State of practice report
UK stabilisation/solidification treatment and remediation
Part VII: good practice guidance documents

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1 INTRODUCTION

Although stabilisation/solidification (S/S) is an established remediation technique in USA and some EU countries, it has not yet received sufficient recognition in UK. This lack of recognition is caused by several direct and indirect factors, which has resulted in lack of confidence in this technology expressed by stakeholders, consultants, contractors and regulators. This lack of confidence in the technology can be addressed by increasing clarification and the level of awareness of the details of the various aspects of the technology and developing good practice guidance documents. Such documents should encompass the effective use of the technology, through which the factors that have been the cause for the lack of confidence should also be addressed. The documents should ideally only provide technical guidelines without conferring the legally binding status of a final regulation (LaGrega et al. 1994). The documents should cover the entire regime of the work and should have clear references to other relevant guidance documents including codes of practice. Hence the use of these documents should also enable the users to conduct the relevant tasks in a consistent and accepted manner. Although the overall framework of these documents would be expected only to change marginally in most cases, the specific details within the documents could be changed as considered appropriate over time with increased knowledge of the subject.

Unfortunately, until recently there has been no guidance documents produced in the UK, which are specifically on S/S. However, several guidance documents on work related to S/S have been in place for a number of years and several codes of practice (BS and ASTM) have also been in existence (with updates) on more specific issues. These include site investigation, sampling, testing and design. These have been made use of, but not always in a consistent manner. Recently, two guidance documents were published in the UK on the use of S/S in the treatment of contaminated soil; one by the Environment Agency (EA 2004) and the other by the British Cement Association on the use of cement and lime (BCA 2004). For the S/S of other wastes, currently available relevant guidance documents deal mainly with the disposal of waste to landfill (EA 2001a, 2002, 2003a & b). Other relevant documents include further publications by the Environment Agency, and guidance documents and information produced by the Highway Agency, British Lime Association and EU Technical Committees.

In the USA a number of published documents exist offering some form of guidance (and policy) on the use of S/S technologies for wastes and contaminated land. These include publications by the USEPA (1994, 1997), USACE (1995, 2000), Portland Cement Association (Conner 1997) and books by Cullinane et al. (1986) and Barth et al. (1990).

Other related publications have also been produced in recent years in other parts of the world. These include further publications in the UK and USA as well as the evaluation protocol for cement-based solidified waste produced by Environment Canada and the Japanese document on the design and execution of deep mixing applications.

This report summarises the guidance documents above. More details are given on the UK documents while only brief summaries are given on those document produced in other parts of the world.

2 UK/EU GUIDANCE DOCUMENTS

2.1 *Documents specific to S/S*

2.1.1 *Guidance on the use of stabilisation/ solidification for treatment of contaminated soil (EA 2004)*

The UK Environment Agency has recently produced a document which provides good practice guidance on the use of S/S for the treatment of contaminated soils (EA 2004). This guidance document is intended for private and public sector organisations

involved in the decision making process for contaminated land risk management which includes problem holders, consultants, technology vendors and contractors, regulators, environmental insurance companies, local interest groups and the public. It provides the framework for assessing the viability of S/S, its design and construction, and long-term monitoring and maintenance, based on several key investigation steps. This is shown in Figure 1. These set out a recommended approach for S/S treatment but which is not mandatory. However, all work and procedures mentioned in the document require compliance with any prevailing statute, regulation and codes of practice.

The framework begins with the screening stage to assess the viability of S/S as a feasible risk management option (Figure 2). Consideration is given to the contaminants present, type of material to be treated and end-use during this assessment. This process enables the development of a good understanding of the material properties and of any constraints that may need to be given due consideration.

The next stage in the framework is the design stage. Several mix designs will be generated based on the objectives and data gathered from the initial stage of screening. However, at this stage, after the development of site-specific design objectives (which should be defined at the start but reviewed regularly to suit the proposal), and before the treatability studies, the design proposals should be submitted to the regulatory authority for approval.

The bench-scale treatability studies then follow and these are used to evaluate the mix designs developed and to demonstrate that a binder system can be selected to meet the requirements of the remediation. Here the performance of mix designs is compared against one other and with the desired site-specific assessment criteria. Binder systems could be developed using a plethora of binders, but cementitious binder systems are generally used. The testing regime used for these evaluations should incorporate those tests desired for the fieldwork. These are developed based on the site specific assessment criteria, the site-specific conditions, the process to be used and the end-use of the treated material. Furthermore, in order to enable an accurate evaluation to be made, it is vital that the samples are prepared to be as representative as possible of the field conditions. The bench-scale tests will also establish the compliance criteria for the full-scale implementation.

Following a successful bench-scale, the next recommended step is a small-scale field trial, which is conducted using one or more of the optimised design mixes. This site trial is required to confirm that the desired performance is obtained in the more variable environment of the field conditions. The results from this enables further optimisation of the mix design for use in the actual full-scale fieldwork. It also gives the opportunity to evaluate the equipment to be used in the full-scale work. The selection of plant and equipment will be site-specific and process dependent. The objectives for this stage should be identified before the planning and implementation stages. Furthermore, the planning has to be conducted properly to obtain the maximum benefit from the site trial. The flowchart showing the role of treatability studies is given in Figure 3.

On completion of the bench-scale testing and site trial, an evaluation of the test results should be submitted to the regulatory authority along with the work plan. This information should include variations in the results, main conclusions, and any unforeseen occurrences and associated proposed course of action. Once these precursors are satisfactorily completed then the actual remediation implementation could commence. Figure 4 shows the flowchart depicting key stages of construction using S/S

The remediation implementation stage will require several key steps to be considered. These include site planning, monitoring the actual work, sampling and testing, and health and safety. After construction, the final stage in the framework considers monitoring and maintenance work that may be required following remediation. The need for this should be considered earlier at the design stage and should take into account the use of the site after the S/S treatment. The purpose of monitoring should be to demonstrate whether the treatment is effective for a time-scale based on the end-use. This is a site-specific decision based on the risk associated with realistic contaminant release scenarios. The guidance involves design and implementation of the monitoring programme, where the receptors to be monitored are mainly groundwater and surface water.

The purpose of maintenance is to put in place measures to protect the treated material from disturbance and weathering or to isolate it from receptors after construction. The design of such protective measures will need to take into account the use of the site and once installed should be maintained to provide the required level of service for the predetermined time-scale. Hence, the end-use and regulatory requirements will have to be considered in developing and implementing the maintenance plan.

It will also be necessary at this stage to educate the end-user on the site conditions, design assumptions and any monitoring that is required. Throughout the document, emphasis is placed on close involvement with the regulator. Hence the communication referred to here is not only with the regulator, but also with all parties concerned at the relevant stages of the project which is also very important for the success of the work.

The guidance document is accompanied by a science review on S/S which contains a review of scientific information including identification and as-

sessment of technical uncertainties associated with the treatment of inorganic and organic contaminants.

2.1.2 *The essential guide to stabilisation/ solidification for the remediation of brownfield land using cement and lime (BCA 2004)*

The British Cement Association recently published a document entitled 'The Essential Guide to Stabilisation/Solidification for the Remediation of Brownfield Land using Cement and Lime' (BCA 2004). Although only cement and lime are mentioned in the title, the document does make reference to other binders used in S/S such as fly ash, ground granulated blastfurnace slag, and cement and lime kiln dust. The document has many similarities to that of the Environment Agency (EA 2004) guidance document detailed above.

The BCA document recognises that S/S can be considered to be a natural extension of soil stabilisation techniques, but which is more difficult

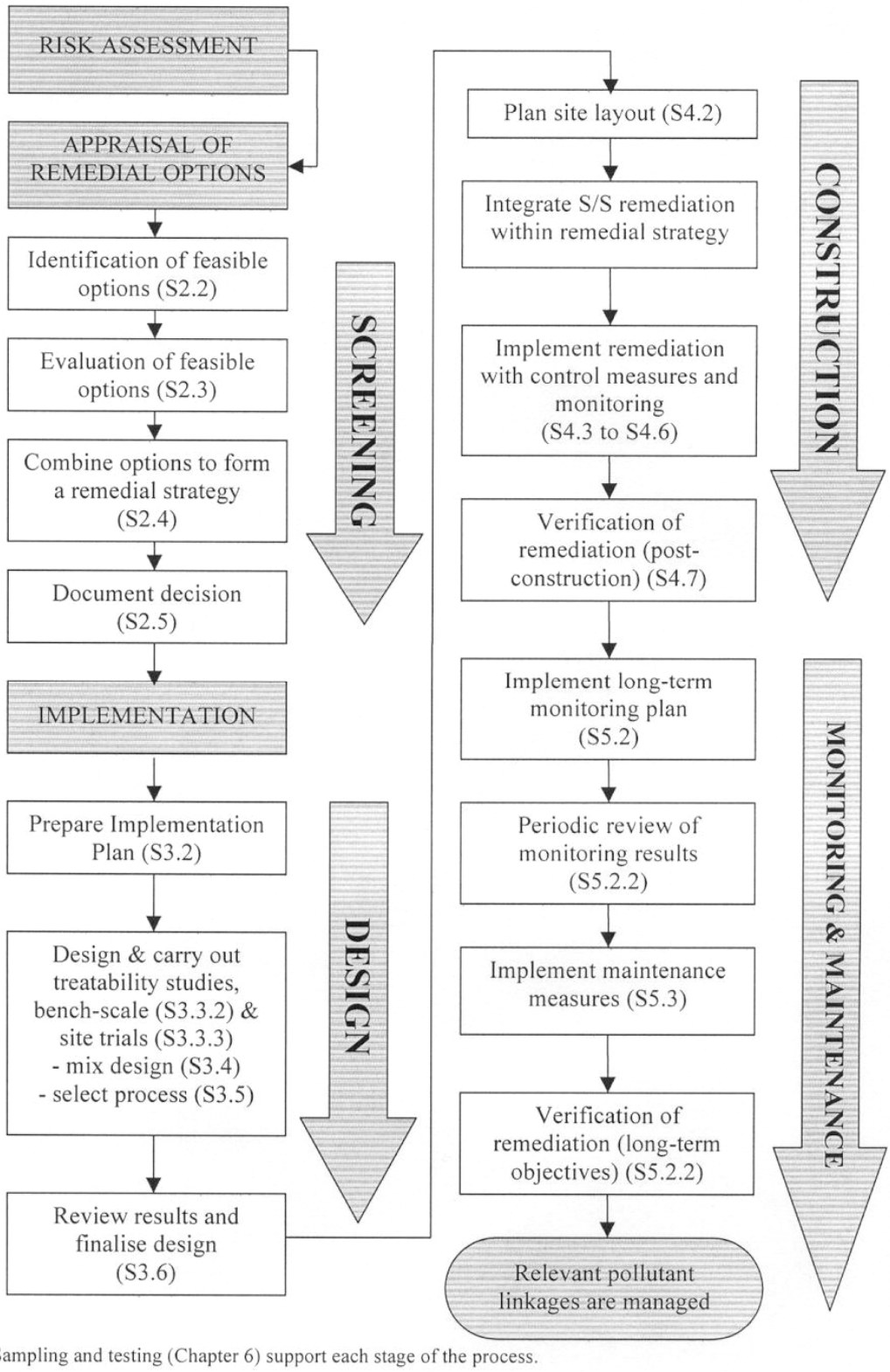

Figure 1. Overview of S/S treatment process (EA 2004).

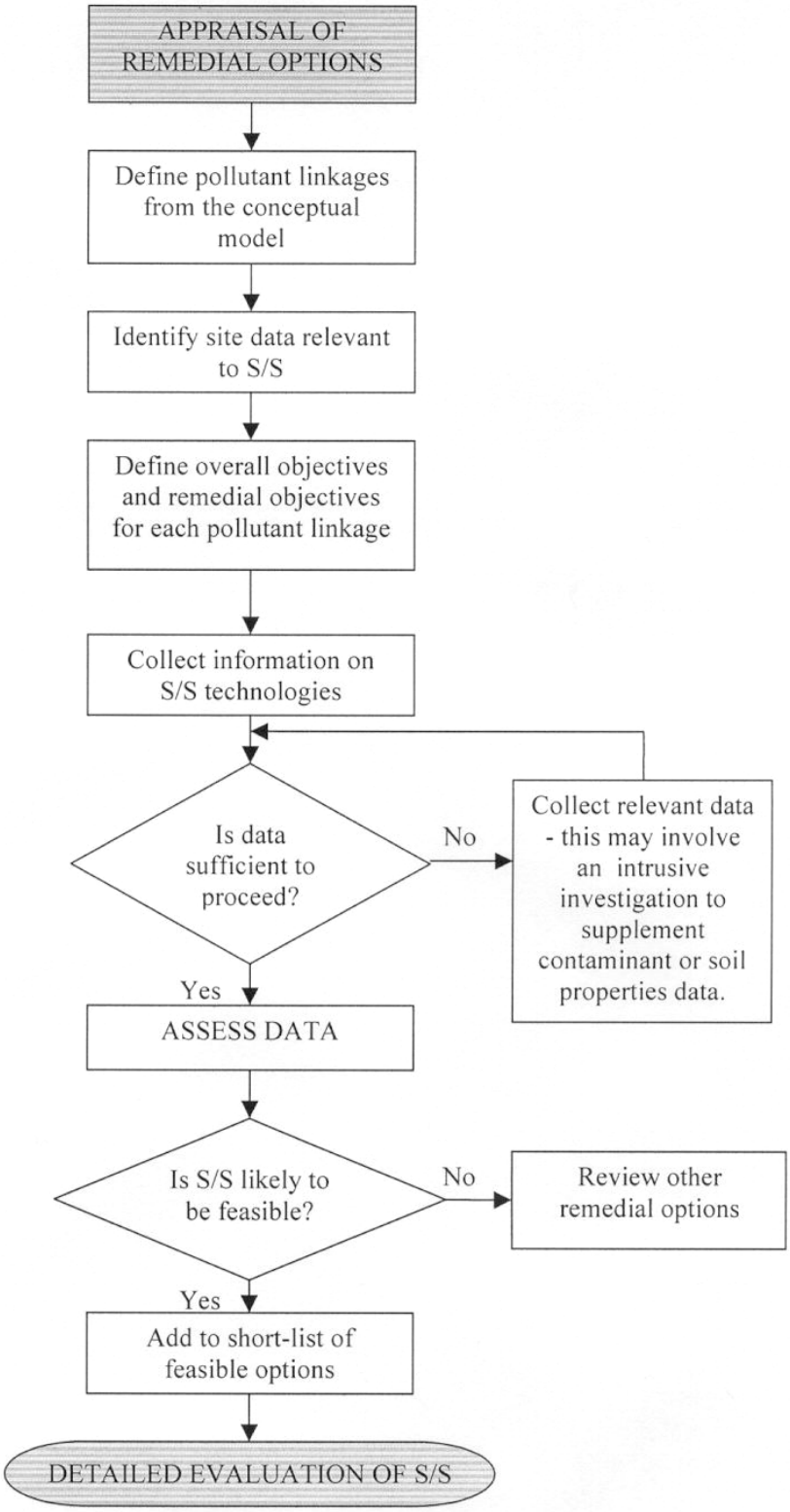

Figure 2. Flowchart for identifying whether S/S is potentially feasible (EA 2004).

to design, plan and implement. The difficulties arising are as a result of the complex nature of soils and contaminants within brownfield and derelict sites. It also recognises that although S/S has not had widespread use as soil stabilisation, that its use has regularly been successful in remediating contaminated land. The document gives an overview of the whole S/S process after addressing the essential risk assessment, generally undertaken to establish the extent and nature of any hazardous contamination (Figure 5). This assessment gives rise to the development of a remediation strategy to manage the risk and it is at this point that S/S is considered as a remediation option.

Thereafter, the document gives an introduction to S/S which also essentially identifies that S/S is always designed on a project-specific basis. Then it gives general guidance on design, implementation and completion of remediation. It appreciates that the site-specific working plan should be drawn up by

skilled professionals in liaison with the main contractors and subcontractors and that the working plan should include remediation objectives agreed with the appropriate regulator. At the design stage (Figure 6), it recognises that a treatability study is required and that it consists of two parts. The first part would be to develop a bench-scale solution at laboratory level for treating the problematic material. This involves sampling, characterisation, S/S mix design development and its optimisation. Test protocols used at this stage will be those determined at the beginning based mainly on end-use of the treated material. The second part of the treatability would be to conduct a site trial to confirm the optimised S/S mix

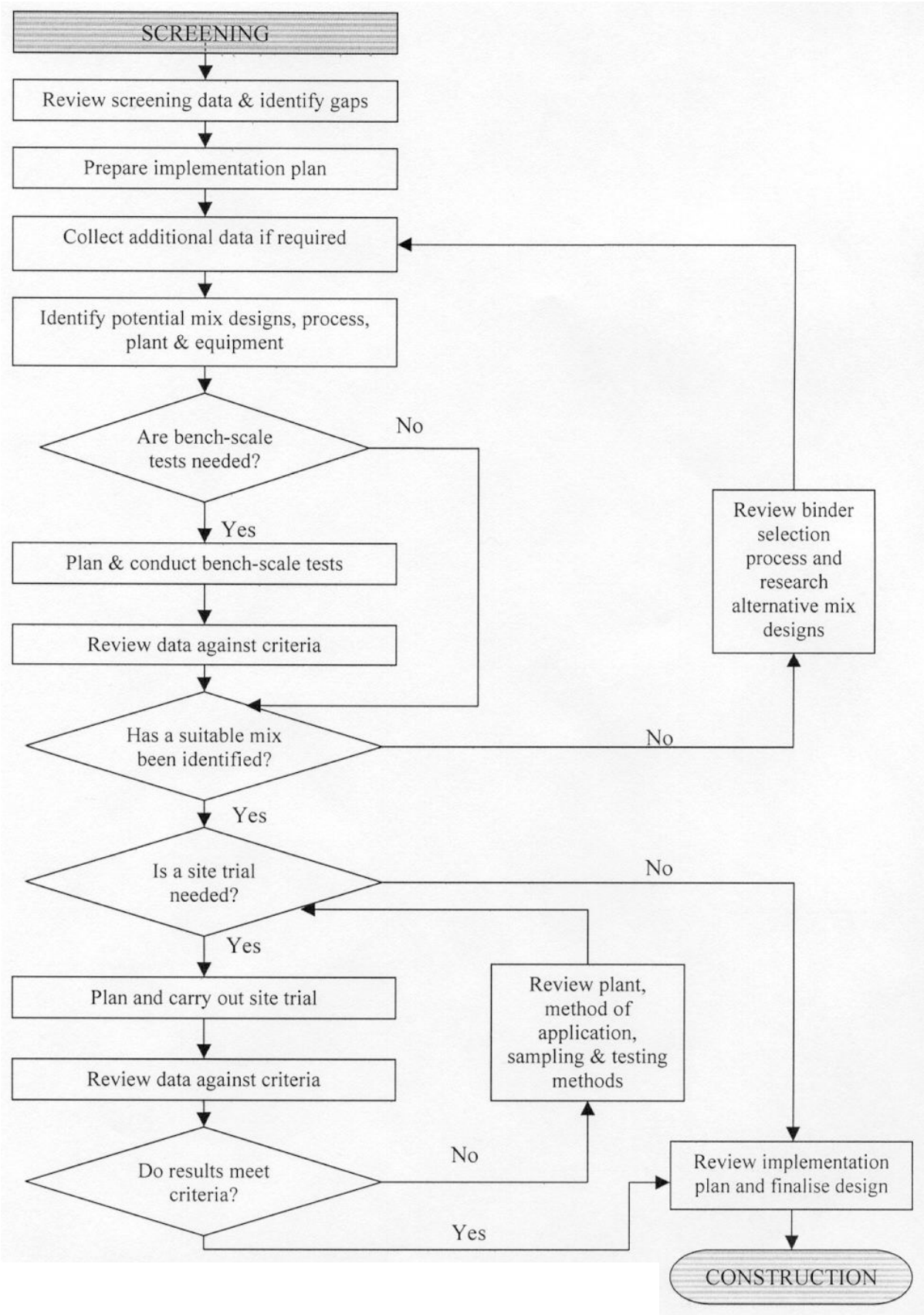

Figure 3. Role of treatability studies in design (EA 2004).

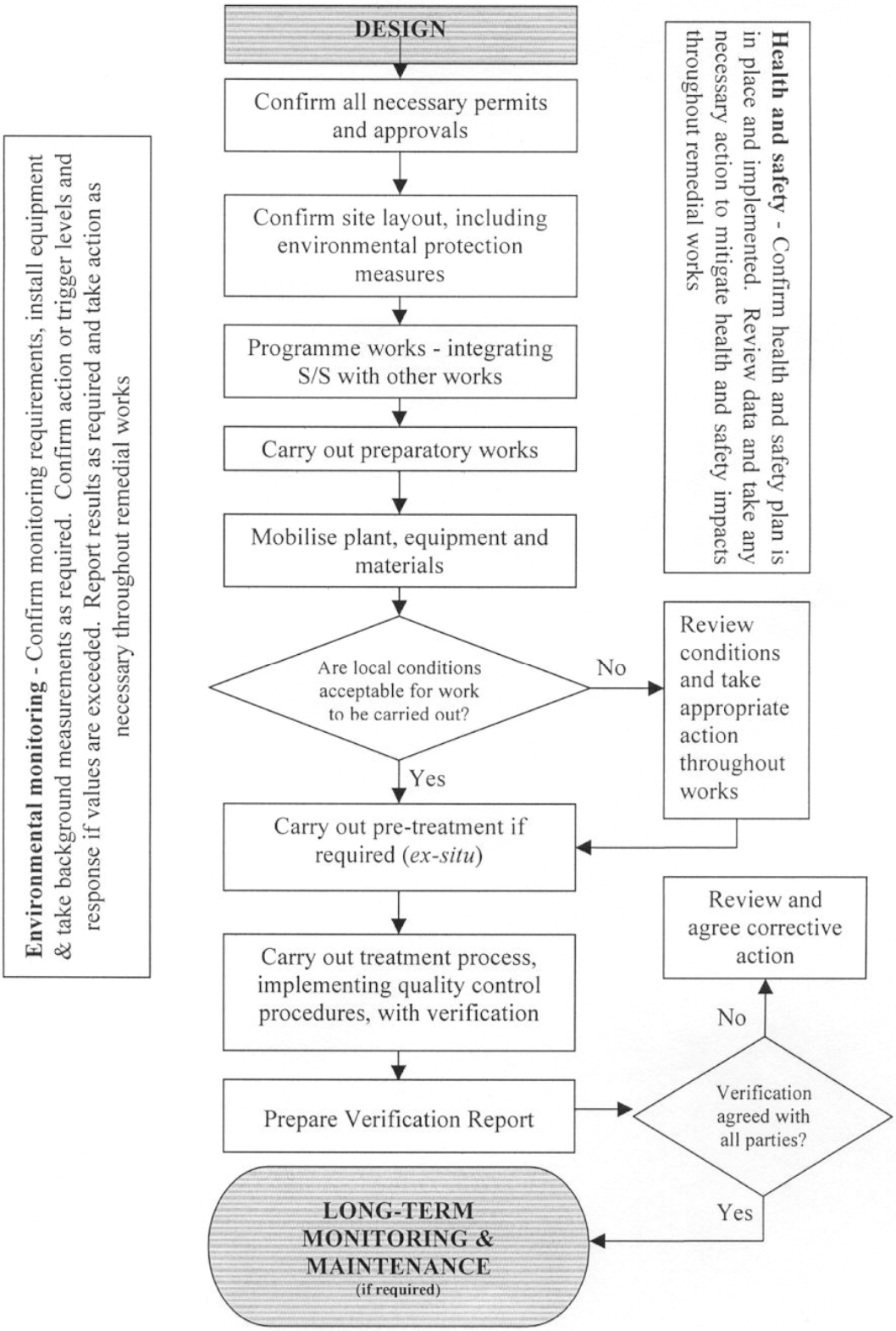

Figure 4. Flowchart showing key stages of construction using S/S (EA 2004).

design. This is considered essential as it is used to highlight any problems not apparent in the laboratory studies.

The next step will be the implementation stage which is normally a continuation of the site-trial. Once again implementation of the remediation involves considerable planning and liaison with the relevant authorities and individuals. This section in the guidance document discusses the wide range of legislations and regulations, site processing equipment (both ex-situ and in-situ) and the remediation plan. Finally, the section on remediation completion considers the monitoring and maintenance that, in most cases, would be required by the regulator in order to demonstrate the effectiveness of the treatment. Others who might also request this are the client and other stakeholders. The document discusses situations where these would be required and gives

typical parameters that would be included in the programme.

2.2 *Related documents*

2.2.1 *Execution of special geotechnical works – Deep mixing (prEN 14679 2003)*

This document (prEN 14679 2003) was prepared by the EU Technical Committee CEN/TC 288. It is stated that this document has been prepared to stand alongside the Eurocode 7 ENV 1997, Part 1: Geotechnical design, general rules; Part 2: Geotechnical design assisted by field tests and Part 3: Geotechnical design assisted by laboratory testing. This document sets out general principles for execution, testing, supervision and monitoring of deep mixing works. It considers both the dry and wet mixing methods. Guidance on the practical aspects of deep mixing in relation to execution procedures and equipment, and methods of testing, specifications and assessment of design are placed in annexes. These are referred to in the main body of the text as appropriate.

The document covers methods which involve the following. (i) mixing by rotating mechanical mixing tools where the lateral support provided to the surrounding soil is not removed, (ii) treatment of the soil to a minimum depth of 3m, and (iii) application

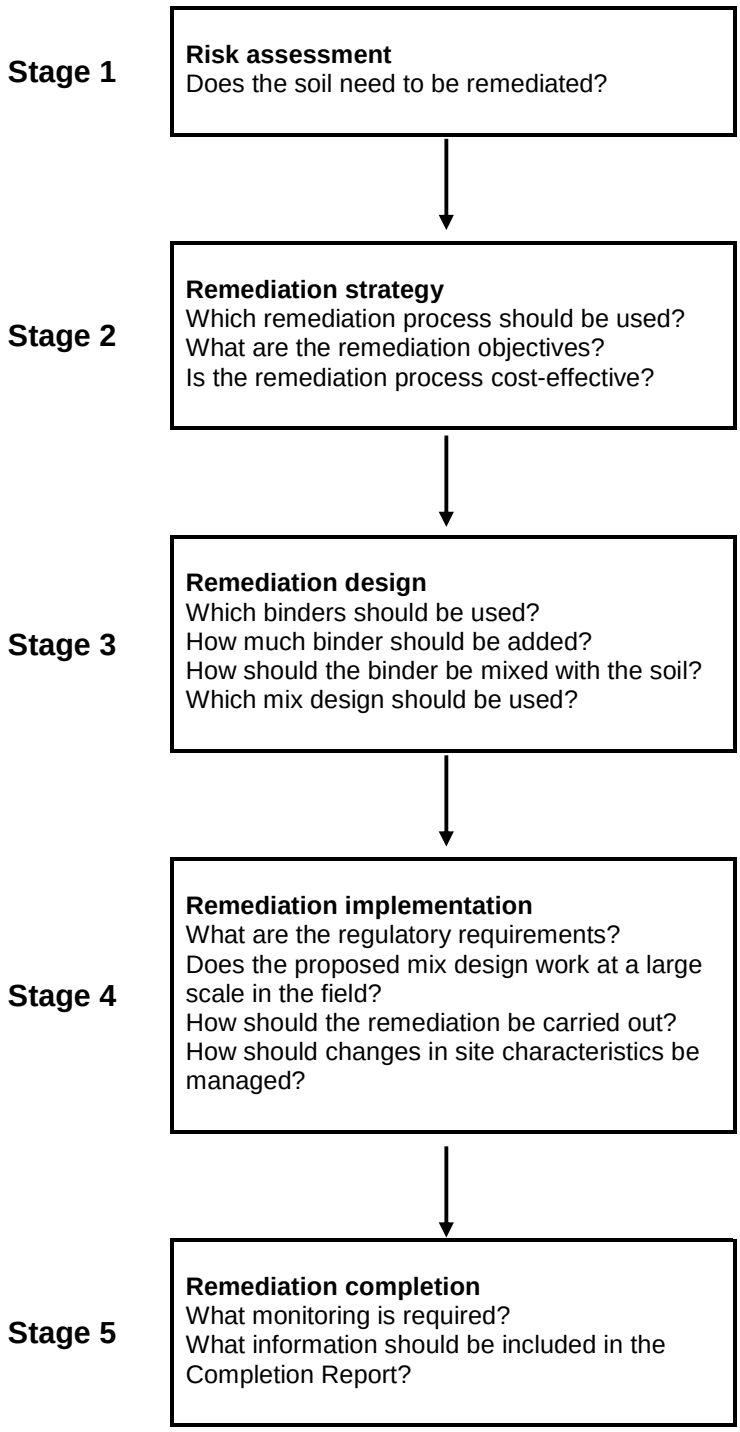

Figure 5. Stages within the design and implementation of Brownfield Remediation projects (BCA 2004).

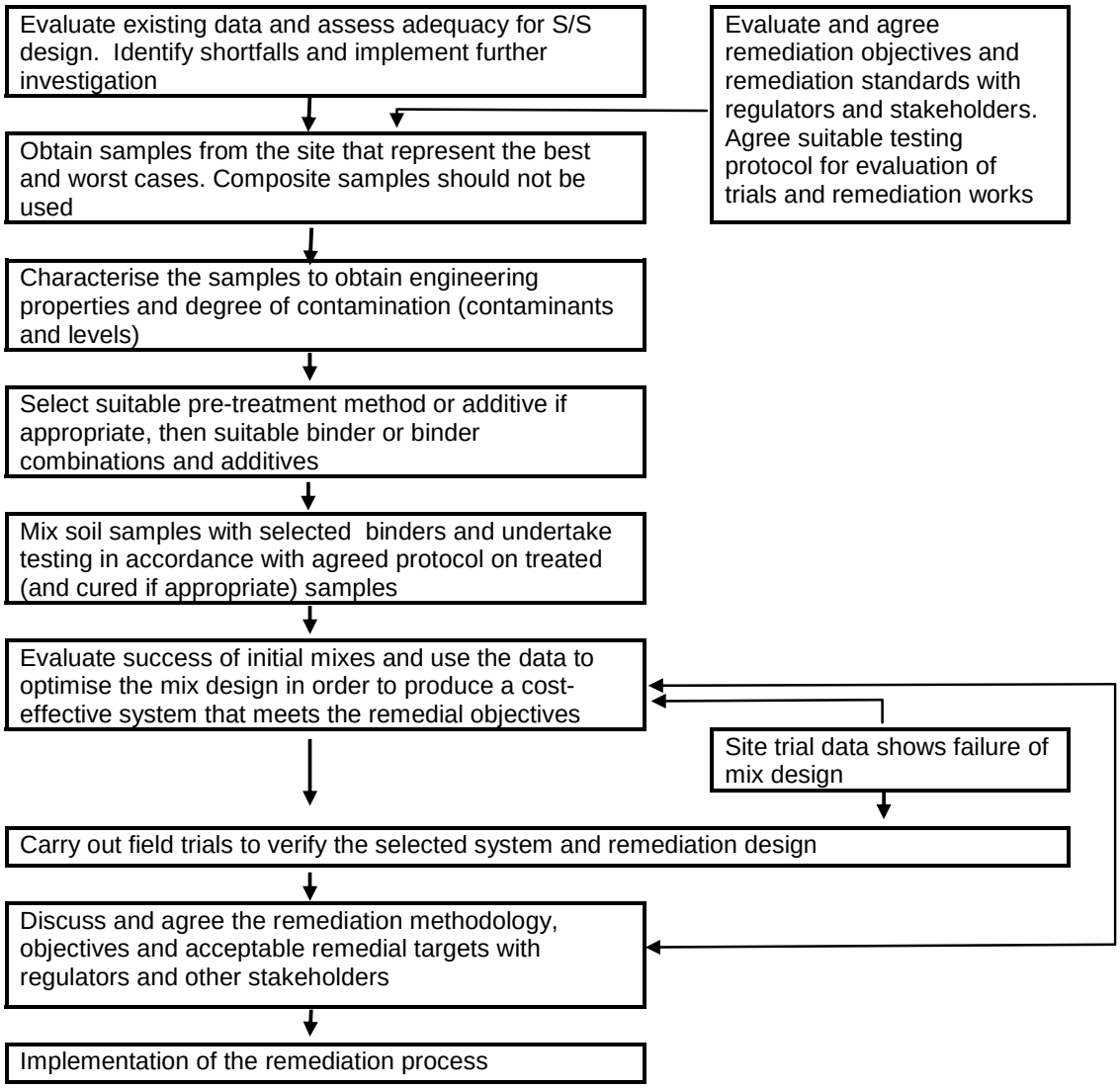

Figure 6. Key stages in remediation design (BCA 2004).

of different shapes and configurations, consisting of any of single columns, panels, grids, blocks, walls or any combination of more than one single column, overlapping or not. It also covers the use of deep mixing in the treatment of natural soil, fill, waste deposits and slurries. Other ground improvement methods using similar techniques are briefly referred to in this standard.

The document begins by considering the information required for the execution of the works, which includes legal or statutory restrictions, specifications for the deep mixing work, history of the site and surrounding areas, construction programme and reporting procedures. It then sets out the requirements for the geotechnical investigation and information sought from it. The next stage involves consideration and assessment of the materials and products to be used in the works. This is followed by considerations of the design to be based on DD ENV 1991 and DD ENV 1997. A design statement is also required, stating the performance objectives, geometry of the treatment and details of construction columns, and specification of the materials and products assumed in the design.

The execution stage cannot commence prior to the submittal of a method statement incorporating as a minimum the items laid out in the document. It also cannot begin until the site has been prepared in accordance with the design specifications and specific environmental site conditions. The execution of work will commence with the field trials. These should be conducted to confirm that the design requirements are achieved and to ascertain the vital control values. The latter includes penetration and retrieval speed of mixing tool, rotation speed of the rotating units of mixing tool, air pressure in dry mixing and rate of delivery of binder. Once everything is satisfied then the actual work would commence.

The document details the general working procedures involved with deep mixing and lays out some quality control and quality assurance requirements. Under supervision, testing and monitoring it states that the extent of testing and monitoring should be included in the design specifications. It further mentions that the exact procedures for verification, control and acceptance should be given prior to the work commencement. The supervision is required to check that the construction fulfils the design and

other documents, that the relevant competent persons are conducting the execution work and to report any new information or unforeseen conditions that arise to the treatment design team.

The section on testing gives the parameters that should be tested together with the extent of testing and testing methods to be used. The latter should be based on the application and functional requirements of the specific project. The quality control tests should take place over uniform time intervals and equally between the mixing tools. They should cover a sufficient number of columns to ensure that the results are representative of the work. It also suggests that chemical tests should be conducted where applicable such as cut-off and retaining walls, immobilisation and containment. Another important issue mentioned is where column overlap is an essential part of the design. Here, the width of the overlapping portion between adjacent columns should be checked.

The document suggests that the construction process and the performance of the treated soil should be monitored. Under the construction process, it stipulates that the construction parameters as well as information concerning ground conditions and construction tolerances should be monitored during execution. It also states that the execution should be monitored automatically. Where applicable, the vertical and lateral movements of the ground should be monitored using the appropriate methods and where applicable other parameters such as pore water pressure also need to be monitored.

The document states the records need to be kept during construction and after completion of the work. The document finally considers site safety and environmental protection, and impact on adjacent structures. The annexes also contain discussion on the Japanese and Nordic techniques for dry mixing and the Japanese and European techniques for wet mixing.

2.2.2 *Specifications for highway works (Highway Agency et al. 2001)*

The Manual of Contract Documents for Highway Works (Highway Agency et al. 2001) provides the details and notes for guidance on the specifications for highway works (SHW, Volumes 1 and 2 respectively). One section in both volumes is dedicated to earthworks and considers stabilisation of soil, uncontaminated only, using cement or lime or both.

The documents classify the material to be treated (and treated material) with a class number, and describe in detail how these materials should be stabilised. It includes such things as spreading, thickness of layer, pulverising and mixing, overlap width on adjacent passes and depth of cutting-in when subsequent layers are required, compaction and curing. It also provides guidance on weather conditions under which stabilisation work should not be carried out.

The detailed methodology for these works is given in HA 74/00 (Highway Agency et al. 2000). This document, after giving appropriate consideration to applications and fundamentals, considers site investigation requirements, specific design aspects, construction and control methods, testing and monitoring. A preliminary sources study is conducted to gather relevant information, which forms the preliminary part of the site investigation. This includes a desk study, field studies, site description, ground conditions, preliminary engineering assessment and comparison of project options and risks. The preliminary source study ends by giving proposals for ground investigation and drawings.

The document provides details on the requirements and execution of the ground investigation. The execution involves sampling and testing of materials and groundwater, where these have been obtained from trial pits, trenches and boreholes. Visual inspection of the material will also be used as the first step in the assessment. The tests conducted on soils at this stage will be for checking suitability and acceptability of the material. It then describes the way the designer should extract relevant limiting values for material acceptability and details of the addition of cement or lime or both.

It also recommends that trials should be conducted prior to commencement of the main work to demonstrate the suitability of the material, method of working and equipment. Here, details also include the requirements for a demonstration area where the trials are to be carried out. Guidance is also given on the preparation of the formation where this is applicable. Furthermore, the untreated and treated materials are required to be monitored during construction for ensuring compliance. The test methods to be used and limiting values are also given for untreated soils and treated material in the SHW (Highway Agency et al. 2001). Also the guidance on the frequency of testing is found in the HA 74/00 (Highways Agency et al. 2000) and in the notes for guidance on the SHW (Highway Agency et al. 2001).

2.2.3 *Lime stabilisation documents on the British Lime Association (BLA) website*

Several documents giving promotional data and technical data on lime stabilisation are posted on the BLA website (www.britishlime.org). Lime treatment (BLA 2002a) is a promotional sheet, which stipulates what could be achieved by lime stabilisation and states other advantages of use as well. The other two documents on Earthworks Improvement (BLA 2002b), and Subbase and Roadbase Material (BLA 2004) provide technical data on the said process. A major difference between the above two documents is on the treatment material used. The BLA (2002b) stipulates the use of only lime whereas the BLA (2004) adopts a ‘two shot’ treatment approach where lime is used purely to condition the soil in prepara-

tion for the addition of cementitious or pozzolanic material which imparts the majority of the strength to the treated material.

Both documents detail the requirements of site investigation including laboratory procedures needed prior to the construction stage for these processes. On construction, the documents discuss the methods available for carrying out this task. In the case of BLA (2002b), the spreading of lime is stated to be best carried out by a towed spreader, and mixing could be carried out by rotovator. However, the use of disc harrows and purpose made ploughs are also deemed acceptable for mixing provided adequate mixing can be achieved. The material could treated either in-situ or after being taken to the point of use. In the case of BLA (2004), two principle methods are discussed; (a) in-situ and (b) ex-situ. In-situ construction involves site preparation, lime spreading, rotovating lime in to the soil (mixing), water addition, light compaction to seal the top surface, re-mixing after the maturing period for achieving the necessary pulverisation and light rolling. Thereafter, the second binder is spread, thoroughly mixed, which is followed full compaction. Mixing in the ex-situ method involves mixing the material, which are fine enough to already meet the pulverisation requirements, usually in a pug-mill type mixer. Here, both binders can be mixed together. Both documents also discuss testing of the processed material to ensure that the specified requirements are met.

2.2.4 *Guidance on the disposal of contaminated soil (EA 2001b)*

The guidance on the disposal of contaminated soil (EA 2001b) was drafted primarily to target the Environment Agency's regulatory officers. It provides them with guidance on disposal options for contaminated soils where a decision has been made to dispose or recover them off-site. The document considers disposal to landfill and also the use of such materials in cases where exemptions have been registered under the Waste Management Licensing Regulations (1994, as amended). This document supersedes the Interim Guidance on the Disposal of Contaminated Soils (EA 1997) and it does not relate to the Contaminated Land Provisions of Part II of the Environmental Protection Act 1990.

Others who benefit from this would be the developers, haulage contractors, landfill operators and their agents, as it sets out the approach for the most suitable option for the recovery or disposal of contaminated soils. It gives greater clarity as to the information required, the way it is interpreted and how decisions should be made on the suitability of particular sites to receive these materials in question.

The document outlines the decision process to ensure that contaminated soils are managed and disposed of appropriately. A three-step process is adopted and comprises of (i) hazard assessment (source characterisation), (ii) risk assessment (hazards posed at the disposal site) and (iii) disposal options. Hazard assessment outlines the information that should be considered about the source of the contaminated soil. This information could be obtained from considering sources of contamination and site history, and conducting site investigations. The former would be useful to form the basis of chemical testing suites and the latter when conducted properly should allow the sampling and analysis strategies to characterise the material sufficiently.

The risk assessment stage gives two approaches to estimate the risk of the characterised material. One is the generic approach and this refers to the approach where criteria developed are applied to all disposal sites without modification. The other is the site-specific approach and refers to the approach where criteria are developed on a site-by-site basis that takes into account the actual hazards and exposure pathways that prevail for each disposal site.

Thereafter disposal options are identified and recommendations made through reference to a flow chart (see Figure 7). This section mainly discusses contaminated soils that are considered as non-special waste. However, some reference is also made of those considered as special waste. For those designated as special wastes under the Special Wastes Regulations (1996, as amended), the document specifies that the soil should be disposed of or treated at a site which is authorised to receive such a contaminated material. For non-special wastes, the document suggests the type of site that might be suitable to receive the contaminated soil with relation to the threshold concentrations. Additionally, other matters which need to be considered and addressed are identified. These include segregation, treatment, other pollutants, plant damage, licence conditions, surrender Duty of Care and landfill tax implications. The document also provides guidance for the minimum amount of information that should be provided and makes suggestions about sampling competencies, early contact with developers and actions that need to be taken in situations where only short notice of contaminated soil movement is given.

2.2.5 *Guidance on sampling and testing of wastes to meet landfill acceptance procedures (EA 2003a)*

The guidance on sampling and testing of wastes to meet landfill acceptance procedures (EA 2003) was produced to: (i) outline the responsibilities of waste testing for acceptance to landfill, (ii) provide background on the technical aspects of waste characterisation, and (iii) provide guidance on compliance measures for waste acceptance to landfill as required

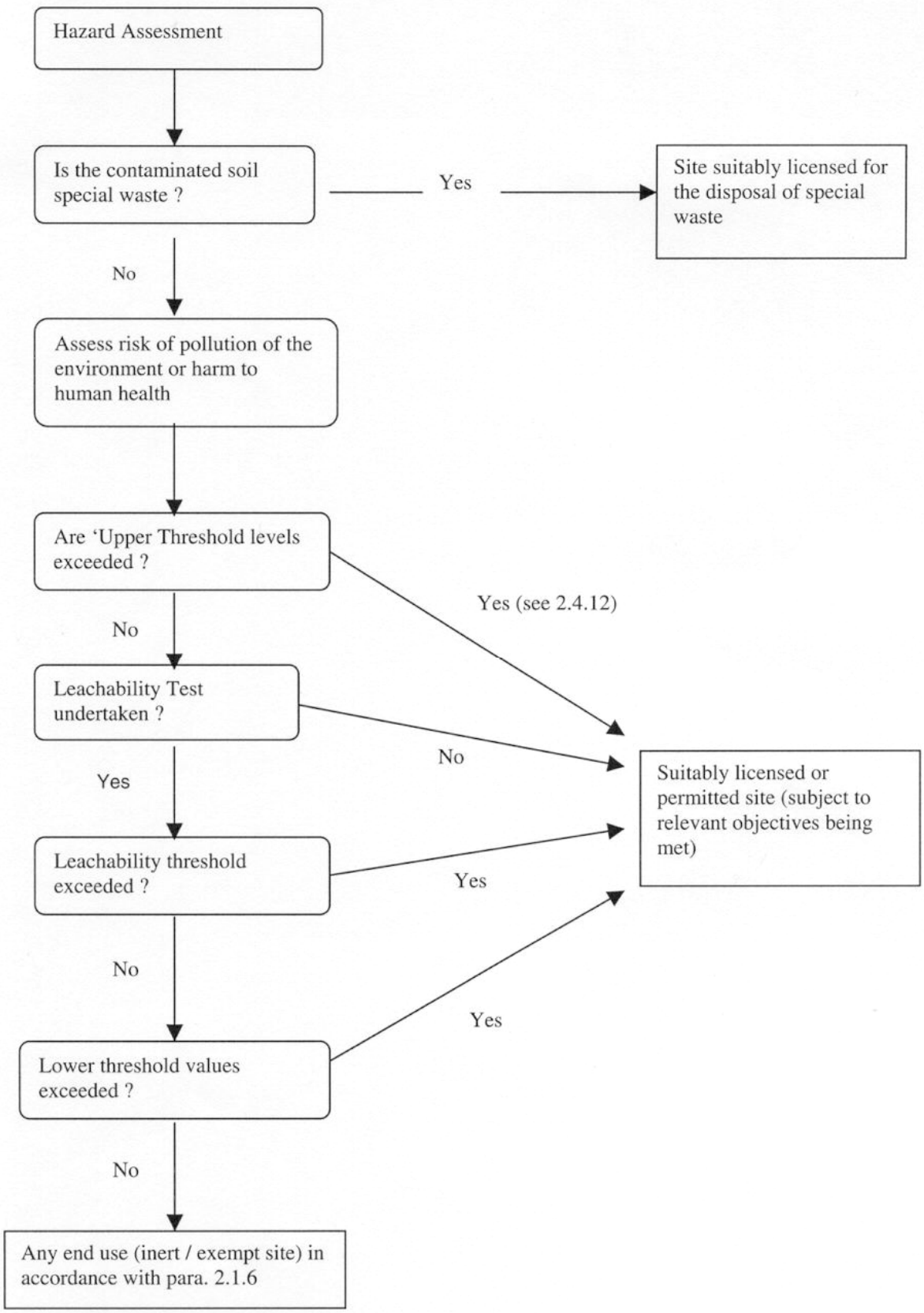

Figure 7. Disposal option identification flowchart (EA 2001b).

by the European Council Decision 2003/33/EC (2003). However, the waste acceptance criteria themself are not included in this document. These are expected to be implemented via modification to the Landfill (England and Wales) Regulations (2002).

The document is primarily aimed at wastes which are generated on a regular basis and are reasonably consistent in quality or where separation at source can generate waste streams which are reasonably consistent. For wastes outside this scope, guidance is given in UK Environment Agency document: Guid-

ance on national interim waste acceptance procedures (EA 2002).

This document (EA 2003a) is intended for use bythe Environment Agency officers, waste producers and the waste management industry. It is intended to assist the end user in developing sampling plans, in undertaking testing programmes for characterisation and in compliance testing and the use of data to determine waste acceptance to landfill. It is mainly aimed at the acceptance criteria procedures for granular wastes. However, most of the document, particularly the approach to compliance, is also relevant to monolithic wastes.

The document is in several sections. It begins with a description of the levels of testing as defined by the Landfill Directive. It then provides advice relevant to primary waste producers followed by secondary waste producers and finally to landfill operators. The technical details relating to sampling, testing and specified analytical methods are contained in the annexes.

2.2.6 *Guidance on waste treatment requirements of article 6(a) of the Landfill Directive (EA 2001c)*

As part of the implementation of the Landfill Directive, all wastes (including contaminated soils), which are not prohibited from being landfilled require treatment prior to landfilling. Those exempt from this treatment are inert waste for which treatment is technically not feasible and non-inert waste where treatment would not reduce the quantity of the hazardous substances. Prohibited wastes are set out in Regulation 9 of the 2002 Landfill Regulations (Landfill Regulations 2002). The selected treatment is required to fulfil three criteria and this is set out in this guidance document. These are: (i) it must be a physical/thermal/chemical or biological process, including sorting, (ii) it must change the characteristics of the waste, and (iii) it must do so in order to: (a) reduce its mass, or (b) reduce its hazardous nature, or (c) facilitate its handling, or (d) enhance its recovery. This is referred to as “the three point test”.

2.2.7 *Requirements for waste destined for disposal in landfill (EA 2003b)*

This summary guidance note has been produced based on information contained in the relevant UK regulations pertaining to the Landfill Directive. It is primarily intended to highlight the requirements of the regulations for the benefit of waste producers and waste managers, but is of use to all those with an interest in waste legislation. The document consists of several sections, each providing information about various aspects of the change taking place. The section on timetable, gives the timings at which various activities will come into effect based on the category of the landfill. This gives timetables for prohibited wastes and prior treatment, waste acceptance criteria, and waste characterisation and testing. The landfills for this purpose have been categorised as new landfill (15 July 2001), existing landfill for hazardous waste and other existing landfill. The document then outlines wastes that are categorised as ‘prohibited wastes’. It then states the new classification for landfills, which are sites for hazardous waste, for non-hazardous waste and for inert waste, and also provide information on the wastes that may be accepted at these sites. This is followed by a section which discusses issues on waste acceptance criteria (WAC), such as who set it up, how it is to be regulated, requirements that need to be met. It also differentiates between interim and full WAC. The document then under waste characterisation and testing considers the three level hierarchy introduced by the regulations for waste going to landfill. The requirements for each level and test methods associated with the full WAC are detailed in the regulations. The UK Environment Agency document on Guidance on sampling and testing of wastes fulfil this purpose (EA 2003a). The document then considers the waste treatment requirements where it refers to the ‘three point test’ criteria mentioned previously under EA (2001c). Thereafter it details the person(s) responsible for compliance, qualifiers of the treatment requirement and other relevant issues about treatment. Finally the document gives the decision process for determining landfill options.

The relevant UK regulations pertaining to this are the Landfill (England and Wales) Regulations 2002(as amended) and the Pollution Prevention and Control Regulations 2000.

3 US GUIDANCE DOCUMENTS

Summaries for most of the US guidance and policy documents on S/S are given in the Solidification/Stabilisation Resource Guide (USEPA 1999). The relevant documents and summaries are reproduced here.

3.1 *Handbook for stabilisation/solidification of hazardous wastes (Cullinane et al. 1986)*

The handbook for stabilisation/solidification of hazardous wastes (Cullinane et al. 1986) is intended for designers and reviewers of remedial action plans at hazardous waste disposal sites. It provides information and guidance needed to judge the feasibility of S/S technology in controlling contaminant migration from hazardous wastes disposed of on land. The document describes reagents and methodologies that have been useful in the S/S of hazardous wastes; such information is useful to industrial and engineering firms that work with handling and disposal of hazardous waste, as well as regulatory agencies and environmental groups that need to assess the feasi-

bility of technical solutions proposed at sites requiring remedial action.

3.2 *Stabilisation and solidification of hazardous wastes (Barth et al. 1990)*

This book on stabilisation and solidification of hazardous wastes (Barth et al. 1990) provides a detailed overview of the state-of-the-art of S/S of hazardous wastes up to 1990. It includes inorganic and organic processes, as well as physical and chemical testing procedures used to evaluate S/S technologies. Guidance is also provided on the selection and use of this technology through bench- and pilot-scale screening. Full-scale treatment operations are presented with numerous examples of ex-situ and in-situ technologies. In addition, quality control, safety and environmental considerations for waste treatment, as well as equipment, costs and regulatory requirements are discussed.

3.3 *Treatability studies for solidification/ stabilisation of contaminated material (USACE 1995) and Solidification/Stabilisation of contaminated material: Unified facility guide specifications (USACE 2000)*

The document by the Department of the Army (USACE 1995) provides information and guidance on scoping a treatability for S/S of contaminated material. It focuses on treatability studies for soils and sludges and includes an outline of topics that should be considered for inclusion in a S/S treatability scope of work.

The guide specification on solidification/stabilisation of contaminated material: unified facility guide specifications (USACE 2000) contains the requirements for the S/S of materials contaminated with hazardous and toxic waste. It is a model specification for actual fieldwork. The United States Army Corps of Engineers and other project personnel can easily incorporate their site- and project-specific requirements to this document. It replaces the former document (USACE 1998).

3.4 *Guide to improving the effectiveness of cement-based solidification/stabilisation (Conner 1997)*

The is a guidance publication by the US Portland Cement Association which provides information on field techniques and additives that can be used to improve the effectiveness of cement-based S/S treatment of wastes. This improved efficacy maybe needed as some situations, arising due to the waste itself, disposal scenario, and/or regulatory requirements, may other wise provide an unsatisfactory S/S material. The problems encountered will have to do with obtaining the required physical properties (solidification problems) and adequately immobilising the hazardous constituents of the waste (stabilisation problems). The guide lists additives and techniques that can be applied to specific solidification problems such as development of set, compressive strength and free liquid. It also lists additives and techniques that can be applied to immobilisation of specific hazardous constituents such as some heavy metals, as well as classes of constituents such as volatile organics, organo-metallics and soluble salts. It additionally lists a variety of generic additives for specific desired S/S effects, which includes those that could be used to control the pH of the wastes; to reduce, oxidise and co-precipitate constituents; and to accelerate or retard set.

These US documents mainly address performance evaluation or testing protocols and contaminant-specific or waste-specific procedures, and do not cover issues such as durability, degradation, and long-term effectiveness.

4 OTHER DOCUMENTS

There are a number of other documents that include guidance on aspects of relevant to S/S. These include the following:

4.1 *The Contaminated Land Report (CLR) series of documents in relation to Soil Guideline Values (DEFRA & EA 2002a-f, 2004)*

This series of documents has been produced to provide regulators, developers, landowners and other interested parties with relevant, appropriate, authoritative and scientifically based information and advice on the assessment of risks arising from the presence of contamination in soil. Hence, it has been written for technical professionals who are familiar with the risks posed by land contamination to human health but who are not necessarily experts in risk assessment. The summary of these document as presented in those documents are given below.

CLR 7 *Assessment of Risks to Human Health from Land Contamination: An Overview of the Development of Soil Guideline Values and Related Research* (DEFRA & EA 2002a). This report serves as an introduction to the other reports in this series. It sets out the legal framework, in particular the statutory definition of contaminated land under Part IIA of the Environmental Protection Act (EPA) 1990; the development and use of Soil Guideline Values (SGV); and references to related research.

CLR 8 *Priority Contaminants for the Assessment of Land* (DEFRA & EA 2002b). This report identifies priority contaminants (or families of contaminants), selected on the basis that they are likely to be present on many current or former sites affected by industrial or waste management activities in the UK in sufficient concentrations to cause harm; and that

they pose a risk, either to human health, buildings, water resources or ecosystems. The report also indicates which contaminants are likely to be associated with particular industries.

CLR 9 *Contaminants in Soil: Collation of Toxicological Data and Intake Values for Humans* (DEFRA & EA 2002c). This sets out the approach to the selection of tolerable daily intakes and Index Doses for contaminants to support the derivation of SGV.

CLR TOX 1-10 (DEFRA & EA 2002d). These reports set out the derivation of tolerable daily intake and Index Doses for the following contaminants, which are arsenic, benzo[a]pyrene, cadmium, chromium, inorganic cyanide, lead, phenol, nickel, mercury and selenium.

CLR 10 *The Contaminated Land Exposure Assessment (CLEA) Model: Technical Basis and Algorithms* (DEFRA & EA 2002e). This report describes the conceptual exposure models for each standard land-use that are used to derive the SGV. It sets out the technical basis for modelling exposure and provides a comprehensive reference to all default parameters and algorithms used.

CLR GV 1-10 (DEFRA & EA 2002f). These reports detail the derivation of the SGV for the following contaminants, which are arsenic, benzo[a]pyrene, cadmium, chromium, cyanide (free, simple and complex inorganic compounds), lead, phenol, nickel, mercury (inorganic compounds) and selenium.

CLR 11 *Model Procedures for the Management of Contaminated Land* DEFRA & EA 2004). This incorporates existing good technical practice, including the use of risk assessment and risk management techniques, into a systematic process for identifying, making decisions about and taking appropriate action to deal with contamination, in a way that is consistent with UK policy and legislation.

4.2 *Method for deriving site-specific human health assessment criteria for contaminants in soil (SNIFFER 2003)*

This report describes a method for deriving site-specific assessment criteria for use when considering the risk to human health from chronic exposure to certain given substances in soil. The document is in two parts. Part I describes a method for deriving site-specific human health assessment criteria for contaminants in soil and Part II provides a sensitive analysis of the method. The document reflects the guidance in R&D publications CLR 9 and CLR 10.

4.3 *Framework protocol for reporting the dissemination of land remediation technologies (Harris 1996)*

This report is part of the Construction Industry Research and Information Association's (CIRIA) GeoEnvironmental research programme on contaminated land. It has been produced as a generic guide to planning, implementing and reporting demonstration projects and case studies on the remediation of contaminated land. It sets out the main issues to be addressed and gives sufficient information to develop plans for specific applications. Although primarily developed for the CIRIA programme, it is equally valid for similar use in other circumstances as its main purpose is stated as to be to ensure that the information obtained is a) valid and can be applied to other similar situations, b) objective in terms of the criteria used to assess technical performance and other characteristics, and c) consistent in terms of addressing the same well defined technical and administrative aspects.

The document is in eleven sections with each representing a distinct reporting element in a demonstration project report. These sections are a) executive summary, b) the CIRIA demonstration project, c) aims and approach, d) project description, e) project management, roles and responsibilities, f) detailed objectives and project plan, g) project result, h) cost analysis, i) interpretation, j) conclusions and recommendations, and k) appendices.

4.4 *Innovative site remediation technology: Volume 4, solidification/stabilisation (USEPA 1994) and Innovative site remediation technology: Design and application, stabilisation/ solidification, volume 4 (USEPA 1997)*

The document on innovative site remediation technologies: Volume 4, solidification/stabilisation (USEPA 1994) addresses innovative stabilisation and solidification technologies that have been sufficiently developed for use in full-scale applications for site remediation and waste treatment. The purpose is to further their use to provide improved cost-effective performance compared to conventional methods. It documents the current state of the technology for a number of innovative solidification and stabilisation processes and considers all waste matrices to which solidification and stabilisation can be reasonably applied, such as soils, liquids and sludges.

The USEPA document (USEPA 1997) covers the design, applications and implementation of S/S technologies and provide guidance on innovative processes considered ready for full-scale application. It is one of a series of monographs covering the description, evaluation and limitations of the technology. The monograph's objective is to provide guidance for experienced professionals with site remediation responsibility. It is intended to aid in the implementation of S/S technologies at specific sites.

4.5 *Proposed evaluation protocol for cement-based solidified wastes (WTC 1991) and a proposed protocol for evaluation of solidified waste (Stegemann & Côté 1996)*

This evaluation protocol, by the Wastewater Technology Centre of Environment Canada, was a first attempt at a decision-making tool for managing S/S wastes. Its approach involves determining whether S/S treated wastes should continue to be classified as hazardous, and what end-use would be appropriate for these wastes based on their measured properties. Four end-use scenarios, unrestricted utilisation, controlled utilisation, segregated landfill and sanitary landfill, are considered in this protocol, based on the performance of the solidified product. The performance itself is based on the treated materials measured characteristics. The evaluation procedure, which involves carrying out tests on the treated material to identify key properties, is in three levels. Level 0 evaluation involves determination of basic information on the process and the S/S material. Level 1 evaluation involves measurement of the amount of leachable contaminants from the S/S material and the chemical resistance to leaching. These tests are conducted on crushed samples. Level 2 evaluates the ability of a S/S material to offer mass transfer resis-

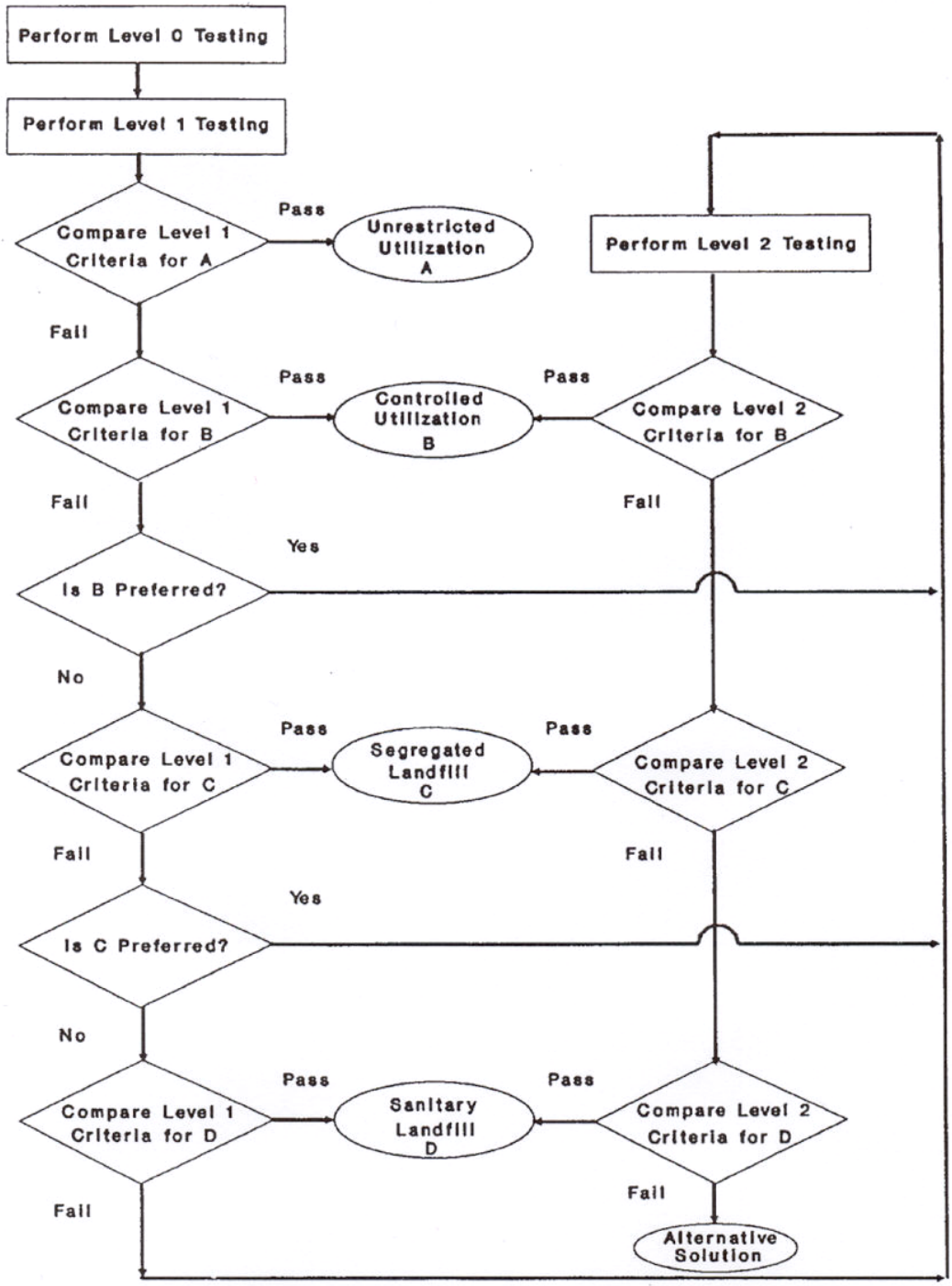

Figure 8. Decision flowchart for the proposed evaluation protocol (WTC 1991, Stegemann & Côté 1996).

tance to the leaching of contaminants in terms of physical containment. Therefore, these tests are carried out on monolithic samples.

The suggested test methods therefore examine partitioning of contaminants because of their chemical speciation, and potential for slow release of contaminants, based on the mobility of the contaminants in the solidified material, and the durability of the material *(Stegemann & Côté 1996)*. The decision flowchart for the proposed evaluation protocol involving the testing levels and end-use scenarios is given in Figure 8.

4.6 *Deep mixing method: Principle, design and construction (CDIT 2001)*

The Coastal Development Institute of Technology in Japan published a manual on Deep mixing method: principle, design and construction (CDIT 2001). The document offers guidance on the design and application of the deep mixing method in Japan. The details in this document are based on considerable research effort and accumulated experience in Japan. The document initially discusses the types of stabilising agents used in the deep mixing method, those being mainly cement and lime, and their basic binding mechanisms, the factors affecting strength increase of treated soils using these agents and the engineering properties of the treated soils.

It then describes details of the various soil mixing applications for various purposes including settlement reduction, increasing bearing capacity of the ground, increasing stability and ground liquefaction strength and cutting off groundwater. The document then details the design procedure for column groups, block and wall type constructions. Quality control and quality assurance issues are also outlined. The appendices detail the practice for making and curing stabilised soil specimens without compaction in the laboratory (which is standardised by Japanese Geotechnical Society), influence of in-situ mixing conditions on the quality of treated soil and recent research activities on column group type improved ground.

5 CONCLUSIONS

This state of practice report presented a summary of the content of currently available good practice guidance documents on stabilisation/solidification practices. The main guidance document in the UK is that recently published by the Environment Agency on the stabilisation/solidification of contaminated soils in addition to the guidance publication by the British Cement Association which relates specifically to the use of cement and lime. There are also a number of other good practice guidance documents available both in the UK and elsewhere, USA in particular, that are useful for S/S treatment and remediation works and which has been produced over the past decade or so. Collectively those documents offer comprehensive guidance on many aspects of stabilisation/solidification practices including screening, design, field trials, implementation and maintenance.

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