C:L:AIRE

guidance bulletin

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CL:AIRE guidance bulletins describe good practice as it applies to the characterisation, monitoring or remediation of contaminated soil or groundwater. This guidance bulletin provides a summary of the Environment Agency's "Guidance on the use of Stabilisation/Solidification for the Treatment of Contaminated Soil" which was published in 2004.

Stabilisation/Solidification for the Treatment of Contaminated Soil

PURPOSE OF THIS BULLETIN

The purpose of this guidance bulletin is to provide a summary of the Environment Agency's "Guidance on the use of Stabilisation/Solidification for the Treatment of Contaminated Soil" (R&D Technical Report P5-064/TR/1) and to encourage readers to obtain a copy for themselves. The document was published in 2004 as one of the outputs from the CASSST (Codes And Standards for Stabilisation/Solidification Technology) work programme with the objective to provide good practice guidance on Stabilisation/Solidification (S/S) techniques. It is intended to encourage the effective use of S/S in appropriate circumstances by itself or as part of a remedial strategy. An authoritative (>300 page) Science Review has also been produced as part of the CASSST initiative. This provides further detailed information on published literature associated with S/S and is referred to throughout the Guidance document. Both the Guidance and the Science Review are available as free downloads or can be ordered on CD (see page 7 for details).

This bulletin will summarise the main sections of the Guidance - (introduction, screening, design, construction, long-term monitoring and maintenance, and sampling and testing programmes) - and also provides a brief overview of the Science Review.

1. INTRODUCTION

1.1. Background

Stabilisation/solidification (S/S) is a remediation technology that relies on the reaction between a binder and soil to reduce the mobility of contaminants.

Stabilisation - involves the addition of reagents to a contaminated material (e.g. soil or sludge) to produce more chemically stable constituents; and

Solidification - involves the addition of reagents to a contaminated material to impart physical/dimensional stability in order to contain contaminants in a solid product and reduce access by external agents (e.g. air, rainfall).

S/S is an established remediation technology for contaminated soils and treatment technology for hazardous wastes in the USA and some EU member states. However, the uptake of S/S technologies in the UK has been relatively poor, and a number of barriers have been identified including:

- the relatively low cost and widespread use of disposal to landfill (prior to 2004);
- the lack of authoritative technical guidance on S/S in the UK;
- uncertainty over the durability and rate of contaminant release of S/S-treated material;
- experiences of past poor practice in the application of cement stabilisation processes used in waste disposal in the 1980s and 1990s; and
- residual liability associated with immobilised contaminants remaining on-site, rather than their removal or destruction.

S/S may be used on its own or in combination with other risk management approaches as part of a remedial strategy to address the pollutant linkages that need

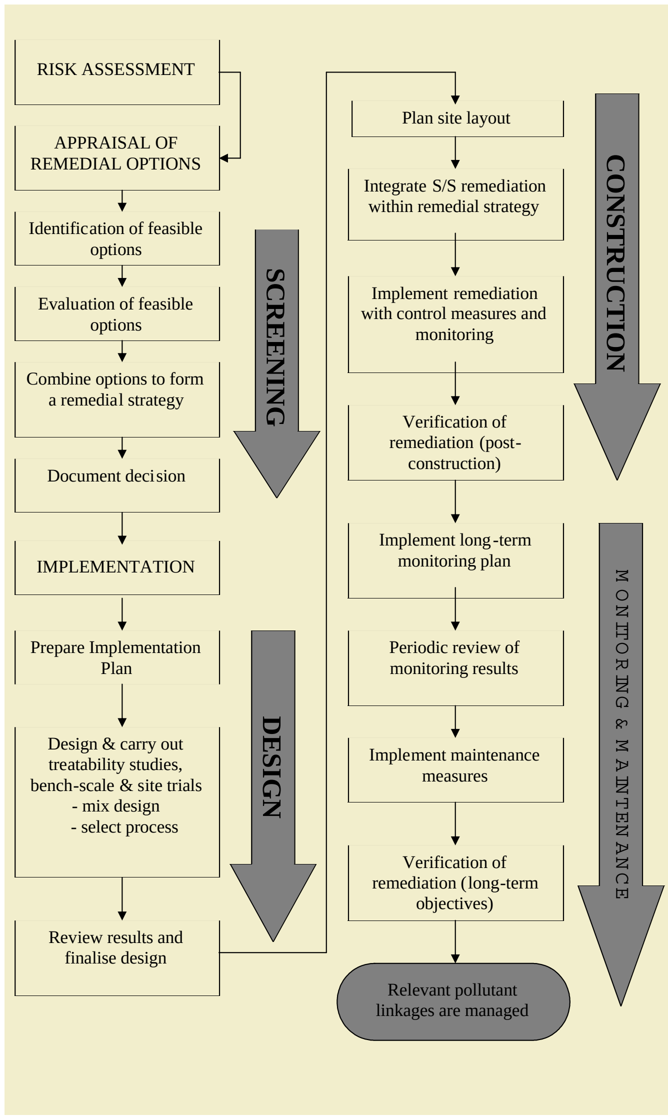

Figure 1: Overview of S/S treatment process.

to be managed. S/S technologies achieve immobilisation by reaction of the soil matrix and contaminants with reagents to promote sorption, precipitation or incorporation into crystal lattices, and/or by physically encapsulating the contaminants. The mixture of reagents and additives used for S/S is commonly referred to as the binder, and can range from a single reagent to a multi-component system. Hydraulic binders react with water to form solid matrices and are the most commonly used binders. The Guidance document primarily examines the use of hydraulic binder systems that are usually designed to provide both chemical and physical improvements to the contaminated material.

Hydraulic binders have been used to effectively treat a wide range of inorganic contaminants and some organic contaminants, including:

- metals and metalloids;
- asbestos;
- radionuclides;
- inorganic corrosives;
- inorganic cyanides;
- solid organics (e.g. plastics, resins, tars);
- polychlorinated biphenyls (PCBs);
- polycyclic aromatic hydrocarbons (PAHs); and
- dioxins.

In addition to contaminant type and properties, the efficacy of S/S will be influenced by the presence of inhibitory compounds (e.g. sulfate, oil), physical properties of the material to be treated, characteristics of the site and future land use. Treatability studies are considered an integral part of the selection and use of S/S technologies. They will usually be required to select the binder and to demonstrate the efficacy of treatment using selected plant and equipment during a field trial, before finalising the design for full-scale implementation.

A range of both *ex situ* and *in situ* methods of application have been developed to address potential practical constraints and site characteristics, including:

- excavation and mixing with reagent in plant designed for that purpose (e.g. pugmill);
- direct mixing of soil with reagent in thin layers, e.g. by rotovation, followed by compaction;
- in-drum processing; and
- using soil mixing equipment, e.g. modified hollow-stem auger, to inject and mix reagent.

If S/S is effective, the availability of the contaminants and potential to impact on receptors will be greatly reduced and risks will be effectively managed during the time that those pollutant linkages would otherwise continue. However, the release of contaminants will occur and the durability of the remediation will need to be demonstrated. Key issues that may need to be addressed include the structural integrity of the treated material, the buffering capacity of the system, and the rate and time scale of contaminant release.

The cost of remediation will be strongly influenced by the cost of materials, volume and throughput of material, nature and concentration of contaminants, and physical properties of the material to be treated. Other costs that may apply to S/S remediation include the provision and maintenance of measures to protect the treated material and long-term monitoring.

The principal advantages and disadvantages of S/S are summarised in Table 1:

Table 1: Advantages and disadvantages of S/S

Advantages	Disadvantages
• can be completed in a relatively short time period	• does not destroy or remove the contaminants
• can be used to treat recalcitrant contaminants (e.g. heavy metals, PCBs, dioxins)	• may be difficult to predict long-term behaviour
• may be performed *in situ* or *ex situ*	• may result in an overall increase in volume of material
• process equipment occupies a relatively small footprint	• consumption of natural resources
• the physical properties of the soil are often improved by treatment (e.g. increased strength, lower permeability)	• may require long-term maintenance of protection systems and/or long-term monitoring

The Codes and Standards for Stabilisation and Solidification Technologies (CASSST) is a British Cement Association/University of Greenwich initiative to produce and disseminate guidance for consulting engineers, contaminated land stakeholders and regulators on the use of S/S technologies in the UK. The CASSST work programme has included:

- **a series of annual conferences (Recycling Contaminated Land) addressing the problems of land contamination and potential solutions using S/S technology;**
- **a Department of Trade and Industry-sponsored study visit to the USA to assess current practice; and**
- **a telephone and internet-based helpline.**

Further information on the CASSST project is available through the web-site www.cassst.co.uk.

1.2. Objectives of the Guidance

To support Government policy, the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency have developed guidance for landowners, regulators and others making decisions about, and taking appropriate action to deal with, land contamination. This guidance is embodied in CLR11, *The Model Procedures for the Management of Land Contamination* (Defra/Environment Agency, 2004), which presents a framework for risk assessment and risk management of land contamination, whatever the circumstances of the land and regulatory regime that applies.

Guidance on the Use of Stabilisation/Solidification (S/S) for the Treatment of Contaminated Soil is intended to support the *Model Procedures* by providing a structured framework for the selection, design and implementation of S/S technologies as part of a remedial strategy for dealing with land contamination. The Guidance document is supported by a comprehensive review of the scientific literature on S/S technologies (see summary on page 8). It has been prepared for use by Agency staff, problem holders, environmental consultants, technology vendors and contractors, other regulators and other interested parties.

1.3. Legislative Framework for Remediation

The Environment Agency would seek to support the use of S/S in England and Wales for the remediation of contaminated soil where it is likely to be effective, practicable, durable and reasonable. The use of S/S technology for the treatment of contaminated soil will be regulated by the Environment Agency and may be controlled under either the waste management licensing or Pollution Prevention and Control (PPC) regimes, depending on whether:

- treatment is at a fixed plant that is put into operation before 31 October 1999 (licensed under the Waste Management Licensing Regulations 1994 - WMLR);
- a substantial change to a waste management licence brings the installation under the Pollution Prevention & Control (England and Wales) Regulations, 2000;
- a new installation is put into operation on or after 31 October 1999 (permitted under PPC); or
- treatment of contaminated soil is carried out at the site of production using mobile plant issued under WMLR.

1.4. Structure of the Guidance

The chapters of the Guidance set out a recommended approach for the treatment of contaminated soil by S/S. The key steps are described below and the overall process is summarised in Figure 1 (page 1):

Chapter 2: Screening - is S/S likely to be feasible?
Chapter 3: Design - what binder should be used and how should S/S be applied?
Chapter 4: Construction - what are the key issues for successful implementation?
Chapter 5: Long-term monitoring and maintenance - is action required to ensure long-term performance?
Chapter 6: Sampling and testing programmes - what tests are required to demonstrate compliance with remedial objectives and predict long-term performance of the waste form?
Chapter 7: Summary

Science Review (on compact disc) – what science is used to underpin the guidance?

2. SCREENING

2.1. Introduction

This chapter describes a screening methodology to evaluate whether S/S is a feasible risk management option on its own or in combination with other remediation techniques. It discusses the evaluation of S/S against a number of site-specific screening criteria. This chapter only considers screening S/S and not the comparison with other potential options leading to selection. The generic process of options appraisal and selection is detailed in CLR11 (2004).

2.2. The Screening Method

The screening methodology follows a series of logical steps as summarised below:

- identify feasible options for each identified pollutant linkage;
- evaluate short-listed feasible options for each pollutant linkage;
- combine selected remedial options to address the pollutant linkages; and
- document decision.

The first stage of the screening process (Figure 2) is to quickly assess whether S/S is likely to be a feasible remedial option to deal with one or more of the relevant pollutant linkages identified from the conceptual model.

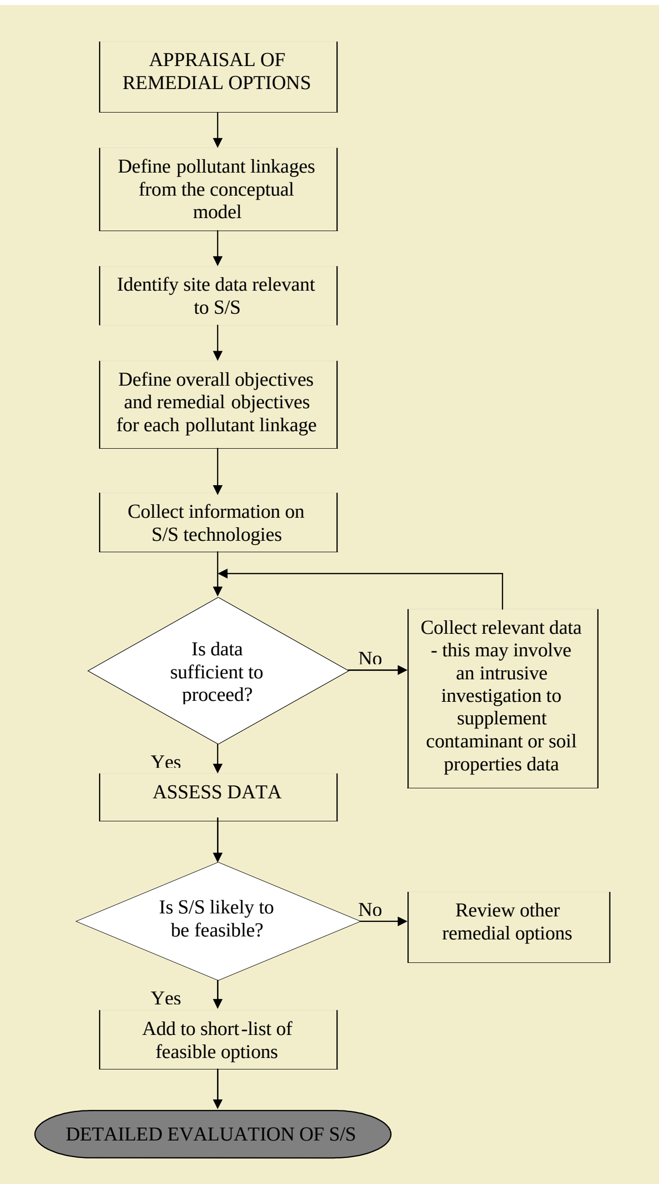

Figure 2: Flowchart to assess the feasibility of S/S at a particular site.

Plate 1: Royal Engineers taking samples at an S/S site in Dartford.

Where S/S is being evaluated, the conceptual model should be reviewed to indicate how the remedial process interacts with the site and its surroundings, including the changes to, and potential creation of, pollutant linkages as a consequence of the remedial process. The conceptual model should be reviewed, as additional data becomes available, following initial evaluation of data and throughout the screening process.

This stage will usually be carried out using existing information, although may be supplemented by more information, e.g. from an additional intrusive investigation, if there is insufficient data to carry out the assessment. At the end of this stage a short list of feasible options will be identified for each relevant pollutant linkage to be taken forward for detailed evaluation.

3. DESIGN

3.1. Introduction

This chapter discusses the design of S/S remediation. In particular it details the use of treatability studies to validate mix designs and site trials to assess the proposed plant and construction methods (Figure 3). Reference should be made to CLR11 (2004) for guidance on the general aspects of designing and implementing remedial works.

3.2. Treatability Studies

Treatability studies should be designed and carried out to achieve specific objectives, which may include:

- determination of the most economical mix design;
- identification of handling problems;
- identification of environmental issues, e.g. volatile emissions;
- assessment of physical and chemical properties and uniformity of the material;
- determination of volume increase associated with the S/S process.

3.2.1. Desk study

The desk study may be used to identify suitable mix designs by considering factors such as soil types and the types of contaminant present. Reference to the documents cited in the Guidance should reduce the number of mix designs to a manageable level.

3.2.2. Bench-scale testing

Bench-scale tests are usually undertaken to evaluate the efficacy of various binder formulations using representative samples from the site. The bench-scale tests also enable compliance criteria to be developed to assess and monitor the performance of full-scale construction.

Due to the variable nature of contaminated materials encountered, bench-scale tests are an essential stage in evaluating the effectiveness of potential binder systems to determine the optimum mix design. In addition, information on otherwise unidentified interference effects (e.g. set retardation) and emissions (e.g. VOCs) can be established.

3.2.3. Site trials

The site trial involves taking the most successful mix or mixes determined during the bench-scale testing, to perform a small-scale trial in the field. This is a valuable opportunity to evaluate the equipment to be used to treat the material in the full-scale works and to compare the properties of the treated material against those predicted from the bench-scale tests.

3.3. Key Technical Considerations for Mix Design

A number of issues must be resolved for the optimum binder to be selected, and the key issues are discussed below.

3.3.1. Pre-treatment

Pre-treatment may be carried out to modify one or more of the initial properties of a soil or contaminant to enhance performance during treatment.

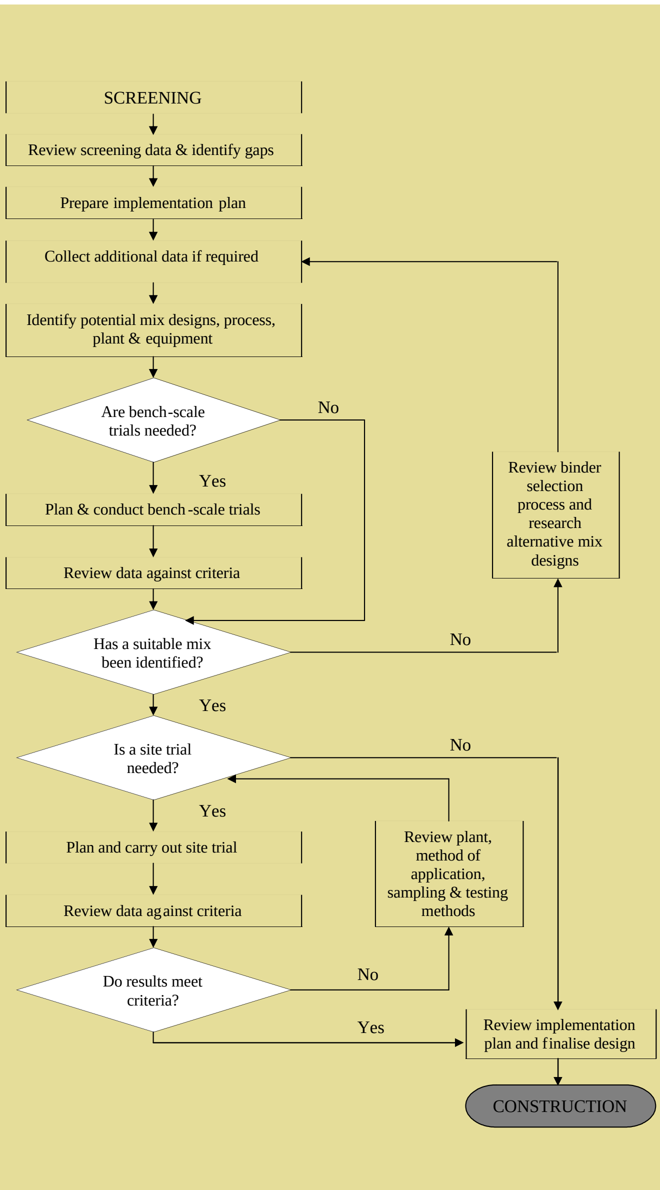

Figure 3: Role of treatability studies and site trials in design.

3.3.2. Binder selection

Based on consideration of the data collected on the chemical and physical material properties and the disposal or re-use scenario, a number of mix designs can be proposed for evaluation. In some situations the nature of contaminants may vary across a site, and it may be preferable to consider using more than one mix design to treat different zones, either on a technical and/or economical basis.

Factors to consider when selecting a binder include:

- any possible interference effects of contaminants on the performance of the binder;
- the moisture content of the material and whether it will affect the binder performance;
- the workability of the binder-soil-water mixture having regard to the method of application and/or compaction;
- the ability to chemically stabilise or permanently bind contaminants;
- the ability to achieve and retain the desired physical properties required for the end use of the material, such as strength;
- factors that could affect durability; and
- potential impacts on the surrounding environment.

The binder may comprise a single reagent or a complex combination of reagents with or without additives. The most commonly used binders are cement or lime based with or without secondary reagents such as pulverised fuel ash (PFA) or ground granulated blastfurnace slag (GGBS). Knowledge of reagent properties and interaction with soil and contaminants is of vital importance in designing effective S/S remediation, and can reduce the cost of treatability studies.

3.3.3. Mix quantities

The type and quantity of binder will be determined from the results of the treatability studies. It is recommended that the manufacturer and supply of binder remains constant from treatability studies through to full-scale treatment to avoid the potential for inconsistent performance due to minor variations in binder properties. The quantities of binder specified, should take account of the following:

- the findings of treatability studies;
- conditions on site;
- variation in the properties of the material to be treated;
- calibration and accuracy of batching/mixing plant to deliver the correct binder quantity;
- any variation in the properties of the binder; and
- the variation in properties of the treated material.

The quantity of water used is also important for workability of the mix, to minimise bleed water, ensure sufficient water for hydration reactions to proceed, and to ensure physical characteristics of the treated material (e.g. density, strength, permeability).

3.3.4. Volume increase

Since most S/S methods involve the addition of solid reagents to the contaminated soil, an increase in the final volume of the treated product, typically ranging from 30 % to 130 %, is expected for *ex situ* application. Such volume increase is typically related to the proportion of binder added and the bulking properties of the material when excavated. Lesser volume increases are expected for *in situ* application, and cases have been reported where volume increase is insignificant or a net decrease has occurred due to an efficient mixing and compaction process and the high void ratio of the original material. This may be an important aspect in terms of practicability and should be assessed during treatability studies.

3.4. Process and Plant Selection

The key issues that should be taken into consideration when identifying suitable process and plant are:

- material characteristics and ground conditions (e.g. bearing capacity);
- quantity of material to be treated and rate of treatment;
- size of treatment area available;
- any restriction on time or capacity of vehicles on local roads;
- compatibility of equipment with proposed binder system;
- any specific requirements of the end-product;
- dust generation of plant with respect to environmental and health and safety aspects;

- ability of plant to deal with volatile contaminants if present; and
- movement of materials around site, before and after treatment.

3.5. Summary

Treatability studies are of fundamental importance to the design process - building confidence that an effective binder and mix have been selected to achieve remedial objectives, including long-term objectives for both structural integrity and leaching performance for the design life of the remediation.

4. CONSTRUCTION

4.1. Introduction

This chapter describes some of the key considerations in carrying out S/S remediation to encourage a safe, environmentally sound and efficient working environment. It emphasises the importance of quality control to check consistency and compliance during treatment, and thereby increase confidence in the quality and performance of the treated material. Environmental monitoring is also addressed to confirm that the remedial activities do not cause significant pollution or harm.

4.2. Site Planning

Site planning is an important step in order to efficiently integrate with other works being carried out on-site, e.g. other remedial works and redevelopment activities. It will also ensure that works can progress smoothly and safely, with minimal downtime, double-handling and risk of accidents. During planning, it should be confirmed that any permits or approvals required have been obtained. The site layout and programming of works should also be confirmed and preparatory works (e.g. scrub clearance, construction of access roads and drainage) be carried out before mobilisation and commencement of construction activities. Provision of health and safety equipment and compliance with all relevant health and safety legislation should also be ensured throughout all construction activities.

4.3. Control of Quality Throughout Construction

The treatment process should be carried out according to the method statements /working plan developed during the design process and submitted to the regulator before implementation. A key aspect of treatment will be the management and control of quality throughout construction, both to ensure the appropriate control of the process and that the long-term performance of the treated material is not compromised through poor monitoring or incorrect application. A quality assurance plan should have been prepared as part of the overall working plan during the design process.

4.4. Environmental Protection

The main areas of environmental impact during a remediation relate to uncontrolled emissions to air, land or water, management of waste arisings and protection of archaeological resources. The contractor must ensure that all reasonable steps are taken to minimise any environmental impacts with specific issues including:
- disturbance and mobilisation of contaminants;
- storage and containment of reagents;
- spill response measures;
- uncontrolled emissions to water, land or air;
- working near water courses;
- storage, transport and disposal of waste (duty of care);
- waste minimisation;
- decontamination of vehicles and equipment;
- increased traffic movements;
- protection of archaeological resources; and
- protection of ecological receptors.

4.5. Environmental Monitoring

Environmental monitoring activities will need to be programmed into the works to ensure that remedial activities do not give rise to uncontrolled emissions to air, land or water. Monitoring may also be required to demonstrate that S/S remains effective for a pre-defined time scale depending on the disposal or re-use scenario. The long-term monitoring requirements to satisfy the latter are discussed in Chapter 5 of the Guidance.

Plate 2: S/S of a tar lagoon in France.

4.6. Health and Safety

The health and safety implications of all site activities and materials need to be considered in respect of the work force, office staff, visitors to site, members of the public, and the end users of the site. Health and safety legislation imposes duties on everyone on site to take responsibility for their own safety and that of their co-workers.

4.7. Verification

A verification programme is integral to the remediation and should be planned at the design stage of the project and reviewed until all remediation objectives have been satisfied. It may require the collection of data before, during and after treatment, and in the long-term (years to decades) in order to assess compliance with remedial criteria.

The verification requirements will be taken into account when developing the sampling and testing strategies to address specific lines of evidence developed from the conceptual model. Lines of evidence could be required to demonstrate some of the following issues:

Before and during remediation:
- baseline or initial conditions before remediation (for surface water, groundwater and air quality);
- soil with contaminant concentrations above pre-determined criteria have been excavated and removed (for *ex situ* treatment);
- process conditions are within operating parameters (e.g. pH, temperature, slurry viscosity (*in situ*), mixing rate);
- process emissions are within pre-determined limits;
- contaminants in treated material meet pre-determined leaching levels (from eluate tests); and
- contaminants in fugitive emissions at specified monitoring points are within predefined criteria.

Long-term:
- groundwater levels around the waste form are within acceptable limits;
- groundwater quality down-gradient is within acceptable limits; and
- contaminants in treated material (cored) meet pre-determined leaching levels at predetermined time intervals.

4.8. Summary

The achievement of remedial objectives and criteria must be assured and demonstrated for S/S remediation. Key elements include good quality site planing and programming, quality control procedures to manage the treatment process, and consideration of the impacts of treatment activities through environmental protection and monitoring, and health and safety management. A verification report should also be prepared to provide a detailed and permanent record to demonstrate that all remedial objectives and criteria have been achieved.

Plate 3: S/S tar pit sample in USA.

5. LONG-TERM MONITORING AND MAINTENANCE

5.1. Introduction

This chapter describes the long-term monitoring and maintenance activities that may be required at a site after S/S remediation has been completed. In particular it discusses the significance of monitoring and maintenance with regard to the durability of the waste form and protection from anthropogenic disturbance.

5.2. Monitoring

The overall purpose of long-term monitoring is to demonstrate whether S/S remains effective for a pre-defined time scale, depending on the disposal or re-use scenario.

Re-use scenarios will vary, but where the treated material is recovered and retained on-site, monitoring may be required for the duration that the pollutant linkages addressed by the remediation would otherwise have existed. This will be a site-specific decision based on the risk associated with realistic contaminant release scenarios. In most cases, long-term environmental monitoring requirements are likely to focus on impact to the water environment. A monitoring plan should be developed during the design of the remediation to document monitoring activities to be carried out.

5.3. Maintenance

The disposal or re-use scenario may include measures to protect the waste form from disturbance or weathering, or isolate it from receptors after construction. The end use of the site will have a significant influence on the design of protective measures and it is important that any change of land use will not compromise the long-term structural and leaching performance of the treated material. It is also important that protective measures, once installed, are maintained to deliver the designed level of service for a pre-determined time scale. This time scale may relate to the design life of a building or road if the treated material is used as an engineering material or for the anticipated period that the pollutant linkages addressed by the treatment would otherwise have existed.

6. SAMPLING AND TESTING PROGRAMMES

6.1. Introduction

This chapter focuses on the selection of an appropriate testing strategy to develop confidence in the long-term leaching performance of the S/S treated material. Sampling and testing activities are an integral component of the activities described in the preceding sections, and separate strategies may need to be prepared for the following purposes:

- **Screening** - characterisation of the material and contaminants before binder addition, possibly with limited leach tests to confirm feasibility of remedial option.
- **Design** - in addition to the above, information will be needed on the soil - binder mixtures proposed. Treatability studies will be used to assess the ability of potential mixes to achieve remedial criteria with regard to leaching and physical characteristics (e.g. strength, permeability). Data may also be collected to assess baseline conditions before remediation commences to ensure that the remedial activities do not give rise to pollution or harm and/or to verify that the remediation has broken relevant pollutant linkages.
- **Construction** - sampling of the binder and uncured treated material may be required to confirm the specification of the reagents and for process control. Compliance testing is carried out on cured samples (usually stored for a pre-defined period) to verify that the treated material meets physical (e.g. strength, permeability) and chemical (e.g. contaminant leaching) remedial criteria.
- **Post-construction** - further compliance or characterisation testing of cured material in its disposal or re-use scenario may be required at pre-defined time intervals to verify the long-term performance. Sampling in the event of an unexpected release of contaminants from the treated material, as identified from long-term monitoring may also be carried out.

6.2. Sampling Strategies

A sampling strategy should be developed for each stage of sampling carried out during the S/S remedial process, and may need to be developed for a number of activities including:

- sampling excavated soil/waste before *ex situ* treatment;
- sampling screened, blended and/or pre-treated soil before *ex situ* treatment;
- sampling during *in situ* treatment;
- sampling from a stockpile;
- sampling from an *ex situ* moving stream process (e.g. a pugmill);
- sampling of a manufactured product (e.g. a sub-grade or capping layer) before reuse; or
- sampling of treated material before landfilling.

6.2.1. Sampling objectives

It is important that samples used for treatability studies are representative of the material designated for treatment and the objectives of the treatability study are clearly set out. It is not appropriate to conduct treatability studies on a sub-set of the material (e.g. a single stockpile or from a small part of the site to be treated) for the purpose of scaling-up to implementation for the whole site.

Some parameters may show significant variation with time caused by attenuation, migration, extrinsic effects (e.g. weathering, temperature, barometric pressure) or land use. This should be taken into account in the event of any significant time delays between sampling exercises.

6.2.2. Sample locations and pattern

The selection of sampling locations will depend on:
- information already available;
- number and type of samples required;
- variability;
- site conditions (topography & access);
- depth of material; and
- remediation process (e.g. column patterns or moving-stream process).

Where *in situ* augering techniques are used, sample locations after treatment should include both column centres and overlap areas to ensure that the remedial criteria are achieved. An *ex situ* moving stream process (e.g. pugmill mixing) will usually have a single designated sampling location for the treated material. Direct mixing methods (e.g. spread, rotovate and compact) will tend to be verified by grid sampling material from each treated and compacted layer.

This section of the Guidance also discusses sample size, sampling techniques, sample preservation, labelling, storage, handling and transportation, and sample testing and analysis.

6.3. Testing Programme for Evaluating the Leaching Performance of a S/S Waste Form

The durability, including physical and long-term leaching performance of the waste form is a key consideration that should be determined over realistic time scales. Assessment of the performance of S/S material may be considered:
- post-construction (1-2 years);

Plate 4: Trial hole in weathered S/S at Dartford site.

- in the medium-term, e.g. 10-30 years; and
- in the long-term, realistically no more than hundreds of years.

The approach and time scale selected to address durability questions will depend on the design life, properties of the treated material, protection against extrinsic factors, and potential risk to receptors (e.g. groundwater). Long-term assessment will require a modelling approach to predict performance and a period of monitoring to validate the model.

Limited testing will provide basic information on the contaminant availability under a limited range of conditions. Tests will usually be selected to provide relatively low cost and rapid turnaround of data. Such testing may be performed during screening or initial selection of binder-soil mixes.

Comprehensive (equilibrium) testing will be designed to provide information on the treated material under a range of realistic scenarios, with leaching assumed to be equilibrium controlled. It may be appropriate not to conduct comprehensive testing under equilibrium conditions, for example where a decision is already made to use diffusion testing to assess the leaching performance of a monolithic material.

Testing to assess diffusive mass transport will only be considered where the treated material is monolithic or designed to allow water to flow around rather than through, either where granular material is compacted to a high density and/or protected by a low permeability sealing layer (e.g. compacted clay, geomembrane or blacktop). In such cases, diffusive mass transfer of contaminants from porewater to the leachant flowing around the treated material will control contaminant release.

7. SUMMARY AND CONCLUSIONS

This chapter provides a brief overview of S/S and highlights the benefits of using the approach recommended in the Guidance.

Stabilisation/solidification can be an effective, practicable and durable remedial technique if used on its own or in combination with other risk management methods under appropriate circumstances. It can also represent a reasonable solution, with regard to costs, and a viable alternative to "dig and dump". The Guidance document provides good practice guidance for the use of S/S technologies for the treatment of contaminated soil and provides technical information that may be used for the treatment of other waste streams, including sludges and sediments.

The acceptability of S/S as part of a remedial strategy will depend on demonstrating to the regulator and other stakeholders that:

- the contaminants are immobilised to an appropriate standard and will remain so under future foreseeable conditions;
- the remediation process does not give rise to detrimental impact on the environment or human health;
- it is practicable to achieve remediation within an appropriate time scale; and
- procedures are put in place to carry out necessary maintenance and long-term monitoring.

The Guidance recommends that:

- the site is adequately characterised to demonstrate the feasibility of the remedial solution and to carry out the detailed design;
- bench-scale treatability studies are carried out to confirm the performance of the proposed mix designs;
- field trials are carried out to demonstrate the ability of the plant and equipment to adequately mix the soil and binder and achieve remedial criteria;
- all relevant activities are appropriately documented and validated;
- proposals for maintenance of the waste form and long-term monitoring, when necessary, are implemented and reviewed; and
- appropriate testing strategies are developed, having regard to the conceptual model, to take account of foreseeable exposure scenarios and verify that the remedial criteria can be achieved in both the short and long term. In some circumstances this will involve predictive modelling.

Acknowledgements
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This guidance bulletin was prepared by CL:AIRE staff from information contained in the Guidance and Science Review.

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References
Individual references are not provided in this bulletin, but they may be found in both the Guidance and the Science Review.

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Obtaining your copy
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Hyperlinks to the documents are given below:
Guidance
http://publications.environment-agency.gov.uk/pdf/SCHO0904BIFO-e-e.pdf
Science Review
http://publications.environment-agency.gov.uk/pdf/SCHO0904BIFP-e-e.pdf

Alternatively, contact the Environment Agency's National Customer Contact Centre by emailing enquiries@environment-agency.gov.uk or by telephoning 08708 506506 and quote R&D Technical Report P5-064/TR/1.

Science Review

A summary of the 300-page document which supports the Guidance.

INTRODUCTION

Stabilisation/solidification technology is utilised widely outside of the UK as a treatment or remediation option. Indeed, in countries such as France and the United States, S/S is used to treat substantial volumes of contaminated materials each year.

S/S is a technology based on the principle that contaminants can be rendered immobile in a product that is chemically and physically stable over long time scales. The S/S waste forms will gradually release contaminants into the environment but, when adequately designed and constructed, at a rate that causes minimal environmental impact. In some cases, regular monitoring of contaminants in groundwater within the vicinity of the waste form is required to ensure that concentrations remain within environmental quality targets.

In practice, the application of S/S to hazardous waste and contaminated soil is supported by a significant body of scientific evidence gathered from numerous laboratory investigations and the widespread application of S/S in the field, extending over several decades.

The main cost considerations in the application of S/S include:

- availability of binding agents;
- need for additional treatment steps;
- site access and space requirements; and
- cost of alternative remediation technologies.

In the USA, for example, the cost of landfilling hazardous waste is high, and this places alternative remediation options such as S/S at an advantage. In the UK, the landfill tax escalator, requirement for pre-treatment and restrictions on use of landfill resulting from the Landfill Directive are expected to have a similar impact.

The following discusses the main findings of the Science Review and their importance in the context of the application of S/S within the UK.

BASIC PRINCIPLES

The specific nature of contaminated materials, in respect of substrate and speciation of contaminants has an obvious influence on the impact they may have on the environment. Other factors, including temperature, pH, moisture content and redox environment can also influence the mobility of contaminants. Thus, careful consideration of soil properties and the nature of contamination are important when predicting the outcome of remediation by S/S.

A wide range of binder-materials suitable for use during S/S is available. Binding agents commonly include lime and cement (the hydraulic binders) and bitumen (an organic binder). The hydraulic binders can be blended with other materials which include PFA, GGBS and silica fume to optimise the treated product and meet design criteria. In addition, the chemical environment within the bound S/S system can be adjusted by adding specific materials. In this way difficult contaminants can be targeted and remedial targets achieved.

The application of hydraulic binders can result in a product in which contaminants are both physically and chemically encapsulated. The interaction of soils themselves with cementitious binders during S/S invariably improves the encapsulation of contaminants and the engineering properties of the treated waste form. When bitumen is used, soil particles (and contaminants) are physically encapsulated in the binder emulsion but are unlikely to take part in any chemical reactions.

FIXATION

Inorganic and organic contaminants are commonly found together in contaminated soil or hazardous waste. In media where the contaminants are predominantly inorganic in nature, S/S is a well established and a reliable treatment technique. However, the speciation of heavy metals may mean that additional pre-treatment steps are necessary.

Inorganic contaminants may be strongly bound to soil-like matrices by sorption processes. Addition of binders to soil or waste is likely to cause changes in speciation (and potentially mobility) of inorganic contaminants, but as the S/S products have low permeabilities and a high pH, mobile contaminants can become fixed in the treated product. Metals are immobilised in solidified waste forms through a number of mechanisms, which include pH control, sorption, precipitation and physical encapsulation. Nevertheless, chemical fixation is the most important factor for long-term stability and, as the binder system can be tailored to the contaminants to be treated, it is possible to design S/S for optimised waste form performance. The interference effects from some inorganic or combinations of inorganic contaminants can adversely affect setting and hardening reactions and the ultimate performance of the S/S waste form. Knowledge of the nature of contaminants, supported by adequate bench testing will ensure the best choice of binder-system and eliminate any threat to performance from interference effects.

Where organic contaminants are present in significant quantities they may present difficulties during treatment. Many organic compounds are mobilised at the high pH associated with hydraulic binders because they form organic complexes. In addition, soil organic matter can be soluble at high pH and organic compounds may undergo complex reactions, sorption, and degradation reactions during solidification.

Organic compounds may also interfere with the hydration reactions that take place in cement or lime-based systems, resulting in unsatisfactory physical characteristics and unacceptably high leachate concentrations. Nevertheless, organic contaminants can be successfully treated by S/S. When leaching of organic contaminants is deemed to be a problem a number of sorbents suitable for use with S/S systems may be used in a pretreatment step or as a component of the binder system itself. These include activated carbon, shredded car tyres and modified bentonite.

To ensure that S/S is successful there must be an effective interaction between the contaminants and the binding agent (either chemically, physically or both). In addition, extrinsic factors such as temperature and humidity and waste-borne compounds, that may cause interference, should be controlled. A large body of historical data and objective guidance, especially in the USA, exists to help vendors successfully apply S/S.

CONSTRUCTION

If the simple procedures recommended for use in the guidance are followed, the chances of failure of S/S are low. One of the most important steps to be employed during S/S is the treatability trial. Here, the most appropriate mix can be determined and tested and problem materials can be addressed. Treatability trials should include testing methods that enable an assessment of leaching performance against key influences and a range of tests have been developed to be applicable to a range of materials, including contaminated soil. The disposal or re-use scenario should be identified, and test boundaries (e.g. pH or liquid to solid ratio) should be set having regard to most likely and extreme field conditions. In doing this, the vendor is able to demonstrate that full-scale operations are based on optimised systems that meet remedial targets.

Once the mix design(s) have been chosen, the plant and process options for field implementation can be selected. It should be emphasised, however, that the application of S/S utilises well-established civil engineering techniques that may involve *in situ* or *ex situ* process operations. The proper application of S/S in the field is another critical factor in the successful implementation of S/S.

With respect to the treatment of wastes, it is important to emphasise that S/S is an accepted technology in the USA, Europe and elsewhere, prior to disposal in landfill. The UK also has a history of treatment of wastes prior to landfill. Between the 1970-1990s a small number of S/S plants were in operation, however, unlike elsewhere (e.g. USA), the criteria for judging success were defined on a local basis.

LONG-TERM PERFORMANCE CONSIDERATIONS

Our understanding of the management of risk in the longer term is currently dependent upon predictive studies that are augmented by field-based data from deposited materials. Although S/S has been widely applied over the past 20-30 years there are few reliable studies yielding data showing performance with time. However, confidence in long-term performance is essential if risk-based management tools, such as S/S are to be routinely employed.

Weathering/degradation of S/S materials may be similar to that affecting concrete or rock, particularly if the exposure environment is near-surface. The mechanisms may include carbonation, sulfate attack and freeze/thaw. However, with specific reference to the degradation processes known in rocks and soils, physical weathering (heat/cool, freeze/thaw, wet/dry, and crystal growth) and chemical weathering (hydrolysis, oxidation, carbonation and solution) are the anticipated primary mechanisms that will influence waste form performance.

CONCLUSION

It will be seen from the preceding review that the remediation of contaminated soil and treatment of hazardous waste using S/S is widely practised and regulated in a number of countries around the world. This review when used together with the accompanying guidance document should provide the basis for a sound understanding of S/S technology and what steps are necessary to ensure the technology is used as an appropriate risk management strategy in the future.