CL:AIRE technical bulletin

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CL:AIRE technical bulletins describe specific techniques, practices and methodologies currently being employed on sites in the UK within the scope of CL:AIRE technology demonstration and research projects. This Bulletin summarises the first four State of Practice Reports, produced by STARNET, which present the state of practice of stabilisation/solidification technologies in the UK.

Stabilisation/Solidification Treatment and Remediation: Part 1: Summary of the State of Practice Reports I-IV

INTRODUCTION

This Bulletin summarises the first four State of Practice Reports produced by STARNET. STARNET is an EPSRC funded Network on 'Stabilisation/Solidification Treatment and Remediation'. The Reports present the state of practice of stabilisation/solidification technologies in the UK, and form part of the activities of STARNET. The purpose of these reports is to identify the knowledge gaps and future research needs in this field.

The first three State of Practice Reports focus on Binders and Technologies. Part I describes basic principles of available binders and technologies in the UK, Part II investigates research activity in this area, whilst Part III reviews the practical demonstrations of S/S technology in the UK through field trials and commercial applications. The final part of this Bulletin, Part IV, reviews the current practice in test methods and performance criteria used to assess S/S materials.

1. BINDERS AND TECHNOLOGIES: PART I - BASIC PRINCIPLES

1.1 BACKGROUND

Stabilisation/solidification (S/S) treatment methodologies have been widely used over the past three decades, particularly in the United States where it is now an established treatment methodology. S/S has been used to treat hazardous waste, residues from treatment processes and contaminated soils. Such methodologies have been mainly used to treat inorganic contamination, but more recently some organic contamination has also been successfully treated. Initial treatments were carried out *ex situ* but more recently, *in situ* treatments have also been applied. Stabilisation, with chemical admixtures, for ground improvement purposes is a technology which can be correlated with S/S treatments of waste and contaminated ground. S/S treatments have been carried out in the UK over the past 15 years. S/S treatments include a wide range of similar processes that usually involve mixing inorganic cementitious binders, such as Portland cement, into the waste or soil to transform it into a new, solid, non-leachable material. The treated waste product encapsulates potentially hazardous contaminants, reducing contact between the waste and any potential leachant. In addition to encapsulation, various waste-binder interactions and chemical effects occur that lock contaminants into the product, further reducing the potential for pollutant transfer into the environment. Binders are usually selected according to some mix design criteria which depend on the application. This could be landfilling, redevelopment of a contaminated site or reuse of waste as aggregate in construction.

1.2 STARNET

The overall aim of STARNET is to build a Network of key participants who will work together to promote the development of research work on, and implementation of, UK S/S technologies. Its core membership includes leading UK scientists and engineers, organisations and regulators involved with S/S treatment technologies. This currently (as of June 2004) comprises Imperial College, University College, Universities of Cambridge, Greenwich, Newcastle, Birmingham and Surrey, TRL Limited, May Gurney Technical Services, British Nuclear Fuels, Environment Agency, Lafarge Cement UK, Buxton Lime Industries, MJ Carter Associates, Shell Global Solutions, CL:AIRE, CIRIA, SITA, EDGE Consultants UK, Enverity, Arcadis GMI, Grundon Waste Management, David Johnson and the British Cement Association.

Key scientific and technical issues for S/S technologies which are being addressed by the Network include: (a) Binder selection; (b) Technology selection; (c) Testing and performance level; (d) Long-term performance and environmental impact; (e) Quality assurance and quality control issues; and (f) Good practice guidance documents.

1.3 LEGISLATION

The use of S/S treatment is compatible with UK and EU legislation. The recent EU Landfill Directive will have a significant impact on UK waste management. In particular, it will ban the co-disposal of hazardous and non-hazardous wastes and place bans or restrictions on the landfilling of liquid wastes and some other materials. The end of co-disposal in the UK and the associated requirements contained in the Landfill Directive mean that some form of waste treatment prior to landfill is likely to be increasingly required. An EU Technical Adaptation Committee (TAC) has set acceptance criteria for different classes of landfill which will determine the degree of pretreatment required. S/S technologies will almost certainly represent the most cost-effective treatment method available for major types of industrial wastes that are predominantly inorganic, and will likely be an option for organics as well. The use of S/S is compatible with the Government's approach to the remediation of contaminated land under Part IIA of the Environmental Protection Act 1990 which is based on the principle of risk management and suitability for use. There is a legacy of contaminated industrial sites in the UK that require some form of treatment before they can be either redeveloped or otherwise re-used. This has become increasingly important in recent years, as greater environmental awareness and growing pressure on land resources have brought about the protection of greenbelt and agricultural land. The government has stated that it requires the construction of 2.4 million new homes by the year 2016, 60% on brownfield sites. This has placed the onus firmly on the re-development of land originally used for industrial purposes. However, as a result of past usage, increased levels of contamination within the soil and groundwater may preclude the site from immediate construction activity. Some type of ground remediation is therefore required, the choice of which is governed by performance, speed and economics. These requirements have promoted research into fast, effective and economical remediation techniques that enable future land commercialisation. Immobilisation of contaminants in the ground using S/S treatment is emerging as viable and economic.

NB: The EA will shortly be releasing a guidance document on S/S of contaminated soils, produced as part of the CASSST (Codes and Standards for Stabilisation/Solidification Technology) initiative. This release will be reviewed in a forthcoming CL:AIRE Guidance Bulletin.

1.4 BINDERS IN S/S TREATMENT SYSTEMS

This section provides general information on available binders in the UK; their properties, applications and advantages and disadvantages.

1.4.1 Cement

Cement is frequently employed as the binder in S/S of contaminated material, be it as a means of pretreatment prior to disposal in landfill or treatment of contaminated land. Various types of cements have been developed over time but the most commonly used for S/S is Portland cement (PC), with calcium aluminate cement (CAC) also being considered in some work. Extensive literature exists regarding the chemical reactions that take place when cement combines with water, a process known as hydration, which describes all the chemical reactions. In cement-based stabilisation the contaminated material is mixed with the cement and water is added. In some cases water is not needed as the waste itself contains sufficient water. Immobilisation is achieved by physical entrapment of the contaminants within the cement paste matrix and/or by the reaction of the contaminants directly with the compounds formed during hydration. Cement-based stabilisation is best suited for inorganic wastes, in particular those containing heavy metals. For example, metal cations may be retained in the form of insoluble hydroxide salts within the hardened structure as a result of the high pH of the cement. Some of these metals are likely to be bound in the matrix due to chemical fixation, whereas others are immobilised due to physical encapsulation. Although inorganic wastes are best suited to Portland cement-based S/S, some inorganic compounds strongly affect the setting, strength development and final strength of the binder. Organic contaminants can be more problematic by interfering with the hydration process. Additives, such as pulverised fuel ash and ground granulated blastfurnace slag, are sometimes used as partial replacement material for cement. Other binders such as calcium sulphoaluminate cement (CSA) have also been investigated.

1.4.2 Pulverised Fuel Ash

Pulverised fuel ash (PFA) is a synthetic pozzolana created by the combustion of coal. In the UK, ashes are generally classified as low-lime PFA. PFA can be described as a siliceous and aluminous material which on its own possesses little or no cementitious value. However, in a finely divided form and in the presence of moisture it will chemically react with lime to form compounds possessing cementitious properties. The stabilising effect of PFA stems from the formation of calcium silicate gels which gradually harden over a long period of time to form a stable material, with hydration products similar to those of Portland cement. PFA may be suitable for the stabilisation of both inorganics and organics. However, in general, PFA-lime solidified waste products are less durable and have higher leaching rates than those containing cement.

1.4.3 Blastfurnace Slag

Blastfurnace slag is obtained from the manufacture of pig iron and contains silica, alumina and lime. Ground granulated blastfurnace slag (GGBS), which is the type most commonly available in the UK, is classed as a latent hydraulic cement with compositions broadly intermediate between pozzolanic material and Portland cements. The hydration of slag is initiated when lime provides the correct alkalinity, but subsequent hydration does not rely on lime. GGBS is available as a separate ingredient to be added to treatment systems at the point of mixing either alone or with other binders, and as blends in various proportions with Portland cement.

1.4.4 Lime

Although several forms of lime exist, generally it is only quicklime (calcium oxide) and hydrated lime (calcium hydroxide) that are used as binders. Quicklime, which exists either in granular or powder form, is produced from heating chalk or limestone, and hydrated lime, which is generally available as a fine, dry powder, is produced as a result of the reaction of quicklime with water. The materials generally treated using these limes are fine-grained soils, ranging from clayey gravels through to clays, and some industrial by-products such as fly ash. However for the purpose of S/S, lime is used to control the pH of the waste form so as to keep metals in the range in which they are least soluble, with a compromise being needed on pH control when several metals are present. However, due to the difficulty in controlling the pH, lime is generally used with other reagents such as cement, PFA and carbonate ions.

1.4.5 Clays

Natural bentonite clays: Bentonite is classed as a clay which is formed by the decomposition of volcanic ash and is characterised by the clay mineral montmorillonite. The hydration of bentonite particles produces a suspension with a gel-like structure. Bentonite has good adsorption characteristics for heavy metals, radioactive substances and polar molecules. Although suitable as a binder in its own right, bentonite is generally used with other binders, especially cement, for treating contaminants.

Organophilic clays: Organophilic clays are produced from natural clays by increasing their adsorptive capacity by chemical treatment. This is accomplished by various reactions such as adsorption, ion exchange and intercalation. Although these clays can be used alone to remove certain contaminants, they are more effective in treating wastes when used together with conventional binders such as cement. In the latter scenario, the organophilic clays are ideally mixed with the waste first and allowed to absorb the organic contaminants prior to the addition of an S/S binder which is used to encapsulate the material within the monolithic mass.

1.4.6 Bitumen

Bitumen occurs in natural asphalt or can be obtained from petroleum and consists mainly of hydrocarbons. It can be in the form of a solid or viscous liquid and commonly has to be made more fluid prior to use in S/S. Bitumen acts as a binding agent and does not react chemically with the material like cement and lime. Therefore, bitumen simply sticks to the particles forming a fairly water tight material.

1.4.7 Waste Binders

Certain materials that might be considered as waste have been investigated as chemical binders because of their capacity to sorb various contaminants and also their low cost. Examples include granulated tyre, wood shavings, straw and used peat.

1.5 IMPLEMENTATION PROCESSES FOR S/S TREATMENT SYSTEMS

This section provides general information on available process technologies based on *in situ* and *ex situ* operations. *In situ* (or in-place) operations refer to all processes taking place within the ground, including locations such as lagoons, while *ex situ* operations refer to all processes taking place away from the original contamination location either on-site or off-site.

1.5.1 *Ex Situ* S/S Implementation Processes

Commercial *ex situ* mixing can involve one of three main methods: plant processing, direct mixing (area mixing and layering) and in-drum processing.

Plant processing: In plant processing the contaminated material is mixed with the appropriate binder, and other additives if necessary, and in some cases after some form of pretreatment. The treated material is then placed at its final disposal site. The mixing plant could be fixed (off-site) or mobile (typically on-site) and is designed specifically for this purpose or adapted from other applications such as concrete batching and mixing. The mixing is carried out with mechanical mixers (e.g. Fig 1a) using either batch or continuous processes. The final disposal location could be on-site or off-site. On-site would typically mean that the blended material is placed back in its original location, compacted using suitable plant and left to cure in-place.

Direct mixing: Direct mixing involves the transport of the contaminated material to a designated final disposal area, which could be on-site or off-site. The material is spread out in layers along with the binder(s) and is mixed in-place using the appropriate mechanical equipment. The blended material is then compacted and left to cure in-place.

In-drum processing: In in-drum processing the binder(s) is added to the contaminated material which is placed in a drum or similar container. This initially acts as the container for mixing and then for setting and hardening. Once hardened, the treated material and the drum are disposed of together. Normally the mixing paddles are left in the drum after mixing and are also disposed of.

Each of the methods described above has its own advantages and disadvantages and these are explored in the report.

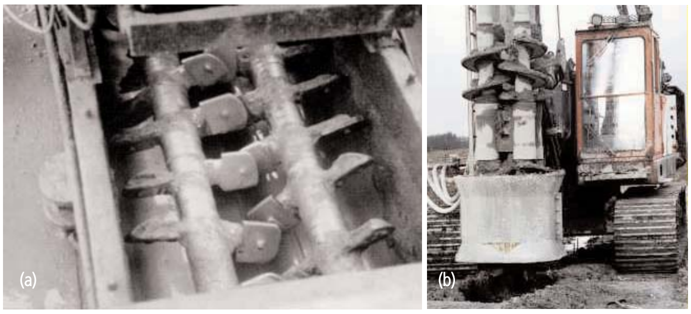

Fig 1. Examples of equipment used in the implementation of S/S: (a) a pugmill used for *ex situ* soil mixing and (b) a soil mixing auger for *in situ* mixing.

1.5.2 *In Situ* S/S Implementation Processes

In situ mixing methods can involve one of two processes: mechanical mixing and pressure mixing.

Mechanical mixing: This approach utilises equipment such as mixing augers (Fig 1b), backhoes and blenders or mixers. Mechanical mixing using augers results in the formation of monolithic contaminated material-binder columns by mixing the binder with the contaminated material in-place using hollow mixing augers. The columns are usually either constructed in an overlapping configuration to ensure complete treatment of the contaminated area or to form a barrier wall around a contaminated site as shown by the exposed columns in Figs 2 (a) and (b) respectively. Soil mixing can be deep or shallow. Deep mixing is usually carried out using augers while shallow mixing can be carried out using one of a number of equipment types including augers, backhoes, blenders or mass stabilisation tools.

Fig 2. Examples of constructed columns using soil mixing augers: (a) overlapping configuration and (b) barrier wall configuration.

Pressure mixing: This method is similar to conventional grouting and involves injection of binders under pressure directly into the contaminated material. This method has not been developed on a commercial scale, however, due to the difficulty of ensuring even permeation of the treatment grout into the ground and the fact that depths in excess of 2 m are usually required to ensure that there is sufficient overburden pressure to withstand the injection.

The selection of the appropriate S/S implementation process depends on a wide range of factors which include, amongst others, waste characteristics, material handling and processing, objectives, regulatory requirements, and economics. The principal advantages and disadvantages of *ex situ* and *in situ* implementation systems with specific references to contaminated soils only are given in the report. *Ex situ* implementation was the method more commonly used until recently when a number of *in situ* implementation techniques were applied commercially in the UK.

It is clear that numerous binders and technologies exist which have been successfully used world-wide and in particular in France and the USA. It is also clear that many binders and technologies are site specific. Hence a considerable amount of research is needed to access the validity of certain binders and technologies on specific sites.

2. BINDERS AND TECHNOLOGIES: PART II - RESEARCH

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 significant earlier research. 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.

2.1 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 been dependent 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 have included: (i) Unconfined compressive strength; (ii) Leachate pH; (iii) Leachability; (iv) Permeability; (v) Freeze-thaw and wet-dry durability and; (vi) Acid neutralisation capacity (ANC). 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.

2.2 INTERACTION BETWEEN BINDER AND WASTE

It is well-known 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. 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 in Table 1 addresses this issue.

Table 1: Research on interaction between binder and waste

Research Area	Specific details
S/S with Portland cement	effect of cyanide, organics, industrial waste and organics, cement chemistry, uniaxial pressing, calcium chloride treatment of PFA and flue gas; metal nitrate salts; foundry dusts
S/S with lime	treatment of lead and iron nitrates
S/S with organophilic clays	pre-solidification absorbance
S/S with blended binders	Portland cement and PFA blends Effect of acid addition; carbonation; binder variability on performance Treatment of metal nitrates by zeolite and silica fume blended cements; incinerator fly ash by sodium silicate blended cements; mine tailings; radioactive waste
S/S with waste materials	use of spent bleaching earth, woodshavings, straw, waste peat
Databases: NNAPICS	neural network analysis for prediction of interactions in cement/waste systems

This Section also includes details of research work on the use of laboratory-scale augers.

3. BINDERS AND TECHNOLOGIES: PART III - APPLICATIONS

This report presents field trials and commercial applications of S/S treatment technologies in the UK for both hazardous wastes and contaminated land. It shows that over the past decade activities in this area and in particular site trials and commercial applications have increased. However, given the wide range of materials and applications available this quantity of projects is still relatively small compared to the amount of similar activities taking place in the US and France. Joint research initiatives between academia and industry would provide the required validation of S/S technologies which will lead to its widespread use. Although S/S treatments do not remove contamination, they prevent further migration and pollution of the environment and are compatible with the Government policy of risk-based management of hazardous water and contaminated land. Until clean-up methods become effective, S/S will remain the most cost-effective and practical method for the treatment of hazardous waste and contaminated ground. However, although there is great pressure to redevelop brownfield sites and despite the clear advantages of stabilisation/solidification, particularly in terms of low costs, landfilling is currently still the preferred option. The fear of later liability and risk which could be associated with stabilisation/solidification is the reason preventing its rapid use. The lack of any liability and risk associated with landfilling maintains its position as the most preferred remediation method, even if involves higher costs are involved. Such risks need to be quantified, particularly in the longer term, so that firm evidence can be used to provide further validation of S/S treatments. Increased research efforts which include full-scale trials, post-treatment monitoring and long-term assessment will provide better understanding and more confidence in the technology. More commercial projects with monitoring and subsequent publication of the results would also help alleviate some of the concerns present.

Table 2 lists the practical applications of S/S that are detailed in the report.

Table 2: Field trials and commercial applications of S/S.

Field Trials
Field treatment of electric arc furnace dust using sodium silicate activated blastfurnace slag
In situ S/S site trial for organic contamination in West Drayton
CIRIA demonstration project –Geodur process
EuroSoilStab EU Project
Treatment of river dredgings and sewage sludge by lime
Greenwich/Blue Circle demonstration project with special cement
Commercial Applications
The Sealosafe process
A13: Thames Avenue to Wennington highway scheme
Ardeer Site, Scotland
West Drayton site, Middlesex
Pumpherston site, nr Edinburgh
Gas Hill Site, Norwich
Long Eaton Site, Nottingham
Greenwich Millennium Experience Site
Leytonstone Site, London
Winterton Holme Water Treatment Works Site
BNFL Sellafield Site

4. PART IV - TESTING AND PERFORMANCE CRITERIA

The purpose of this report is to review current practices in test methods and performance criteria, with an emphasis on the UK. It includes tests, under the broad categories of physical and chemical tests, which are used or could be used in the UK to consider the acceptability of S/S materials for their intended management scenarios. Some of these tests are also often carried out on the original material to be treated to assess its suitability for S/S treatment, and also on binders to assess their effectiveness. Both test methods and performance criteria are also placed in the context of a number of international regulatory frameworks.

Whether in preparation for full-scale treatment, or to verify the effectiveness of treated material *in situ*, it is necessary to assess the performance of an S/S material in order to judge its improved properties and the effectiveness of the binder matrix in containing contaminants. This is achieved by carrying out various tests, the results of which may be compared against performance criteria. It is appropriate to establish a testing regime that addresses the relevant issues for the management scenario being considered (e.g., disposal or utilisation). Performance criteria are also usually developed in conjunction with the objectives of the treatment and the management scenario of the end material.

It is difficult to predict, and also simulate in the laboratory, the long-term environmental conditions that the S/S material might be subjected to. For this reason, and also because the behaviour of a S/S material is complex, its performance is generally evaluated using a combination of several physical and chemical tests. Each test provides a partial insight into the behaviour of the S/S material and hence the effectiveness of the S/S treatment system. Several different tests may exist with the objective of measuring the same intrinsic property; the results of these tests will differ depending on the specific testing conditions. Therefore, consideration of the results and their relationship to the performance criteria in light of the specific testing conditions is essential.

Physical tests are used to predict mixing behaviour, reagent needs and volume increases, and compare treated and untreated materials in terms of their strength and durability. Chemical tests are used to determine the leaching behaviour of the S/S material.

4.1 TEST METHODS

Various test methods have been adopted in research and practice to assess the efficiency of S/S processes. Such assessment could be generally categorised as:

1) Basic information tests, which measure basic material properties (e.g., grading, plasticity, particle density, total contaminant concentration). These tests are often referred to as index tests.
2) Performance tests, which relate to the properties of the material in use (e.g., strength, leachability).

These categories include physical and chemical (predominantly leaching) tests, and may be used for understanding mechanisms, assessing compliance with reference criteria (e.g., regulatory) or on-site verification, i.e., quality control in practical field situations.

This report summarises the details and relevance of the most commonly used tests. In addition, other tests which are considered important for certain management scenarios are also briefly described.

It is common to use standard test methods in the practical application of S/S, but both standard and non-standard tests are commonly employed in research, where a more mechanistic understanding is sought.

After characterisation of total contaminant concentrations, the most commonly used tests were found to be batch (or extraction), leaching tests, and measurements of unconfined compressive strength, weathering resistance, and hydraulic conductivity. These are all performance (rather than index) tests.

Acknowledgements

This Bulletin was prepared by CL:AIRE staff from the first four State of Practice Reports produced by STARNET.

REFERENCES

Each of the State of Practice Reports have extensive reference sections. Individual references are not provided in this Bulletin, so please refer to the Reports for full references.

State of Practice Report - UK Stabilisation/Solidification Treatment and Remediation:
Binders & Technologies
Part I Basic Principles
Part II Research
Part III Applications
A Al-Tabbaa and ASR Perera (December 2002)

State of Practice Report - UK Stabilisation/Solidification Treatment and Remediation:
Part IV: Testing & Performance Criteria
ASR Perera, A Al-Tabbaa, JM Reid, JA Stegemann (January 2004)

The STARNET State of Practice Reports are available to download, free of charge, from the STARNET website: http://www-starnet.eng.cam.ac.uk/SoPReports.htm

Forthcoming reports include:
State of Practice Report - UK Stabilisation/Solidification Treatment and Remediation:
Part V: Long-Term Performance and Environmental Impact
Part VI: Quality Assurance and Quality Control
Part VII: Best Practice Guidance Document

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