

STATE OF PRACTICE REPORT UK STABILISATION/SOLIDIFICATION TREATMENT AND REMEDIATION: BINDERS & TECHNOLOGIES – Part II RESEARCH

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SYNOPSIS

The first part of this three-part report entitled 'Basic Principles' presented details of the binders and technologies available and used in the stabilisation/ solidification (S/S) treatment of hazardous waste and contaminated land. This second-part of the report presents an overview of the main research work, both experimental and numerical, carried out in the UK concentrating on the last decade or so but also highlighting earlier significant research work.

The research work is reported under the headings of the individual binders and for each binder the work is presented in chronological order. In this work, most of the S/S materials are prepared by manual/mechanical mixing. The latter part of this report presents research work on S/S materials prepared using soil mixing with mixing augers.

COMMON BINDER SELECTION CRITERIA

Treatability studies are an essential part of an S/S treatment methodology during which the appropriate binder system is selected for a specific site and contaminants based on a set of design criteria. The design criteria used, in terms of specified properties or parameters and their target values, have usually depended on the properties of the end products required taking into account the nature of the material and contaminants being treated. In the US, some criteria were developed for the immobilisation of waste and have since been applied to the immobilisation of soils. Commonly used design criteria and typical target values have included:

- (i) Unconfined compressive strength; >350kPa (soaked) at 28 days (USEPA, 1986);
- (ii) Leachate pH; 7 to 11 (Conner, 1993; Harris et al, 1995);
- (iii) Leachability; using standard leaching tests such as the USEPA Toxicity Characteristic Leaching Procedure (TCLP test) (Federal Register, 1986), or the UK NRA leaching test (Lewin et al, 1994); acceptable limits are usually quantified using a multiplier of drinking water standards, commonly 100 (Conner, 1993);
- (iv) Permeability; <10⁻⁹m/s (as for cut-off walls).
- (v) Freeze-thaw and wet-dry durability; pass in the ASTM tests (ASTM, 1988; 1990);

- (vi) Acid neutralisation capacity (ANC); using the Environment Canada test method (Stegemann and Coté, 1991). ANC is a measure of the stability of the chemical environment in the contaminated material, relating particularly to its ability to immobilise metals (Stegemann and Coté, 1990).

Microstructural analyses have also been used to examine the development of the hydration products and their interaction with contaminants.

Design criteria and target values should be selected to meet site-specific requirements, in terms of the required mechanical properties and acceptable levels of leaching.

INTERACTION BETWEEN BINDER AND WASTE

It is a well-known fact that binders interact with various materials, whether chemical compounds in the waste or the waste material itself. A considerable amount of research has been carried out mainly in the US on interactions between specific chemical compounds, specific waste materials and specific binders and recommendations have been produced in the literature on materials which affect S/S (Spooner et al., 1984, Conner, 1993; LaGrega 1994; USEPA, 1999). Compatibility between the binder and the waste is clearly a major aspect which needs to be taken into account in the selection of appropriate binders. Some of the research work presented here clearly addresses this issue.

S/S with ORDINARY PORTLAND CEMENT

Effect of Cyanide

A study was carried out of the effect cyanide, in the form of sodium cyanide, on the hydration of an OPC binder system (Hills et al., 1994a). The hydration of OPC was found to be significantly retarded and the retardation reaction was monitored by calorimetry. XRD analysis attributed the retardation to complexation reactions involving iron.

Treatment of PFA and flue gas

Mix designs adapted from a commercial process were used for S/S of PFA and flue gas desulphurisation waste (Pollard et al., 1994) using OPC up to 3.75% w/w. UCS at 84 days exceeded 2

MPa and leaching test results showed progressive removal of cationic species over time. Microstructural investigation differentiated between solidification and cation fixation and also suggested that the leachability of metals from the S/S products were controlled by the ettringite crystallites formed in the presence of the available sulphate.

Effect of organics

The influence of organics on OPC was observed using seven organic compounds commonly found in toxic wastes (Hills et al., 1995). The organics, which displayed a variety of chemical characteristics, were added to OPC at varying concentrations. The indicators used were heat of hydration, setting, strength development and microstructure. The results indicated that although most organics had an influence on early hydration by retardation or acceleration that mature samples had similar phase composition to that of the OPC control. Although there was no significant interference with the normal hydration reactions in OPC/organic mixes, the microstructural observations indicated slight variations in the distribution of hydration phases and topographic features.

Effect of industrial waste and organics

A study was conducted to observe the products of OPC hydration in the presence of stabilised waste, containing heavy metals, organics and PFA using Si-29 and Al-27 nuclear magnetic resonance (NMR) and Fourier transform infrared (FTIR) spectroscopy (Hanna et al., 1995a). Si-29 NMR indicated severe retardation of silicate polymerisation in mixes containing stabilised waste. Al-27 NMR showed ettringite and monosulphate in mixes containing 2% stabilised waste, but showed only ettringite in mixes with 19-30% additions. Some organics also reduced the silicate condensation. Band overlap in the region of interest made it difficult to give firm conclusions on results from FTIR.

The formation of Ca(OH)_2 was compared in cement solidified industrial wastes hydrated for different time periods (Hanna et al., 1995b). Both differential thermal analysis (DTA) and XRD, indicated a decrease in Ca(OH)_2 and an increase in unreacted clinker for three solidified industrial wastes. These wastes changed the normal hydration reactions, the amount of change also depended on the concentration. However, TCLP results did not indicate significant variations due to the loading of the waste.

Effect of cement chemistry

The influence of cement chemistry on the properties of solidified wastes forms was studied (Hills et al., 1996). In this study Portland cements

with alite bore composition ranging from 25 to 65%, and ferrite and aluminate fixed at 10% were used. The waste used was a commercially blended and neutralised hazardous waste, which was solidified at three loading rates. The cement composition mainly the amount of calcium silicate hydrate (CSH) was seen to influence the strength development and the differences in phase development were more apparent at the highest waste additions. The morphology of the inner gel products appeared to be different based on the Ca/Si ratio. The metallic waste species had the optimum lowest leaching level.

Effect of uniaxial pressing

The effect of uniaxially pressing OPC pastes containing synthetic metal hydroxide wastes was investigated (Cheeseman et al, 1998). Synthetic wastes of Zn and Pb hydroxide were mixed independently at a loading of 1:10 with partially hydrated OPC and uniaxially pressed. The results indicated that the pressed solidified materials had increased density, reduced porosity, reduced Ca(OH)_2 content and reduced weight loss during acid attack. The leachate pH values obtained over time indicated that the pressed samples reached a steady state at a slower rate, however once equilibrium is reached leaching of contaminants was low for all samples.

Treatment of metal nitrate salts

The effects of metal nitrate salts on the microstructural development of OPC were examined (Hills and Ouki, 1999; Ouki and Hills, 2002). Nitrate salts were selected because of their general high aqueous solubility. The SEM and image analysis results indicated that the amount of cement hydration and porosity were affected, with both the type and concentration of the metal salts being important. Combined metal additions had a more extreme effect on the microstructural development when compared to individual additions.

Effect of calcium chloride on treated synthetic waste

The effect of addition of calcium chloride on the hydration and leaching of lead-retarded OPC was investigated (Cheeseman and Asavapisit, 1999). Samples comprised of varying concentrations of CaCl_2 added to OPC and OPC spiked with 10% by weight of a synthetic lead hydroxide waste. The results showed that the addition of CaCl_2 reduced the otherwise noticeable retarding effect due to the waste, but it reduced the overall extent of hydration and significantly increased the weight loss during leaching. Thus, it was concluded that CaCl_2 did not produce improved materials for disposal.

Treatment of foundry dusts

Three wastes containing metal contaminants from foundry plants were solidified using ordinary Portland cement (OPC) (Gervais and Ouki, 2000) to investigate its potential for reuse. The mix formulations included waste/cement ratio of up to 0.1 and water/cement ratio of 0.4-0.45. The results indicated a retardation of setting time, but the UCS of most waste products after 28 days was within 10% of the controls. The 56 day XRD results indicated that the wastes suppressed the level of hydration. The ANC results showed that the buffering capacity of the solidified products were not affected by the presence of waste.

S/S with LIME

Treatment of lead and iron nitrates

Laboratory investigations were carried out to investigate the time dependent interaction of clays with metal ions and quicklime, using physical and chemical techniques (Boardman et al. 1998). The clays used in this study were English china and Wyoming bentonite clays. The metal ions used were Pb^{+2} ion and Fe^{+3} ion, in the form of nitrates and were individually added to the clays. The quicklime was added at up to 2.5% and 7% to the English china and Wyoming bentonite clays respectively.

The results indicated large increases in the shear vane strength with time when the lime content was increased. This also resulted in the removal of these contaminants from the aqueous phase, increases in soluble Al concentrations, reductions in Ca concentrations and very low but relatively constant Si concentrations with an increase in curing times for the English china clay. Thus, as English china clay has essentially no cation exchange capacity it is plausible to suggest that the changes in concentrations are as a result of pozzolanic reactions, and perhaps to a lesser extent equilibrium conditions.

In the case of the Wyoming bentonite, there was an increase of leachable Si, and to a lesser extent Al, and decrease of leachable Ca and Na. It is suggested that a small quantity of Pb may improve the strength of English china clay. Fe seemed to impede pozzolanic stabilisation reactions of both clays, but the measured concentrations, pH and conductivity results indicate that the negative effect of Fe on the stabilisation of Wyoming bentonite clay is less than that on English china clay. This may be linked to the exchange of Na by Fe in the former. The batch test data further indicated that a high pH is required to successfully remove specific contaminants from solution of lime treated clays.

The processes that combine to reduce future contaminant mobility in lime treated clays have

been specified as follows (Glendinning et al, 1998):

- Cation exchange in the clay minerals
- Increased metal absorption due to the creation of a high pH environment
- Precipitation of salts in the high pH environment
- Binding in of contaminants due to the pozzolanic reactions

However, it is further stated that the success of the process is soil/sediment specific as different contaminants will react with lime in different ways.

S/S with ORGANOPHILIC CLAYS

Extensive OPC-based s/s work to investigate the use of organophilic clays as a pre-solidification absorbent for problematic inorganic wastes containing organic contaminants was carried out at Imperial College in the early 1990s:

- a) Modified clay was used as a pre-solidification absorbent to treat two industrial inorganic wastes containing up to 12% organic content (Montgomery et al., 1988). Calcium carbonate was used as a filler. Wyoming Bentonite clay modified using Quaternary Ammonium Salts (QAS) showed improved performance on phenol adsorption. Perchem 462®, a commercially exchanged clay, showed improvement on the leaching tests and UCS. This work indicated the viability of the use of organophilic clays in S/S systems containing organic compounds. A similar study was then conducted utilising three industrial wastes, but with the intention of optimising the OPC:filler:QAS-clay:liquid ratios by minimising the OPC and QAS-clay content in relation to the waste (Montgomery et al., 1991a).
- b) Microstructural analyses were carried out by Montgomery et al. (1991b) to investigate some fundamental aspects of OPC-organic interactions using two organic compounds, namely 3-chloro-phenol and chloronaphthalene. The results indicated that while the former retarded the hydration of the cement paste, the latter had no effect on cement hydration, thus showing the importance of understanding these interactions. Extensive microstructural studies were then carried out to investigate the interactions between an organophilic clay, Perchem 462®, which adsorbed the same organic wastes above, and OPC (Montgomery et al., 1991c). The results indicated that the detrimental effects observed with 3-chlorophenol on the OPC hydration could be minimised, provided that the maximum adsorption capacity of the organophilic clay was not exceeded. The study therefore showed that the careful use of the organophilic clay could

reduce the adverse effects of the organic compounds on OPC hydration.

A natural bentonite and a commercial organophilic bentonite (Claytone APA) were used in the S/S treatment of a liquid and a sand containing methylene blue (Al-Tabbaa and Moore, 1996; Al-Tabbaa and Rose, 1996). The binder also consisted of OPC and PFA. Methylene blue was found to reduce the setting time of OPC and varying its concentration was found to have a minimal effect on the UCS of the S/S mix. Given the chemical structure of methylene blue, the two bentonites were found to have a similar sorptive capacity. Optimum binders were developed for both wastes.

S/S with BLENDED BINDERS

OPC and PFA blends

OPC and PFA were used in a variety of mix proportions to solidify a mixed waste stream with the intention of reviewing the role of OPC (Hills et al., 1992; 1993). The results based on calorimetric studies indicated that increasing waste addition in the OPC/waste mixes showed progressive poisoning of normal hydration reactions. However, PFA and other products took the role of acting as a cement when OPC was poisoned. Another outcome of this study was that the strength development and heat of hydration was found to be related. This suggested that the suitability of a waste to OPC-based S/S could be determined using conduction calorimetry.

A two part study was conducted using calorimetric and microstructural analysis techniques to classify the interference effects of OPC/waste and to modify a model for poisoning of OPC hydration. In the first part (Hills et al., 1994b), several wastes capable of poisoning the hydration of OPC were solidified. The results indicated that the waste/OPC interactions could be classified by phase development and evolved heat of hydration. In the second part (Hills et al., 1994c), the above wastes were characterised and waste components identified as being significant in single or combined addition to OPC. The results showed that the poisoning effects observed with real wastes could be reproduced only by the addition of combined metal hydroxides. A model representing the early hydration of OPC was proposed.

The effectiveness of OPC and a cementitious foam, Hydrofoam (HFR), in the immobilisation of a sand, contaminated with copper nitrate and vegetable oil, was investigated. The effect of the addition of PFA to the cements was also considered. The immobilisation effectiveness was assessed using unconfined compressive strength and leachability tests. It was concluded that the contaminants had a stronger retardation effect on

the early strength development of OPC-based mixes than on HFR-based mixes. However, the OPC-based mixes retained a greater percentage of both the copper and the vegetable oil.

Effect of acid addition

Studies were conducted to investigate the effect of acid addition to different binders and solidified wastes, in ground and monolithic forms (Stegemann et al, 1997; Stegemann and Shi, 1997 respectively). OPC, OPC with silica fume, alkali-activated blastfurnace slag, lime and coal fly ash, and high alumina cement with lime and gypsum were used with and without waste addition as shown in Table 1. In the former study (Stegemann et al., 1997), the different systems were tested using the ANC test at different ages. The results indicated that the different binder systems varied in their response to acid addition with different pH plateaus being exhibited and this appears to be due to the structure and composition of the hydration products formed and is affected by the waste. In the latter study (Stegemann and Shi, 1997) the monolithic binders were immersed in three types of acids. The results indicated that the CSH-based formulations with a low Ca/Si ratio exhibited the greatest acid resistance even though Portland cement containing formulations generally have the higher ANC, and that the high alumina cement specimens had poor acid resistance.

Treatment of metal nitrates by zeolite and silica fumes blended cements

The effects of four metal nitrates, viz. chromium, manganese, lead and zinc, on the primary mechanical (setting time, UCS) and leaching characteristics (ANC, solubility of the metal contaminants as a function of pH) of cement-blended materials were examined (Gervais and Ouki, 2001). The three binders considered were Portland cement, Portland cement with silica fume and Portland cement with natural zeolite. The results obtained from the various cement-based materials prepared indicated the importance of the contaminant/matrix couple considered and the need for care when using blended cements for S/S of waste.

Treatment of IFA by sodium silicate blended cements

Wilkes et al. (2000) conducted a study to investigate the effects of sodium silicate on the stabilisation of municipal solid waste incinerator fly ash (IFA). Soluble sodium silicate/Portland cement mixes, where the sodium silicate addition was 8% by weight, was mixed with differing percentage additions of IFA. Increasing the addition of IFA retarded the setting time and strength development. The addition of sodium silicate gave lower final strengths and reduced

strength development in mixes with IFA. Distinct 'gel' phases were formed in the presence of sodium silicate and IFA, with a volume change occurs causing development of large voids.

Treatment of mine tailings

OPC and OPC blends were used for the S/S treatment of two typical mine tailings, namely copper/nickel and lead/zinc, for different tailing soils constituents. The pH of the former was 3 and the latter was 12 and both tailings were also produced at a pH of 7. The tailings were stabilised with OPC, PFA, PFA/lime, blastfurnace slag and waste materials including dried sewage sludge (in the form of Biogran) in a cement blend. The binders were added at 30-50% by weight. The results showed that (i) OPC alone was the best binder in terms of leaching, (ii) lead was the least stabilised heavy metal, (iii) the dried sewage sludge was effective in stabilising all the heavy metals except copper which was present in large concentrations in the original sewage sludge and (iv) the extent of leaching was dependant on the tailings pH: lead, which is amphoteric, was soluble in alkaline conditions, while copper and nickel were soluble in acidic conditions (Mojapelo, 2002).

Effect of carbonation

Carbonation of S/S waste involving cement-based material is one aspect of S/S which has been receiving some attention in the last decade. The mechanism for the complete process of carbonation has been postulated by Maries (1992). In most of the work reported here, the S/S products are cured in three environments: nitrogen, air and carbon dioxide:

- a) Preliminary investigation into the effect of carbonation on solidified hazardous waste were undertaken by Lange et al. (1996a) utilising a commercially blended waste material and OPC. The improved the 28-day results of calcite content, strength and leaching, indicated that carbonation has played an important role in accelerating the apparent hydration. Lange et al. (1997) investigated the effect of carbonation on properties of blended and non-blended cement solidified waste forms utilising five types of cement and two pozzolans, and a commercially blended waste. The 28-day results were similar to those from the earlier study above, but also indicated that the type of cement-based system could be optimised to obtain improved results in a carbonated S/S product.
- b) The kinetics of carbonation of cement-based solidified hazardous wastes was explored based on the effect of variations in the mix parameters and binder choice (Lange et al., (1996b). Three types of Portland cement and two mineral admixtures were used in this study to S/S two commercially produced heavy metal wastes.

Both the rate of carbonation and total uptake of carbon dioxide was considered. Accelerated regimes were identified within the variations considered. Based on this, the effect of accelerated carbonation on several properties of cement-solidified waste forms were investigated (Lange et al., 1996c). OPC and OPC blended with blast furnace slag and PFA was used to solidify two industrial wastes. The study indicated that carbonating optimum mix designs gave improved properties of the solidified waste forms.

- c) Investigations were conducted to observe the effect of accelerated carbonation of S/S synthetic waste (Sweeney et al., 1998) containing high levels of heavy metals. The initial work did not give the expected enhanced strength or heavy metal retention indicating insufficient carbonation of waste forms. Subsequent modification improved carbonation and achieved higher retention of metals.
- d) Microstructural studies were conducted on carbonated and non-carbonated synthetic heavy metal waste solidified using OPC (Hills et al., 1999). The microstructures of the two systems were distinct, with the cement grains being largely decalcified and porosity significantly reduced in the carbonated samples. The latter being due to the formation of precipitated carbonates as a result decalcification.
- e) Sweeney et al. (1999) carried out a study to assess the acid resistance capability of carbonated waste forms. Carbonation, by reducing the buffering capacity of a solidified matrix, may make the waste more susceptible to acid attack. OPC was used to solidify two heavy metal wastes. The design mix consisted of 50% waste and 50% OPC slurry. ANC tests were conducted on the samples and selected extraction solutions were analysed for heavy metals. The results while demonstrating the poor ANC of carbonated solidified wastes at low acid additions showed that the overall ANC may be similar to that of the non-carbonated product.

The effect of carbonation on the immobilisation of Cr(III) and Cr(IV) was investigated for both Portland cements and cement blends incorporating blast furnace slag (Macias et al., 1997). Portland cement matrices were found to be more resistant to carbonation than cement matrices containing slag. However, the content of chromium in the pore solution was more in Portland cement matrices for both forms of chromium.

Effect of binder variability on performance

The binders and additives, which are normally used in S/S are usually supplied in accordance with their relevant British or national standards. Although this can give the user some degree of confidence in the performance of the material, it is

important to note that the standards only control the properties of the materials with respect to their use in concrete, which may differ to their use in solidifying and stabilising a waste stream. Thus, one source of binder may behave similar to a second in a concrete mix, but could potentially fail to solidify a certain waste, which the second source succeeds. Although, no specific examples are available for waste stabilisation, two examples from the construction industry are used to demonstrate this effect (Johnson, 2002).

The first example is provided by the use of OPC in a rapid hardening composition with calcium sulfoaluminate and anhydrite, where (unlike standard concrete), early age strength development is one of the most important properties. When used in the same ratio of ingredients and water, different sources of OPC gave different rates of early age strengths, even though all the sources complied with the same part of the British standard. The strengths at 28 days were similar, however, it was the strength at 3 hours which was the most important value.

The second example is provided by the use of pulverised-fuel ash in civil engineering grout formulations, in combination with Portland cement. The use of different sources of PFA in the same mix with OPC and water gave different strengths at various ages up to 1 year and also different rates of strength development. Again, both PFA and OPC sources complied with their respective standards, yet gave different strengths.

These two examples, although not directly related to the stabilisation/solidification of waste and contaminated soils, do demonstrate that different sources of OPC and PFA can drastically change specific properties and show the inadequacies of the standards currently in use for the binder and additive. Further, it shows that is important that in treatability studies, the same source of binder and additive is used.

Treatment of radioactive waste

Various studies have been conducted to investigate the S/S of radioactive wastes using cement and cement-blended materials. The role of cement in immobilising radioactive wastes has been reviewed by Glasser (1985 and 1992).

A two-part study on radioactive waste in Portland cement systems was carried out. Part one looked at the radionuclide distribution (Jantzen et al., 1984). In this study, waste loading of 20-30% by weight were achieved by dilute solid solution of waste ions, with higher loadings resulting in compatible non-cementitious radiophases. No loss of compressive strength resulted as a result of the waste. It was predicted that the radionuclide partitioning in the anhydrous clinkered phases will be maintained in the hydration products. The second part which investigated the leaching

characteristics (Jantzen, 1984), using simulated leaching experiments indicating that the resulting hydration products were stable with waste element release rates being lower than for other forms of cementitious wastes.

Kinetics and mechanisms of the reaction between Portland cement and clinoptilolite was studied by Angus et al. (1984). Several reactions occur in three overlapping stages when immobilising clinoptilolite which leads to the release of Cs. The three stages being a rapid ion exchange, then a slower reaction between clinoptilolite and Ca(OH)_2 from cement and in the long-term slower reaction with CSH. The latter may form low-lime CSH at temperatures below 100°C or tobermorite at higher temperatures.

Atkins and Glasser (1992) reported findings of experiments on uranium, iodine and strontium interactions with cement. They pointed out that the impact of higher temperatures is an important factor affecting the cements performance with elevated temperatures being known to cause crystallisation of CSH gel and thereby lowering the pH at which it buffers. Modifying models to incorporate the above and other interactions is stated to be possible provided the appropriate database is available.

McCulloch et al (1984) showed that cesium (Cs) sorption is markedly increased in cement-based systems containing reactive silica, ground blast furnace slag, fly ash and natural pozzolan. Fly ash low in alkali and silicas were considered the most suitable for the immobilisation of Cs. Higher but optimum loadings of these materials, in the range of 20-30% by weight, are sought to ensure permanent excess of sorbent. The sorptive mechanism, which is demonstrated, shows it to be enhanced by the alkaline cement environment.

The immobilisation of molybdenum (VI) (Mo) in several cement mixtures and Portland cement was studied (Kindness et al., 1994). In the case of the cement mixtures, the aqueous Mo content was found to decrease over a short period of time before reaching a steady-state concentration and in the case of Portland cement the 28-day extracted Mo had also decreased in concentration. The distribution of insoluble Mo in the Portland cement matrix was also discussed.

Studies were conducted to investigate the ability of NaCl and MgSO_4 to impair the performance of Portland cement, cement blends containing slag and fly ash, and a permeable backfill (Duerden et al., 1997), considering decrease in pH, changes in mineralogy and loss of physical coherence. Three temperatures were used in this study. While NaCl was found to have a slight impact on performance, MgSO_4 had a higher impact.

S/S with WASTE MATERIALS

S/S with spent bleaching earth

Spent bleaching earth was reused as a low cost absorbent for the pre-adsorption of organic components in mixed waste streams (Pollard et al., 1990). The study which comprised of four synthetic mix wastes compared the activated spent bleaching earth's performance against commercial powdered activated carbon in cement/waste/adsorbent blends. The waste clay added as 10% w/w of the mix, reduced leachable TOC up to 37% w/w and increased the 28 day strengths by 240-1300%. This indicated that while this material gave satisfactory results as an adsorbent it also reduced the cost and provided an opportunity for reducing its disposal as a result of being re-used.

S/S with various waste materials

Tyre has been shown to be effective in sorbing hydrocarbons and sorbs up to its own volume (Al-Tabbaa et al, 2000b). Wood shavings, straw and waste peat are effective in sorbing copper with up to 80% sorption being observed (Al-Tabbaa et al, 2001b). These studies have also shown that some desorption does take place and hence the conditions under which maximum sorption prevails need to be investigated. Related studies which investigated the effectiveness of these waste materials in a cementitious binder have shown that the wastes' sorptive capacity was not affected by the presence of the cementitious matrix.

RESEARCH with LABORATORY-SCALE AUGERS

Laboratory-scale soil mixing work was carried out to investigate different soil and contaminant conditions and different remediation scenarios:

- a) different soil mixing installation techniques (Al-Tabbaa et al, 1997) and arrived at optimum mixing conditions. It was clear that increased number of mixing cycles were beneficial but that 2-3 cycles in sand were sufficient;
- b) soil mixing in layered soils (Al-Tabbaa et al, 2000a, Lightman, 2002) which showed that effective mixing between two different sand types depends strongly on the design of the auger head and that a homogeneously mixed zone does form between the two layers, the extent of which depends on the auger design. When a lens of clay or peat exist in a sand, there is also mixing which increases the strength of the peat stabilised zone.
- c) soil mixing of micro-organisms-based grout for the development of a biofilm barriers and bio-remediation purposes (Brough et al, 1998; 2001). This work is the first of its kind in the UK and investigates the effectiveness of soil mixing in the installation of a biologically active permeable barrier which contains and remediates organic contaminants;
- d) dry soil mixing (Al-Tabbaa et al, 1999) which showed that dry soil mixing requires more vigorous mixing compared to wet soil mixing, to achieve the same level of homogeneity of soil-grout material;
- e) soil mixing of soil-waste and soil-cement-waste materials to form high and low permeability reactive barriers respectively (Al-Tabbaa et al, 2001a and b). This work showed that soil mixing augers were effective in uniformly mixing the waste material tested, such as granulated tyre and wood shavings, with sand and cement. They also produced satisfactory load-displacement behaviour of the resulting columns; and
- f) soil mixing of problematic soils such as organic and soft soils and peat (Lightman, 2002; Tong, 2002). This work has shown that some auger head designs are more effective than others for use in such soils but that some of the auger head designs used for granular soils are also effective for clayey soils. Mixing of soft clays requires particular attention to ensure homogeneous mixing and effective distribution of the grout.

A number of the model augers used in these projects is shown in Figure 1.

There is a considerable amount of work which needs to be done to assess the applicability of soil mixing to various ground conditions in the UK and to the various intended applications and many of these can be carried out using laboratory-scale soil mixing. Soil mixing will not work in all soil conditions and ground conditions suitable for soil mixing need to be established.

DATABASES: NNAPICS

NNAPICS, which stands for 'Neural Network Analysis for Prediction of Interactions in Cement/Waste Systems', was a three-year project funded under the European Commission's Industrial and Materials Technologies Programme (BRITE-EURAM III) which started in November 1997. It involved a consortium of eight partners from industry and universities in the UK, Spain, Italy and Ireland. The primary objective of this project was to examine the use of neural network analysis for predicting interactions in, and final properties of, cement/waste systems. Existing data concerning solidified wastes and building materials containing industrial by-products have been collected into a Microsoft Access database and analysed using neural networks, and appropriate supplementary data were generated in a separate laboratory study. It is intended that identification of predictive relationships will facilitate effective design of cement/waste products for utilisation or disposal and allow selection of the most informative test methods for product evaluation. Discovery of new

relationships between properties of cement/waste products is expected to result in new indications concerning contaminant immobilisation mechanisms, which will be useful information for other fundamental modelling approaches (e.g. thermodynamic modelling) and in development of new binder systems (Irabien et al, 1999; Buckley and Johnston, 1999; Stegemann and Buenfeld, 1999; Pollettini et al, 1999).

CONCLUSIONS

It is clear that a considerable amount of research has been carried out over the past two decades on stabilisation/solidification of hazardous waste and contaminated land in a number of academic institutions in the UK. It is also clear that there is a vast number of variables that need to be considered and hence the difficulty in correlating results from different institutions. There is a need for collective and collaborative research effort so that results can be integrated to work towards a bigger picture of the effectiveness of the use of different binders and implementations techniques in S/S treatments.

It is also clear that there is a need to develop robust and versatile binders and installation techniques which apply to a wide range of waste types. A considerable amount of research has been carried out which validates various S/S treatments in the short term. What is needed is validation in the long-term. The limited work that has been completed on the long-term behaviour will be covered in a future publication.

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Component	Percentage of dry mix									
	1	1W	2	2W	3	3W	4	4W	5	5W
Portland cement	100	40	80	32	-	-	-	-	-	-
Silica fume	-	-	20	8	-	-	-	-	-	-
Blast furnace slag	-	-	-	-	92.5	37	-	-	-	-
Sodium metasilicate	-	-	-	-	7.5	3	-	-	-	-
Class F coal fly ash	-	-	-	-	-	-	80	48	-	-
High calcium lime	-	-	-	-	-	-	20	12	10	10
High alumina	-	-	-	-	-	-	-	-	60	30
Gypsum	-	-	-	-	-	-	-	-	30	-
Metal plating sludge	-	60	-	60	-	60	-	40	-	-
Hazardous waste	-	-	-	-	-	-	-	-	-	60
Water	40	50	40	50	40	50	40	50	40	50
Ca/Si ratio	3	3	1.4	1.4	0.5	0.5	0.5	0.5	-	-

Table 1. Formulations for ground and monolithic specimens (Stegemann et al, 1997).

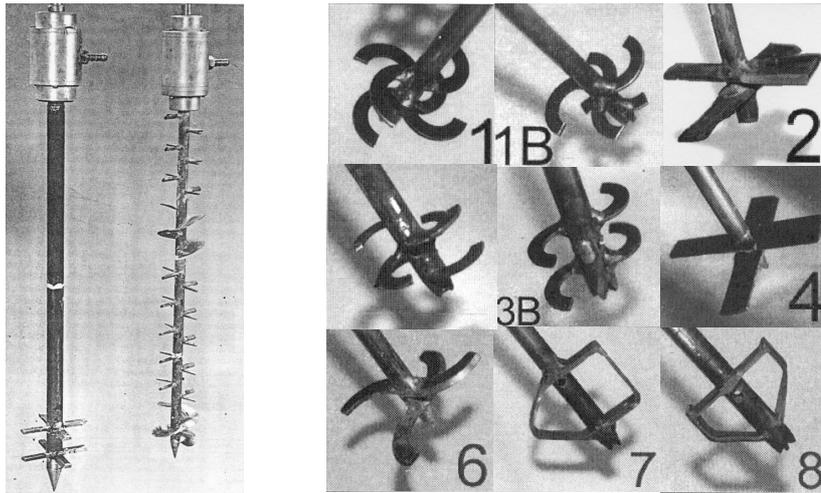


Figure 1. Laboratory-scale model augers (Al-Tabbaa and Evans, 1999; Lightman, 2002; Tong, 2000)

