10^{-9} m/s range. This would satisfy criteria for recycling options, especially in construction works. - The hydraulic conductivity may increase by about half to one order of magnitude over time.	- It is a very versatile and dependable binder that can be used for reducing the leachability of a wide range of metals. - It usually presents problems with Pb immobilisation, such that higher binder dosages increase Pb leachability beyond acceptable levels. Hence, it is not suitable for soils with high Pb concentrations. - It also has fair stabilisation performance for Cu and TPH. It can reduce TPH leachability to some extent. - It can maintain leachability levels below acceptable limits with appropriate binder dosage.
CEMI-PFA	- Strength depends on cement content of the mix. Typical recorded 28-day UCS ranges from 90 kPa for 5% binder dosage to 500 kPa for 12.5% binder dosage. - Strength usually builds up over time since pozzolanic reactions take time to complete. Typical recorded UCS can reach 2 MPa at 90 days.	Hydraulic conductivity is similar to that of CEMI treated soils in the 10^{-8} to 10^{-9} m/s range.	- It can be used for reducing the leachability of many metals in contaminated soils. However, it is very suitable for Cu and Pb-contaminated soils unlike CEMI. Especially, PFA content increases the immobilization pH range for Pb. - It is not suitable for TPH immobilisation as concentrations were found to increase over time especially as the binder has a relatively lower buffering capacity in acidic environments.
CEMI-GGBS	- GGBS replacement levels in excess of 50% leads to significant reduction in strength. UCS could be comparable to those of CEMI depending on mix ratio. - Typical recorded 28-day UCS ranges from 100 kPa with 5% binder dosage to 35 MPa with 50% binder dosage, depending on nature of contamination. - UCS could even be higher than CEMI for similar binder dosages. GGBS could typically replace more cement than PFA for the same strength.	- The binder shows similar hydraulic conductivities (in the 10^{-8} to 10^{-9} m/s range) to CEMI and CEMI-PFA treated soils. - Lower values in the 10^{-10} m/s range have been recorded with 50% binder dosage.	- It offers better immobilisation of Cu than CEMI and is comparable to CEMI-PFA in reducing Cu leachability. Similarly, it also shows good leachability reduction for Pb just like CEMI-PFA. Its good immobilisation potential for Cr has also been recorded. - It also shows good immobilisation potential for Cd, Ni and Zn, albeit with lesser capacity compared to CEMI.

Table 8 (continued). Comparisons of the performance characteristics of different binder systems

Binder system	Strength behaviour	Hydraulic conductivity behaviour	Leaching behaviour
Lime-GGBS	- Typical 28-day UCS in the literature ranges from 40 kPa with 5% binder dosage to around 800 kPa for 20% binder dosage. - The presence of contaminants in the soil has a greater deleterious effect on the strength of lime-GGBS than on CEMI and CEMI-GGBS.	- The binder has much higher hydraulic conductivity compared to other binders due to its lime content. - Increased hydraulic conductivity with lime content is more severe with clay soils.	- Just like CEMI, it offers good immobilisation potential for Cd, Ni and Zn, but it is not very suitable for immobilisation of Cu and Pb due to its high pH regime. - It has a very high buffering capacity similar to CEMI; hence, it is suitable for acidic environments. - It appears to be marginally better than the other binders in reducing TPH leachability.
Lime-PFA	- Typical recorded 28-day UCS values ranges from 1.43 MPa for 25% binder dosage to 6.66 MPa for 35% binder dosage. - Gains strength over time due to pozzolanic reaction. The ultimate strength may be comparable to that of CEMI-treated soil depending on the mix ratio.	- There are very few easily accessible studies on contaminated soil treatment with recorded hydraulic conductivity values. Further work is required in this area. - However, lime-PFA concrete is known to have decreased hydraulic conductivity due to decreased water content and production of additional cementitious compounds, which in turn reduces pore interconnectivity. - Values of the order, 10-9 m/s have been recorded for uncontaminated soils.	- The binder has mostly been used for treatment of As, Cr and Pb. A lime:PFA = 1:2.5 mix has been suggested as optimum for effective reduction of Cr leachability. - It is not very effective for As immobilisation as it showed no difference from untreated soils in some leaching studies. - It is very effective for Pb immobilisation as it widens the immobilisation pH range and adsorbs Pb unto fresh pozzolanic products or incorporates it through chemical inclusions.

Cement generally shows superior performance on strength behavior compared to the other binders, especially for soils with high organic content (Jegandan et al. 2010). However, depending on the mix proportions, contaminated soil treated with CEMI-GGBS binder could even demonstrate higher strength values than CEMI-treated soil at the same binder dosage, especially as curing age increases. This is because the pozzolanic reaction is slow and the formation of calcium hydroxide requires time (Oner and Akyuz 2007). One important aspect of strength development not mentioned earlier is the UCS after immersion in water. The test is used to assess whether the stabilised material has hardened chemically and is not susceptible to deleterious swelling reactions. It has been shown that GGBS-based binders, especially CEMI-GGBS, show superior performance to the other binders in this regard (Kogbara 2011).

The binders generally show hydraulic conductivities in the 10^{-8} to 10^{-9} m/s range. Lime-GGBS binders have been found to yield increased hydraulic conductivity values compared to the other binders, which can fall in the 10^{-7} m/s range over time. Especially, as the hydraulic conductivity of S/S treated soils generally appears to increase with curing age.

Leachability studies showed that CEMI and CEMI-PFA were effective for Cd, but at lower dosages, lime-GGBS was observed to be significantly less effective for the metal. It is well known that Pb presents problems with both rate of setting and leachability in CEMI. However, the PFA and GGBS-based binders were notably effective for Pb immobilization. Nevertheless, it was observed that inclusion of GGBS in a binder blend generally offered superior performance compared to PFA. Further, the pH-dependent leachability of metals in CEMI-GGBS treated soils have been found to decrease as curing age increases over an 84-day period due to continuation of pozolanic reactions (Kogbara and Al-Tabbaa 2011). Overall, CEMI is a very versatile and dependable binder compared to the other binders in this work, for most the metals focused on. In every case, inclusion of CEMI resulted in leachate concentrations as low as or lower than the corresponding mixture without CEMI (Akhter et al. 1990).

Although, there was evidence of reduced strength and increased hydraulic conductivity and leachability in some cases, available information on long-term tests shows that S/S treatment was generally still effective at 5 to 14 years, with continued hydration still taking place without serious sign of deterioration due to ageing. There were cases of fluctuations in mechanical and leaching properties over time owing to the complex nature and variability of S/S treated soils. The effect of the long-term interaction between contaminants and soil-grout materials seems to be dominant over those of small differences in grout constituents over a long period (Al-Tabbaa and Boes 2002).

5 Conclusions

This work reviewed the performance of S/S treated soils utilising blends of CEMI, CEMI-PFA, CEMI-GGBS, lime-GGBS and lime-PFA in terms of the UCS, bulk density, hydraulic conductivity and leachability. The UCS was observed to be optimum around the OMC and it increased with binder dosage for all binders. Acceptable UCS and hydraulic conductivity levels for recycling in construction works, and leachability of most metals can be reduced to acceptable levels, with about 20 – 35% of the binders studied. However, more binder dosage does not always lead to a better stabilised/solidified product. Some binders were more suitable for certain contaminants than others were. This work helps provide useful information on scenarios to choose one binder over another depending on the end use of the S/S treated soil. Long-term performance of S/S treated soils showed consistent effectiveness over a period of 5 to 14 years with the occurrence of fluctuations in mechanical and leaching behaviour owing to the complex nature and variability of S/S treated soils. Further work on pH-dependent leaching behaviour of S/S treated soils cured for long periods is necessary to provide more information on the durability of S/S treated soils.

Acknowledgements

The author is thankful for financial support provided through scholarship(s) from the Cambridge Commonwealth Trust and a UK Technology Strategy Board research grant for doctoral studies in Cambridge University, UK.

References

Akhter H, Butler LG, Branz S, Cartledge FK, Tittlebaum ME (1990) Immobilization of As, Cd, Cr and Pb-containing soils by using cement or pozzolanic fixing agents. Journal of Hazardous Materials 24:145 – 155

Al-Sanad HA, Ismael NF (1997) Aging effects on oil-contaminated Kuwaiti sand. ASCE Journal of Geotechnical and Geoenvironmental Engineering 123 (3):290 – 293

Al-Tabbaa A, Boes N (2002) Pilot in situ auger mixing treatment of a contaminated site. Part 4. Performance at five years. Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 155:187 – 202

Al-Tabbaa A, Evans CW (1998) Pilot in situ auger mixing treatment of a contaminated site. Part 1. Treatability study. Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 131:52 – 59

Al-Tabbaa A, Evans CW (2000) Pilot in situ auger mixing treatment of a contaminated site. Part 3. Time-related performance. Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 143:103 – 114

Al-Tabbaa A, Perera ASR (2005) State of practice report, UK stabilisation/solidification treatment and remediation, part I: binders and technologies – basic principles. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005a. Taylor and Francis, London, pp 365-385

Al-Tabbaa A, Perera ASR (2005) State of practice report, UK stabilisation/solidification treatment and remediation, part II: binders and technologies – research. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005b. Taylor and Francis, London, pp 387-397

Al-Tabbaa A, Perera ASR (2005) State of practice report, UK stabilisation/solidification treatment and remediation, part III: binders and technologies – applications. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005c. Taylor and Francis, London, pp 399-413

Allan ML, Kukacka LE (1995) Blast furnace slag-modified grouts for in situ stabilization of chromium-contaminated soil. Waste Management 15 (3):193 – 202

Alpaslan B, Yukselen MA (2002) Remediation of lead contaminated soils by stabilization/solidification. Water, Air, & Soil Pollution 133:253 – 263

ANS (1986) Measurements of the leachability of solidified low-level radioactive wastes, ANSI/ANS 16.1 American Nuclear Society, La Grandge Park, IL.

Antemir A (2005) Performance assessment of S/S waste-forms: initial results from site characterisation, sampling and testing. International Conference on Stabilisation/Solidification Treatment and Remediation. Cambridge, UK. Available: http://www-starnet.eng.cam.ac.uk/ConferencePresentations/session7/Cambridge%20April,05%20after%20DEES.pdf (Accessed January 2013).

Antemir A, Hills CD, Carey PJ, Magnie M-C, Polettini A (2010) Investigation of 4-year-old stabilised/solidified and accelerated carbonated contaminated soil. Journal of Hazardous Materials 181:543 - 555

Arora S, Aydilek AH (2005) Class F fly-ash-amended soils as highway base materials. Journal of Materials in Civil Engineering 17 (6):640 -649

Bone BD, Barnard LH, Boardman DI, Carey PJ, Hills CD, Jones HM, MacLeod CL (2004) Review of scientific literature on the use of stabilisation/solidification for the treatment of contaminated soil, solid waste and sludges. UK Environment Agency Science Report SC980003/SR2, Bristol

BSI (2002) BS EN 12457: Part 2. Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 4 mm (without or with size reduction). British Standards Institution, London

BSI (2006) DD CEN/TS15364. Characterisation of waste – Leaching behaviour tests – Acid and base neutralisation capacity test. British Standards Institution, London

Chen L, Liu S-Y, Du Y-J, Jin F (2010) Strength comparison of cement solidified/stabilized soils contaminated by lead and copper. In: Proceedings of Shanghai International Conference - Geoenvironmental Engineering and Geotechnics: Progress in Modeling and Applications, Shanghai, China, 2010. pp 103 - 110

Chitambira B (2004) Accelerated ageing of cement stabilised/solidified contaminated soils with elevated temperatures. PhD Thesis, Cambridge University, UK

Christopher BR, Schwartz C, Boudreau R (2006) Geotechnical aspects of pavements. Reference Manual of the United States Federal Highway Administration, U.S. Department of Transportation Publication No. FHWA NHI-05-037. Available: http://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05037.pdf.

Conner JR (1990) Chemical fixation and solidification of hazardous wastes. Van Nostrand Reinhold, New York

Conner JR (1998) The history of stabilisation/solidification technology. Critical Reviews in Environmental Science and Technology 28 (4):325 – 396

Conner JR, Hoeffner SL (1998) A critical review of stabilization/solidification technology. Critical Reviews in Environmental Science and Technology 28 (4):397 - 462

Cook DJ, Hinczak I, Duggan R (1986) Volume changes in Portland blast-furnace slag cement concrete. Second International Conference on Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain.

Day SR, Zarlinski SJ, Jacobson P (1997) Stabilization of cadmium-impacted soils using jet-grouting techniques. In: Evans JC (ed) Proceedings of ASCE Specialty Conference on In-situ Remediation of the Environment, Geotechnical Special Publication, No. 71, 1997.

de Korte ACJ, Brouwers HJH (2009) Contaminated soil concrete blocks. In: Limbachiya MC, Kew HY (eds) Excellence in concrete construction through Innovation - Proceedings of the International conference on concrete construction, London, UK, 2009a. Taylor & Francis, London, pp 107-118

de Korte ACJ, Brouwers HJH (2009b) Production of non-constructive concrete blocks using contaminated soil. Construction and Building Materials 23:3564 – 3578

Deja J (2002) Immobilization of Cr^{6+}, Cd^{2+}, Zn^{2+} and Pb^{2+} in alkali-activated slag binders. Cement and Concrete Research 32:1971 – 1979

Dermatas D (1994a) Stabilisation/solidification of lead contaminated soils: Batch and monolithic extraction leaching. Restoration and Protection of the Environment II. Patra University Press, Greece, pp 156 – 164

Dermatas D (1994b) Stabilisation/solidification of lead contaminated soils: II. Flow through column leaching. Restoration and Protection of the Environment II. Patra University Press, Greece, pp 165 - 172

Dermatas D, Deok HM, Menounou N, Meng X, Hires R (2004) An evaluation of arsenic release from monolithic solids using a modified semi-dynamic leaching test. Journal of Hazardous Materials B116:25–38

Dermatas D, Meng X (2003) Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils. Engineering Geology 70:377 – 394

Dermatas D, Menounou N, Meng XG (2006) Mechanisms of lead immobilization in treated soils. Land Contamination & Reclamation 14 (1):43 - 56

Du Y-J, Liu S-Y, Liu Z-B, Chen L, Zhang F, Jin F (2010) An overview of stabilization/solidification technique for heavy metals contaminated soils. In: Chen Y, Zhan L, Tang X (eds) Advances in Environmental Geotechnics. Springer, Berlin, pp 760 - 766

El-Rawi MN, Awad AAA (1981) Permeability of lime stabilized soils. Journal of Transportation Engineering Division ASCE 107:25 – 35

Environment Agency (2004) NEN 7375: Leaching characteristics of moulded or monolithic building and waste materials – Determination of leaching of inorganic components with diffusion test – 'The Tank Test', Version 1.0. Environment Agency, Bristol

Feigl V, Gruiz K, Anton A (2010) Combined chemical and phytostabilisation of an acidic mine waste – Long-term field experiment. Paper presented at the 11th UFZ-Deltares/TNO International Conference on Management of Contaminated Soil, Groundwater and Sediments (ConSoil), Salzburg, Austria.

Glasser FP (1997) Fundamental aspects of cement solidification and stabilization. Journal of Hazardous Materials 52:151 – 170

Jegandan S, Liska M, Osman AA-M, Al-Tabbaa A (2010) Sustainable binders for soil stabilisation. Proceedings of the Institution of Civil Engineers: Ground Improvement 163 (1):53 - 61

Jing C, Liu S, Korfiatis GP, Meng X (2006) Leaving behaviour of Cr(III) in stabilized/solidified soil. Chemosphere 64:379 - 385

Kabata-Pendias A, Mukherjee AB (2007) Trace elements from soil to human. Springer, Berlin

Kaniraj SR, Havanagi VG (1999) Compressive strength of cement stabilized fly ash-soil mixtures. Cement and Concrete Research 29:673 - 677

Kogbara RB (2011) Process envelopes for and biodegradation within stabilised/solidified contaminated soils. PhD Thesis, Cambridge University, UK

Kogbara RB (2013) Encouraging microbial activity in cementitious systems: An emerging frontier in contaminated soil treatment. Journal of Chemical Technology and Biotechnology 88 (4): 501 - 507

Kogbara RB, Al-Tabbaa A (2011) Mechanical and leaching behaviour of slag-cement and lime-activated slag stabilised/solidified contaminated soil. Science of the Total Environment 409 (11):2325-2335

Kogbara RB, Al-Tabbaa A, Yi Y, Stegemann JA (2012) pH-dependent leaching behaviour and other performance properties of cement-treated mixed contaminated soil. Journal of Environmental Sciences 24 (9):1630 - 1638

Kogbara RB, Al Tabbaa A, Yi Y, Stegemann JA (2013) Cement-fly ash stabilisation/solidification of contaminated soil: Performance properties and initiation of operating envelopes. Applied Geochemistry 33:64 - 75

Kogbara RB, Yi Y, Al-Tabbaa A (2011) Process envelopes for stabilisation/solidification of contaminated soil using lime-slag blend. Environmental Science and Pollution Research 18 (8):1286-1296

Kogbara RB, Yi Y, Al-Tabbaa A, Stegemann JA (2010) Process envelopes for stabilised/solidified contaminated soils: Initiation work. In: Sorial GA, Hong J (eds) Proceedings of the 5th International Conference on Environmental Science & Technology, Houston, Texas, 2010. American Science Press, Vol 2, pp 90–96

Korac M, Kamberovic Z, Tomovic B (2007) Treatment of heavy metals contaminated solid wastes-stabilization. In: Proceedings of European Metallurgical Conference, 2007. Dusseldorf, Germany, pp 691 – 699

Kostarelos K, Reale D, Dermatas D, Rao E, Moon DH (2006) Optimum dose of lime and fly ash for treatment of hexavalent Cr-contaminated soil. Water, Air, & Soil Pollution: Focus 6 (1-2):171 - 189

LaGrega MD, Buckingham PL, Evans JC, ERM (2001) Hazardous waste management. 2nd edn. McGraw Hill, New York

Lewin K, Bradshaw K, Blakey NC, Turrell J, Hennings SM, Flavin RJ (1994) Leaching tests for assessment of contaminated land: Interim NRA guidance, NRA, R&D Note 301. Bristol, UK

Lin SL, Cross WH, Chian ESK, Lai JS, Giabbai M, Hung CH (1996) Stabilisation and solidification of lead in contaminated soils. Journal of Hazardous Materials 48:95 – 110

Moon DH, Dermatas D (2005) Chromium (Cr^{3+}) leachability from monolithic solids under modified semi-dynamic leaching conditions. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005. Taylor and Francis, London, pp 171 – 179

Moon DH, Dermatas D (2006) An evaluation of lead leachability from stabilized/solidified soils under modified semi-dynamic leaching conditions. Engineering Geology 85:67 - 74

Moon DH, Lee J-R, Grubb DG, Park J-H (2010) An assessment of Portland cement, cement kiln dust and Class C fly ash for the immobilization of Zn in contaminated soils. Environmental Earth Sciences 61 (8):1745 – 1750

Naik TR, Sivasundaram V, Singh SS (1991) Use of high-volume class F fly ash for structural grade concrete. Transport Research Record 1301:40 – 47

Oner A, Akyuz S (2007) An experimental study on optimum usage of GGBS for the compressive strength of concrete. Cement and Concrete Composites 29:505 - 514

Paria S, Yuet PK (2006) Solidification/stabilization of organic and inorganic contaminants using portland cement: a literature review. Environmental Reviews 14:217 - 255

Perera ASR (2005) The role of accelerated carbonation in the ageing of cement-based stabilised/solidified contaminated materials. PhD Thesis, Cambridge University, UK

Perera ASR, Al-Tabbaa A (2005) The role of accelerated carbonation in the accelerated ageing of stabilised/solidified waste forms. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005. Taylor and Francis, London, pp 181 - 191

Perera ASR, Al-Tabbaa A, Reid JM, Johnson D (2005) State of practice reports, UK stabilisation/solidification treatment and remediation. Part V: Long-term performance and environmental impact. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005a. Taylor and Francis, London, pp 437 – 457

Perera ASR, Al-Tabbaa A, Reid JM, Stegemann JA (2005) State of practice report, UK stabilisation/solidification treatment and remediation. Part IV: Testing and performance criteria. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005b. Taylor and Francis, London, pp 415 – 435

Qian G, Sun D, Tay JH (2003) Characterization of mercury- and zinc-doped alkali-activated slag matrix: Part II. Zinc. Cement and Concrete Research 33:1257 – 1262

Rha CY, Kang SK, Kim CE (2000) Investigation of the stability of hardened slag paste for the stabilization/solidification of wastes containing heavy metal ions. Journal of Hazardous Materials B73:255 – 267

Sanchez F, Barna R, Garrabrants A, Kosson DS, Moszkowicz P (2000) Environmental assessment of a cement-based solidified soil contaminated with lead. Chemical Engineering Science 55:113 – 128

Sanchez F, Gervais C, Garrabrants AC, Barna R, Kosson DS (2002) Leaching of inorganic contaminants from cement-based waste materials as a result of carbonation during intermittent wetting. Waste Management 22:249 – 260

Schifano V, Macleod CL, Dudeney AWL, R D (2005) Remediation of soils contaminated with petroleum hydrocarbons using quicklime mixing. In: Al-Tabbaa A, Stegemann JA (eds) Proceedings of the International Conference on stabilisation/solidification treatment and remediation, Cambridge, 2005. Taylor and Francis, London, pp 69 – 78

Shah SH, Shroff SV, Patel JV, Tiwari KC, Ramakrishnan D (2003) Stabilization of fuel oil contaminated soil - A case study. Geotechnical and Geological Engineering 21:415 – 427

Shawabkeh RA (2005) Solidification and stabilization of cadmium ions in sand–cement–clay mixture. Journal of Hazardous Materials B125:237 - 243

Shi C, Spence R (2004) Designing of cement-based formula for solidification/stabilization of hazardous, radioactive, and mixed wastes. Critical Reviews in Environmental Science and Technology 34 (4):391 - 417

Spence RD, Shi C (2005) Stabilization and solidification of hazardous, radioactive and mixed wastes. CRC Press, Boca Raton, FL

Stegemann JA, Zhou Q (2009) Screening tests for assessing treatability of inorganic industrial wastes by stabilisation/solidification with cement. Journal of Hazardous materials 161:300 - 306

Tremblay H, Duchesne J, Locat J, Leroueil S (2002) Influence of the nature of organic compounds on fine soil stabilization with cement. Canadian Geotechnical Journal 39:535 – 546

Trussell S, Spence RD (1994) A review of solidification/stabilisation interferences. Waste Management 14:507 – 519

USEPA (1986) Test methods for evaluating solid waste, physical/chemical methods. United States Environmental Protection Agency, Office of Solid Waste and Emergency Response (OSWER) Publication No. SW-846, 3rd ed, Washington DC

van Jarsveld JGS, van Deventer JSJ (1999) The effect of metal contaminants on the formation and properties of waste-based geopolymers. Cement and Concrete Research 29:1189 – 1200

Voglar GE, Lestan D (2010) Solidification/stabilisation of metals contaminated industrial soil from fromer Zn smelter in Celje, Slovenia, using cement as a hydraulic binder. Journal of Hazardous Materials 178:926 - 933

Wiles CC (1987) A review of solidification/stabilisation technology. Journal of Hazardous Materials 14:5 - 21

Yilmaz O, Cokca OE, Unlu K (2003) Comparison of two leaching tests to assess the effectiveness of cement-based hazardous waste solidification/stabilization. Turkish Journal of Engineering and Environmental Sciences 27:201 - 212

Young JF (1972) A review of the mechanisms of set-retardation in Portland cement pastes containing organic admixtures. Cement and Concrete Research 2 (4):415 – 433

Yukselen MA, Alpaslan B (2001) Leaching of metals from soil contaminated by mining activities. Journal of Hazardous Materials B87:289 – 300