CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Technology guide: Chemical immobilisation and solidification

Version 0.1: August 2018

National Remediation Framework

The following guideline is one component of the National Remediation Framework (NRF). The NRF was developed by the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) to enable a nationally consistent approach to the remediation and management of contaminated sites. The NRF is compatible with the *National Environment Protection (Assessment of Site Contamination) Measure* (ASC NEPM).

The NRF has been designed to assist the contaminated land practitioner undertaking a remediation project, and assumes the reader has a basic understanding of site contamination assessment and remediation principles. The NRF provides the underlying context, philosophy and principles for the remediation and management of contaminated sites in Australia. Importantly it provides general guidance based on best practice, as well as links to further information to assist with remediation planning, implementation, review, and long-term management.

This guidance is intended to be utilised by stakeholders within the contaminated sites industry, including site owners, proponents of works, contaminated land professionals, local councils, regulators, and the community.

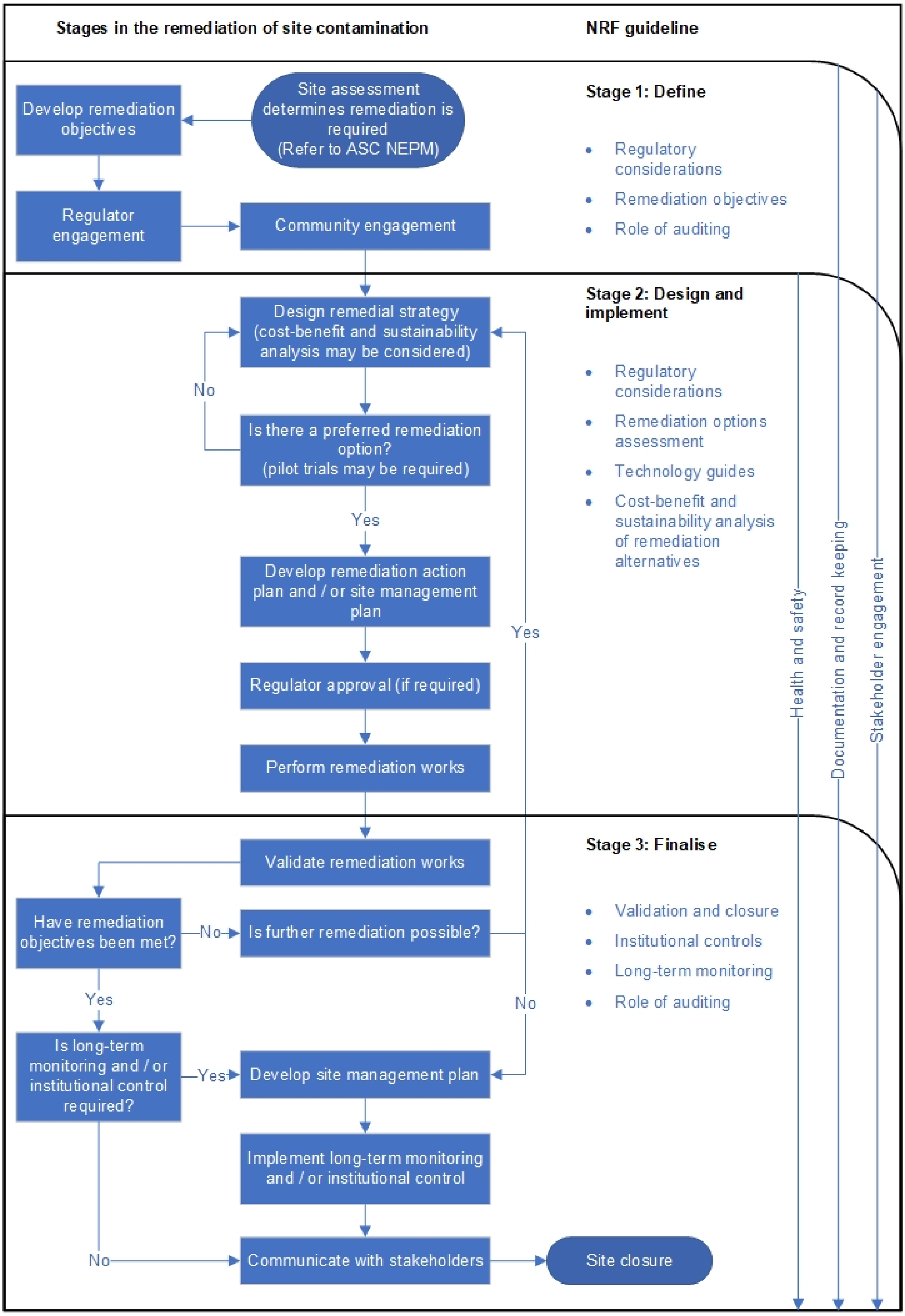
The NRF is intended to be consistent with local jurisdictional requirements, including State, Territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the NRF does not supersede regulatory requirements**.

The NRF has three main components that represent the general stages of a remediation project, noting that the remediation steps may often require an iterative approach. The stages are:

- Define;
- Design and implement; and
- Finalise.

The flowchart overleaf provides an indication of how the various NRF guidelines fit within the stages outlined above, and also indicates that some guidelines are relevant throughout the remediation and management process.

It is assumed that the reader is familiar with the ASC NEPM and will consult other CRC CARE guidelines included within the NRF. This guideline is not intended to provide the sole or primary source of information.


Stages in the remediation of site contamination
NRF guideline
Site assessment determines remediation is required (Refer to ASC NEPM)
Develop remediation objectives
Regulator engagement
Community engagement
Stage 1: Define
Regulatory considerations
Remediation objectives
Role of auditing
Design remedial strategy (cost-benefit and sustainability analysis may be considered)
No
Is there a preferred remediation option? (pilot trials may be required)
Yes
Develop remediation action plan and / or site management plan
Regulator approval (if required)
Perform remediation works
Stage 2: Design and implement
Regulatory considerations
Remediation options assessment
Technology guides
Cost-benefit and sustainability analysis of remediation alternatives
Health and safety
Documentation and record keeping
Stakeholder engagement
Validate remediation works
Have remediation objectives been met?
No
Is further remediation possible?
Yes
No
Is long-term monitoring and / or institutional control required?
Yes
Develop site management plan
Implement long-term monitoring and / or institutional control
No
Communicate with stakeholders
Site closure
Stage 3: Finalise
Validation and closure
Institutional controls
Long-term monitoring
Role of auditing

Executive summary

CIS comprises the addition of reagents and/or additives to contaminated soil to either immobilise and/or solidify contaminants within the soil.

Cement based reagents are the most commonly used as they are widely available and low cost. Cement based reagents includes Portland cement, fly ash, blast furnace slag and lime kiln dust. Clay, bentonite, activated carbon or chemical gelling agents are often added to contaminated soil (with the selected reagent) to increase the sorbing potential of the contaminants to the selected reagent.

The reagents and additives can be mixed into the contaminated soil either in-situ or ex-situ. The most appropriate treatment agents, application and mixing methods will depend on the contaminant properties, distribution and concentrations, together with the geological and hydrogeological conditions at the site such as soil porosity, homogeneity and depth to water table.

CIS has been most commonly applied to treat inorganic contaminants such as metals, cyanides, asbestos and radionuclides, although several organic contaminants are also amenable to CIS treatment such as pesticides/herbicides, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, volatile and semi volatile organic compounds, polychlorinated biphenyls and dioxins/furans.

The treatability studies, including bench tests and pilot trials should test the efficacy of various reagents and additives to effectively stabilise or solidify the contaminated soils.

Abbreviations

CIS	Chemical Immobilisation And Solidification
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
EPA	Environmental Protection Agency / Authority
NRF	National Remediation Framework
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyl
PPE	Personal Protective Equipment
RAP	Remediation Action Plan
SVOC	Semi-Volatile Organic Compounds
UCS	Unconfined Compressive Strength
VOC	Volatile Organic Compounds

Glossary

Amphoteric	A compound, especially a metal oxide or hydroxide, that is able to react both as an acid and a base.
Binder	One or more chemicals that react with water to form a solid matrix. The mixture of reagents and additives used to solidify contaminated material is often referred to collectively as the 'binder'.
Chemical immobilisation and stabilisation	The addition of reagents and/or additives to contaminated soil to either immobilise and / or solidify contaminants within the soil
Concentration	The amount of material or agent dissolved or contained in unit quantity in a given medium or system.
Conceptual site model	A representation of site-related information including the environmental setting, geological, hydrogeological and soil characteristics together with the nature and distribution of contaminants. Contamination sources, exposure pathways and potentially affected receptors are identified. Presentation is usually graphical or tabular with accompanying explanatory text.
Contaminant	Any chemical existing in the environment above background levels and representing, or potentially representing, an adverse health or environment risk.
Contaminated site	A site that is affected by substances that occur at concentrations above background or local levels and which are likely to pose an immediate or long-term risk to human health and/or the environment. It is not necessary for the boundaries of the contaminated site to correspond to the legal ownership boundaries.
Contamination	The presence of a substance at a concentration above background or local levels that represents, or potentially represents, a risk to human health and/or the environment.
Environment(al) protection authority / agency	The government agency in each state or territory that has responsibility for the enforcement of various jurisdictional environmental legislation, including some regulation of contaminated land.
Ex-situ	A Latin phrase that translates literally to "off site" or "out of position". It refers to remediation that is performed on the contamination following removal, ususally the excavation of soil.
In-situ	A Latin phrase that translates literally to "on site" or "in position". It refers to remediation that is performed on

	the contamination while it is in place, without excavating soil.
Leachability	The tendency for a contaminant to dissolve in percolating water and be moved via leaching as the water moves through the soil.
Matrix	A general term for a mixed solid containing many different elements. It may be naturally occurring soil, but may also be fill material or manufactured solids
Off-site	Physical area outside of the site boundary. Includes air, soil, water and groundwater, both above and below ground.
On-site	Physical area inside the site boundary. Includes air, soil, water and groundwater, both above and below ground.
Practitioner	Those in the private sector professionally engaged in the assessment, remediation or management of site contamination.
Proponent	A person who is legally authorised to make decisions about a site. The proponent may be a site owner or occupier or their representative.
Pugmill	A machine through which soil and amendments are processed, such that the end product is thoroughly mixed and homogenous. The individual design will vary according to moisture content, soil type, amendment type, contamination type, cost, timeframe and remediation objectives.
Reagent	A substance that takes part in and undergoes change during a chemical reaction.
Remediation	An action designed to deliberately break the source-pathway-receptor linkage in order to reduce the risk to human health and/or the environment to an acceptable level.
Risk	The probability that in a certain timeframe an adverse outcome will occur in a person, a group of people, plants, animals and/or the ecology of a specified area that is exposed to a particular dose or concentration of a specified substance, i.e. it depends on both the level of toxicity of the substance and the level of exposure. ‘Risk’ differs from ‘hazard’ primarily because risk considers probability.
Site	A parcel of land (including ground and surface water) being assessed for contamination, as identified on a map by parameters including Lot and Plan number(s) and street address. It is not necessary for the site

	boundary to correspond to the Lot and Plan boundary, however it commonly does.
Solidification	The addition of cementitious reagents to contaminated soil to encapsulate the waste materials within the matrix and change its physical properties, reducing its permeability and the extent to which contaminant migration will occur either into or from the treated medium.
Trammel	The funnel or conveyor belt that transports material into a mixer or pugmill.
Treatability studies	A series of tests designed to ascertain the suitability of the treatment for the contaminants under the site conditions

Chemical symbols, formulae and abbreviations

Symbol or abbreviation	Meaning or expansion
$Ca(OH)_2$	Calcium hydroxide
CaO	Calcium oxide
Fe(III)	Ferric oxide, Fe_2O_3

Table of contents

1. Introduction

The purpose of this guideline is to provide information on chemical immobilisation and solidification (CIS) as a treatment technology for the remediation of contaminated sites to assist with selection of remediation options. The document contains information to inform remediation planning and aid compilation of a remediation action plan (RAP).

This guidance is primarily intended to be utilised by remediation practitioners and those reviewing practitioner's work, however it can be utilised by other stakeholders within the contaminated sites industry, including site owners, proponents of works, and the community.

CIS is one of many technologies available for contamination remediation, and other technologies may be more appropriate. It is assumed that the information presented within will be used in a remediation options assessment to identify and select the preferred technologies for more detailed evaluation. This guideline provides information for both initial options screening and more detailed technology evaluation. This guideline does not provide detailed information on the design of CIS systems as this is a complex undertaking and should be carried out by appropriately qualified and experienced practitioners. Readers are directed to the NRF *Guideline on performing remediation options assessment* for detailed advice on assessing remediation options. In addition, the remediation objectives, particularly the required quality of the soil after treatment, are a critical matter and it is assumed that these have been determined and considered in the remediation options assessment and selection process. Readers are directed to the NRF *Guideline on establishing remediation objectives* for more detailed advice.

References to case studies are provided in **Appendix A**.

A number of sources of information were reviewed during the formulation of this document to compile information on potential technologies. These are listed in references, and provide an important resource to readers.

2. Technology description and application

CIS is a treatment technology that involves mixing reagents into contaminated materials (such as soil) to alter their physical properties by the processes of sorption, precipitation or incorporation into crystal lattices, or by encapsulating the contaminants, with the objective of reducing the rate of contaminant migration via leaching. The terms "immobilisation", "solidification" and "stabilisation" are sometimes used interchangeably and without clear distinction; however, for the purposes of this guideline the following distinctions are assumed:

- Immobilisation or stabilisation (referred to in this guideline as immobilisation) involves reagents being added to a contaminated soil to chemically immobilise hazardous materials or reduce their solubility, resulting in a reduction of their leachability. Immobilised material can have a soil-like consistency.
- Solidification comprises the addition of cementitious reagents to contaminated soil to encapsulate the waste materials within the matrix and change its physical properties, reducing its permeability and the extent to which contaminant migration will occur either into or from the treated medium. Solidified material can be in the form of (cement) blocks of material.

Generally, immobilisation is carried out ex-situ, either onsite or off-site, and the material is then disposed of to a landfill, though it is also possible to treat the material in situ and for it to remain onsite once immobilised. Solidification may also be carried out onsite, but it is more usual to carry it out off-site. If small amounts of high level contaminated material are involved, this will usually be solidified off-site and disposed of to landfill. CIS projects undertaken in Australia to date have generally not reused the treated soil onsite or carried out the treatment in situ, and the treated soil was disposed of to landfill.

The combination of reagents added to the contaminated material is referred to as the 'binder' and can consist of a single reagent or a number of various binding agents, which react with water to form a solid matrix. The mixture of binder, water and contaminated materials produces a medium with enriched physical and chemical properties. Many specific immobilisation reagents are added to target immobilisation mechanisms. These include phosphates, sulphides, Fe (III) salts etc. They can also be used as a precursor to solidification.

There are various components involved with the application of CIS remediation programs, including which reagents or additives to be used to fully stabilise or solidify the contaminated soils. Cement based reagents are most widely applied as they are low cost in comparison to other reagents and also widely available. Cement based reagents include Portland cement, fly ash, cement kiln dust and lime, lime kiln dust, and blast furnace slag. It is noted that not all blast furnace slags are suitable, for example crystalline blast furnace slag is generally not very effective. Magnesium oxide-based reagents are commonly used where amphoteric contaminants (e.g. arsenic, mercury) are present. A combination of additives may be more effective. The mixture of reagents and additives used to treat the contaminated soil is often referred to as the 'binder'.

A wide range of additives are often included in the binder, such as clay, bentonite, hydrogen peroxide, lime, activated carbon and chemical gelling agents to facilitate the immobilisation process. Common additives in cement-based CIS and their effect on the binder are provided in **Appendix A.**

The depth and nature of the contamination and geological conditions at the site (including hydrogeological conditions where applicable) will inform the decision of the most appropriate application method. The selected binder can be added to the contaminated soil in dry form or can be mixed with water.

The mechanical mixing process can be undertaken in-situ or ex-situ, and usually on-site but sometimes at a purpose built off-site remediation facility. The site conditions, including space available for equipment, together with the contaminant properties, thickness, depth to the water table and matrix properties (for in-situ mixing) will inform the decision of the best mixing method.

A commonly applied ex-situ system involves feeding excavated soil through a trammel and into a pugmill or mixer where reagents are added. Reagents such as cement will be held in a silo and the plant may have the appearance of a concrete batching plant.

Treating soil in-situ is less common, although often considered, and a simple in situ shallow mixing and application system is shown in Figure 1.

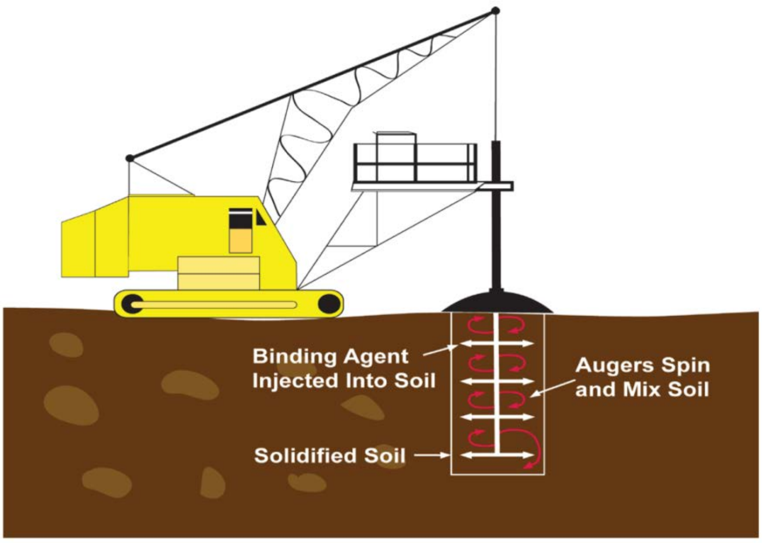


Figure 1 Shallow in-situ CIS application system, from US EPA (2002)

Some jurisdictions do not allow mechanical mixing using an excavator bucket and require ‘high shear mixing’ which typically involves a purpose built mixer with metering capability such as a batch mixer or continuous mixer (but not necessarily a pug mill).

Following completion of the remediation work (and sampling to demonstrate it has been effective), the treated material is generally landfilled, or in some circumstances may be able to be reused onsite.

3. Feasibility assessment

Key site-specific considerations that will often determine the feasibility of CIS as a potential remediation option include:

- Whether the treated material will be accepted for reuse or disposal, and whether the criteria that need to be satisfied are well defined and can be met (if reuse for a sensitive use is proposed then assuring long term stability of the treated material will be a critical requirement);
- Whether variations in the contaminant concentration, distribution and physical form of the material to be treated (e.g. the ability to mix the reagent uniformly through the material) make reliable treatment difficult or increase the required amendment/reagent quantities required;
- Whether the necessary quantity and cost of amendment/reagent is acceptable, and the resulting increased volume and cost of material to be disposed of is acceptable;
- Whether the amendment/reagent added will affect the use of the treated material; and
- Whether the availability and cost of the system required for adding the amendment/reagent application is acceptable.

If there is reasonable confidence that CIS will achieve the required treatment outcome, other issues will need to be considered to determine if CIS is likely to be an appropriate technology for the site. These include:

- Will the relevant regulatory agencies accept CIS as a viable means of remediation?
- Is it likely that other stakeholders (such as local government or members of the public) will accept the use of the technology, particularly those stakeholders that can have a significant bearing on whether the technology is applied at the site? Are there sensitive sites nearby that would not be compatible with the proposed operation?
- Is there a time constraint, and can the application of CIS meet this constraint?
- Is the expected order of cost of treatment acceptable?
- Is there sufficient space to store waste materials onsite or at an off-site facility in the event that ex situ CIS is needed?
- If the treated material is proposed to remain onsite, will the treated material be compatible with the future use of the site and is there sufficient assurance that the treated material will remain in an immobilised form in perpetuity?
- Are the long-term conditions that might occur well defined, and can these affect the level of immobilisation?
- Would the material have to be placed in an engineered repository?
- Is there a requirement to protect ecological beneficial uses of the site, and would immobilised or solidified material remaining onsite be consistent with

this? Are there environmental receptors on or adjacent to the site that could be impacted by the treated material?

- If the treated material is proposed to be landfilled, will the material be acceptable to the landfill?

3.1 Data requirements

Successful implementation and design of a CIS remediation program is dependent upon the following key technical considerations:

- The physical properties of the soil/aquifer matrix to be treated;
- The chemical composition and physical properties of the soil matrix to be treated;
- The type of contaminant and its properties such as solubility, volatility, NAPL etc;
- Groundwater conditions; and
- The depth and distribution of the contaminant (particularly if considering in situ treatment), and volume of material to be treated.

3.1.1 *Physical properties*

The physical composition of the material to be treated needs to be well characterised. Important factors are presented in Table 1:

Table 1: Important physical factors to consider for CIS

Factor	Consideration
Moisture content	May affect the performance of the binder and will determine whether water should be added or removed for processing. An addition of water may be required for the hydration of cement and pozzolan-based CIS.
Clay content	High clay content soils have little aggregate for the cement curing process and may provide limitations if it is required to meet minimum unconfined compressive strength values.
Viscosity	The consistency of the soil may prevent excavation and mixing. For example, creosote impacted soils may be too viscous for effective excavation and mixing. In these cases, heating the impacted soils will reduce viscosity and improve mixing conditions; however, this can have the potential to create noxious organic vapours.
Soil heterogeneity	The geological profile and conditions present at the site will enable an assessment of the grain size and homogeneity of the soils to be treated and inform the selection of appropriate binding agents. The presence of oversize material such as masonry and rock and waste such as timber and metals is also an important consideration, in terms of feeding the soil to a CIS plant.

Factor	Consideration
Particle size analysis	Some contaminants bind preferentially to small soil particles. Large particles may need particle size reduction prior to treatment to improve the effectiveness of CIS.
Strength	A measure of the effectiveness of a CIS process to produce material that complies with strength criteria (such as unconfined compressive strength) that might be set by a regulatory agency
Geotechnical suitability	The CIS treated material can vary in physical form, ranging from a friable soil like material, through to a monolithic block. Consideration needs to be given as to how such material will be handled, transported and placed, and whether the material will be geotechnically suitable and acceptable. These factors encourage disposal of CIS treated material in a landfill or engineered repository.

3.1.2 *Chemical composition and type of contaminant*

The composition of the material to be treated needs to be well characterised. Important factors are presented in Table 2:

Table 2: Important chemical factors to consider for CIS

Factor	Consideration
pH	Inorganic constituent retention mechanisms such as mineral and precipitate dissolution, adsorption/desorption reactions and aqueous solubility of inorganic species are strongly pH dependant. pH can therefore be a controlling variable for the equilibrium-based leaching of many inorganic contaminants. The solubility of organic contaminants on the other hand is usually not directly affected by changes in pH. This is due to additives in CIS formulations being able to target organic constituents through sorption which reduces leaching.
Organic content	Highly organic soils are unlikely to be amenable to treatment by CIS
Contaminant type, concentration and distribution	The nature and extent of the contaminants present can affect the physical properties of the inorganic and organic binder/waste products. Characterising the contamination will facilitate the selection of water-to-binder ratio, the porosity or the final strength of the product (). Some contaminants can slowly deteriorate the organic binder/waste product and thus have long term effects associated with them.
Range of contaminants	Depending on the types of contaminants present several pre-treatments are available to remove a large fraction of organics and inorganics. These treatments include soil washing, thermal removal, chemical oxidation, extraction removal, and biodegradation

3.1.3 *Maximum allowable concentrations*

If stringent clean up criteria or limitations on total contaminant concentrations apply, then CIS technologies may not be sufficient when dealing with these contaminants. Additional pre or post treatments may be required to reduce these contaminants to acceptable levels, increasing the total cost of remediation.

However, if risk-based remediation criteria can be applied then total concentrations may not be the controlling factor, and bioavailability can be taken into account when determining the acceptable concentrations. Where contaminated soil is to be reused or disposed of off-site, then regulatory requirements need to be determined, as these can be framed in terms of total concentrations and leachable concentrations, and require disposal only to the appropriate class of landfill.

CIS treated material is unlikely to sustain plant life as it can be strongly alkaline, not contain available organic or inorganic constituents required by plants, and may not have a physical form suitable as a growth medium. These factors make it unlikely that CIS treated material will be able to remain on a site where protection of terrestrial ecosystems is required, unless the amounts are small and at depth.

Where the total or leachable concentrations of contaminated soil are such that landfill disposal is prohibited or restricted to a landfill that incurs a high cost (such as a prescribed industrial waste landfill), then CIS technology can be an important method of allowing landfill disposal, or allowing material to be classified as material that can be disposed of with less costly landfill acceptance requirements. In such cases, after the material has been treated by CIS, total concentrations are not then the controlling factor and, instead, the status of the material for disposal can be determined on the basis of leachability. Readers are directed to US EPA (2017) for further information on leaching protocols for immobilised or solidified mediums.

3.1.4 *Groundwater conditions*

Groundwater considerations become important if groundwater can intersect the CIS, or the water leaching through CIS treated material passes into groundwater.

Where groundwater can intersect the with the CIS treated material, hydraulic conductivity is important. Depending on the relative hydraulic conductivities of the CIS material and the surrounding soils, groundwater may either flow through a CIS mass or be diverted around it. Modelling may be able to be used to predict the potential impact on groundwater at a compliance point down-gradient of the treated material. Monitoring of groundwater quality down-gradient of the treated materials can also be carried out to confirm that contaminant concentrations are within acceptable limits.

Where groundwater can intersect the with the CIS treated material, the composition of the groundwater can be important. Constituents in the groundwater may affect the level of immobilisation. For example, if the groundwater is acidic and the immobilisation relies on the maintenance of alkaline conditions, then the level of immobilisation can be affected. Saline conditions may affect the strength of solidified material, leading to cracking and weathering and increased leachability.

Seasonal rise and fall of the water table may result in wetting and drying of the material leading to a redistribution of contaminants towards the surface of the stabilised matrix, with increased dissolution in successive wetting cycles.

3.1.5 *Depth, distribution and volume of material to be treated*

The depth of the soils requiring treatment will influence the feasibility of both in situ and ex situ CIS. Contamination at shallow depths may be treated using in-situ or ex-situ CIS application. However, if the contamination is at significant depth (around 10m for example) below ground level, it is likely to reduce the feasibility of in-situ and ex-situ application. In-situ application is unlikely to be viable given the depth that injection and mixing equipment would need to be installed to and the difficulty of collecting validation samples. Ex-situ CIS of soils excavated from significant depths would incur additional costs and time for the remediation implementation (and validation sampling would also be difficult).

The volume of material to be treated is also a key consideration, as this will determine the cost and could also determine the feasibility of the method and how it might relate to other methods. Quantifying the volume will require careful delineation of the material that needs to be excavated for treatment, or which will be treated in-situ. Delineation of the volume and location of material can be expected to require additional sampling and analysis (over that undertaken in the contamination assessment).

Typically, the location and extent of material should be indicated on a map; ideally this should be prepared using software where the available sampling and analytical information can be input as the source data for the plan. The uncertainty in the volume and location of material to be treated should be understood, and related to the requirements for decision making.

3.1.6 *Regulatory requirements*

The regulatory agencies (particularly the agencies responsible for protection of the environment, town planning and licensing treatment facilities) should be consulted to determine specific requirements relating to obtaining the necessary approvals and licences, and controls that can be expected. If inappropriate remedial strategies are adopted, future land use of a site can be permanently restricted.

Because CIS treatment does not reduce the mass of contaminant but relies on permanently changing contaminants to a less hazardous form, uncertainty regarding the permanence of the immobilisation or solidification becomes a critical factor if CIS treated material is placed in a location where exposure or leaching can occur. Risk assessment, considering the possible adverse effect that might occur and the likelihood that this effect will occur, can be a useful method of evaluating the appropriateness of a remedial strategy and gaining agreement that the technology can be applied. Readers are directed to the NRF *Guideline on performing cost-benefit and sustainability analysis of remediation options* for more detailed information on incorporating risk assessment into decision making.

Where it is possible that exposure or leaching might occur, confirmation that the situation is satisfactory may be achieved through monitoring in accordance with an appropriate site management plan and/or groundwater monitoring plan. Such a plan should include triggers and contingency measures if monitoring indicates unexpected impact on groundwater is occurring. Controls on future land use may be required through institutional controls.

It should be noted that financial assurances are required in some jurisdictions when CIS material is remaining on site.

3.1.7 *Approvals*

The need for approvals and the requirements for gaining approval varies with jurisdiction and should be determined when CIS is being considered. Some jurisdictions have prepared guidance documents relating to the disposal of contaminated soil and how CIS is considered in this process, and these should be referred to.

3.2 Treatable contaminants

CIS can be used to treat both organic and inorganic compounds, though it is more commonly used to treat inorganic contaminants.

The contaminants treated by CIS typically include:

- Petroleum hydrocarbons;
- Pesticides;
- Herbicides;
- Polycyclic aromatic hydrocarbons;
- Heavy metals;
- Volatile organic compounds;
- Semi-volatile organic compounds;
- Cyanides (insoluble salts only); and
- Asbestos.

4. Treatability studies

If there is uncertainty regarding whether CIS will achieve the remediation objectives or there are other issues that make it uncertain as to whether CIS will prove to be applicable, treatability studies may be required to provide further information to aid decision making. Treatability studies can provide information on the ability of certain reagents to achieve the desired physical form and reduce leachability, the rates of addition of reagents that are necessary, and costs of implementation.

Designing the treatability study may require input from a number of technical specialists including environmental specialists, chemical engineers, mechanical engineers and air quality specialists to ensure that the study is designed to obtain the data required to enable the applicability of the technology to be determined and the most appropriate implementation strategy to be developed.

The type of additional information required can be decided upon by undertaking a review of the available information on the application of the type of CIS process being evaluated. If results of previous case studies of CIS applied in similar conditions are available, it may be possible to use the information from these previous case studies to avoid carrying out a treatability study or to minimise the scope of trials required.

The purpose of the treatability testing will be to obtain specific data to enable a RAP to be written and the CIS program to be designed. This will include the assessment of the physical and chemical properties as well as the uniformity of the material. Clear objectives should be set at the outset of each stage of treatability testing to ensure the tests are targeted to obtain the information required to fill the data gaps.

4.1 Bench tests

Bench tests can be undertaken to assess the effectiveness of various binder formulations when mixed with contaminated materials from the site in question, or to develop compliance criteria to monitor and evaluate the performance of the full-scale system.

Use of contaminated soil from the actual site is important as small changes in the physical and chemical characteristics of the material can affect the contaminated soil/binder relationship and the final product characteristics. In addition, small changes in the amounts of reagents and additives added can significantly affect the physical strength and containment characteristics of the binder/contaminated soil product.

Testing is usually conducted in a laboratory, applying a tiered approach where the results of each test determine the parameters and conditions to be evaluated in the next test. The tiers are described in Table 3, below.

Table 3: Tiers of bench testing for CIS

Tier	Description
Tier 1	Designed to narrow the range of potential reagents by eliminating those not meeting the remediation criteria.
Tier 2	Testing combinations of reagents and additives to assess contaminant immobilisation/stabilisation.

Tier	Description
Tier 3	Optimising the principal reagent or combination of reagent and additive to minimise the quantity used to meet the regulatory requirements.
Tier 4	Further testing of the principal reagent or proposed combination of reagent and additive, and the development of baseline consistency tests and performance criteria acceptance limits.

The point at which a RAP can be developed will be a matter of judgement, with greater certainty in the requirements for the RAP as more work is undertaken.

Pre-treatment of contaminated material may facilitate the application of CIS, and screening tests can be carried out to determine this. Examples of pre-treatment technologies that have been used at contaminated sites include neutralisation, precipitation, adsorption and chemical oxidation. If ex-situ CIS is to be implemented, the sample can be treated to reduce its heterogeneity, improve its materials handling properties, or adjust its moisture content. This can make the contaminated material more uniform and allow the binder to work across a well-defined material.

As a binder is being added to contaminated materials, the volume of the stabilised matrix will differ from that used in the initial feasibility tests. This is an important factor in consideration of reuse or disposal options and costs. The data from this initial phase of testing can be used to estimate ratios of binder required for each cubic metre of contaminated soil. Where there is a significant volume increase in the immobilised/solidified product, excess amounts may have to be removed and transported to an approved landfill. The analytical, transport and disposal costs could be significant.

4.2 Pilot trials

The next stage of treatability testing is to evaluate the application of the CIS process for the specific site conditions. This involves taking the most successful binder mixes which were determined in the initial screening tests and performing a small-scale pilot trials in the field. The objectives of this stage of treatability testing is to:

- Evaluate the consistency of mix design performance between the initial screening tests and full-scale implementation;
- Assess the applicability and reliability of binder mixtures and predicted outcomes from the initial screening tests;
- Identify factors that need to be considered when scaling the project up to the actual site conditions; and
- Evaluate the properties of the treated product using full-scale equipment.

When collecting samples for ex-situ testing, samples of all relevant strata should be analysed to be as representative of the site ground conditions as possible, ensuring that the results of the treatability tests can be replicated onsite.

If in-situ testing is proposed, it should be recognised that the quality of treated materials produced from in-situ testing will be more variable than ex-situ applications. Variations in composition and physical form of the subsurface materials will occur and it will be difficult to adjust binder and reagent additions as may be necessary, and visual inspection of mixing performance will be limited. If in-situ treatment is involved, investigations in relation to the possible variations in treatment performance with depth should be undertaken.

The total volume of treated material will also increase when undertaking in-situ treatment due to returns to surface of contaminated cementitious slurry. This growth can be very large (20 to 50% of the in-situ volume) and is determined by the porosity and permeability of the matrix, the mixing method and characteristics of the additives. This has implications for management of the excess during treatment, and its ultimate use or disposal.

The results of treatability testing in this stage should be compared against the remediation criteria. The process should be evaluated as a whole to identify potential improvements and the design requirements for the site-specific application. The information obtained in the second stage of testing is usually sufficient to enable development of the RAP.

5. Validation

The following information describes the specific validation appropriate for CIS, to assist validation planning within the RAP. Readers are directed to the NRF *Guideline on validation and closure*, which among other things, provides further information on each of the lines of evidence.

Validation of CIS generally consists of two main parts:

- An assessment of the treated material to determine the leachability of contaminants; and
- If treated material is to be left on site, monitoring of down-gradient receptors to assess whether remedial criteria for groundwater and/or surface water have been met.

Where the requirement is to produce a solid monolithic block, an assessment of the strength of the material and hydraulic conductivity may also be required. The strength of CIS material is usually demonstrated through the unconfined compressive strength (UCS) method, which expresses the load per unit area at which the material demonstrates structural failure. When considering the timeline for monitoring, it should be noted that the UCS of an CIS material generally increases with time until setting is complete. The hydraulic conductivity of S/S materials and surrounding soils can be demonstrated by either field or laboratory tests. Saturated hydraulic conductivity of granular or saturated soils may be demonstrated using ASTM D5084, whilst field tests may be preferable if surrounding soils are unsaturated or coarse-grained. Depending on the technology implemented, structural integrity testing may not be appropriate when validating stabilisation methods.

Leaching tests can be used to assess the ability of the CIS material to retain the contaminants of concern and is likely be a key requirement where treated material is to be retained on site. Readers are directed to US EPA (2017) for further information on leaching protocols for immobilised or solidified mediums.

Where S/S treated material is to be left on site it may be necessary to provide information that confirms that the material will not adversely affect the surrounding environment. There will also be a need to consider hydraulic conductivity of the treated material and the potential for groundwater mounding to occur.

Confirmation that the treated material will not impact on the surrounding environment may include:

- Documented reduction in down-gradient concentrations;
- Estimation of mass discharge from the material;
- Analysis of geochemical and biochemical parameters,

Groundwater modelling using site characterisation and data from a treatability study may also be used to evaluate the anticipated flux of contaminants that might leach from the treated material, and this information can be used to design the groundwater monitoring program.

Testing to determine the bioavailability of the CIS material may also be carried out to demonstrate that the contaminants are no longer in a bioavailable or bioaccessible form; this may be similar to and would complement the leaching tests.

6. Health and safety

CIS is a common treatment process used at contaminated sites to reduce the mobility of the contaminants. In the process, health and safety hazards may arise such as chemical exposure from site contaminants, noise, dust and physical injury from pinching or crushing.

The industrial equipment used in the CIS process pose a variety of hazards to workers. If these risks are identified and controlled, the technology can be used safely. Workers can be exposed to unanticipated safety hazards and receive unexpected exposure to site contaminants while working in and around CIS mixing units.

Some of the hazards associated with CIS and control mechanisms are outlined in Table 4. The list is intended to provide an indication of the hazards potentially associated with CIS application. They will vary significantly from site to site and the list is not intended as a substitute for a detailed hazard assessment of the operation, which should be provided in the RAP.

Readers are directed to the NRF *Guideline on health and safety* for further information on health and safety on remediation sites, including risk assessment, the hierarchy of controls and suggested documentation.

Table 4 Common CIS hazards and controls

Hazard	Sources of hazard	Suggested controls
Site contaminants	• Off-gassing or releasing contaminants as feedstock is loaded, sized, blended, and moved releasing emissions from treatment process. • Releasing or encountering contaminants in feedstock while working on equipment.	• It may be necessary to undertake monitoring and implement PPE (respirators and chemical suits etc.), ventilation. • Odour control enclosures, ventilation and emissions control systems to contain dust and capture odours and harmful contaminants. • Odour suppressants for nuisance odours • Segregate treated feedstock until tested.
Dust	• Excavation of contaminated soils for ex situ CIS. • Handling and addition of reagents if in powder form	• Spray water or use dust suppressants on stored contaminated materials. • Do not operate earth moving equipment during high winds. • Use systems that contain binders and reagents and avoid storage, handling and addition methods that can result in dust.
Binders and reagents	• Handling, storage and mixing of binders and reagents	• Use systems that contain binders and reagents and avoid systems that can result in exposure of personnel or uncontrolled release. • Ensure workers use proper PPE.
Mechanical	• Contacting or becoming entangled in moving/ unguarded equipment, such as an excavator. • Working on any of this moving equipment without isolating the energy source.	• Train workers on hazards. • Ensure use of lockout procedures for maintenance. • Use of guards, who may remove guards, and how to remove guards.
Flying particles and falling material	• Disturbance of the ground from moving equipment or from high winds, leading to dust generation.	• Ensure workers use proper PPE. • Use of dust suppressants as necessary

Hazard	Sources of hazard	Suggested controls
Slips, trips and falls	• Storing construction materials or other unnecessary items on walkways and in work areas. • Creating and/or using uneven terrain in and around work areas.	• Keep walking and working areas free of debris, tools, electrical cords, etc. • Keep walking and working areas as clean and dry as possible. • Train workers on fall hazards.
Moving vehicles	• Moving and stockpiling excavated contaminant material either onsite or at an off-site facility using earth moving equipment. • Receiving and transferring reagents/additives and other materials from commercial vehicles.	• Train affected employees on limitations of equipment and drivers. • Train equipment and vehicle operators in safe operation. • Set acceptable speed limits and traffic patterns. • Do routine maintenance.

Appendix A – Common CIS additives

This appendix summarises the common additives in cement-based CIS, presented in Table 5 overleaf.

Table 5: Common additives in cement-based CIS, from Connor (1997).

Purpose	Additive	Effect
pH control and buffering	Lime – CaO or $Ca(OH)_2$	Neutralises acid, raises pH
	Sodium hydroxide	Neutralises acid, raises pH
	Sodium carbonate	Neutralises acid, raises pH
	Sodium bicarbonate	Buffer
	Magnesium oxide	Buffer
	Ferrous sulphate	Lowers pH (increasing acidity) to control alkalinity
	Sulphuric acid	Lowers pH (increasing acidity) to control alkalinity
Reduction (alter valence state of metals)	Ferrous sulphate	Reducing agent in acid conditions
	Sodium hydrosulphite	Reducing agent in alkaline conditions
	Sodium metabisulphite	Reducing agent in acid conditions
	Blast furnace slag	Reducing agent
	Metallic iron	Reducing agent
Oxidation	Potassium permanganate	Oxidising agent, alteration of biological status
	Sodium or potassium persulfate	Oxidising agent, alteration of biological status
	Sodium or calcium hypochlorite	Oxidising agent, alteration of biological status
	Hydrogen peroxide	Oxidising agent, alteration of biological status
Speciation, re-speciation	Carbonates	With lead, forms carbonates.
	Iron and aluminium compounds	Various

Purpose	Additive	Effect
(alteration of the species of the constituents of concern to fix metals and other ions)	Phosphoric acid and salts	With lead, forms phosphate compounds that have a low solubility through a wide pH range
	Sodium silicate	Forms low solubility, silicate species with a variety of metals in solution; catalyst
	Sodium sulphide	Forms metal sulphides, except with chromium
	Calcium polysulphide	Forms metal sulphides, except with chromium
	Organic sulphur compounds - thiocarbamates	Forms metal sulphides, except with chromium
	Sulphur and alkali	Forms metal sulphides, expect with chromium
	Xanthates	Forms low solubility starch or cellulose xanthate substrates with metals attached
	Sodium chloride	Silver fixant
	Sodium sulphate	Barium fixant
	Ferrous sulphate	Removes sulphide ion from solution
Precipitation and flocculation (aggregation of fine particles, dispersion of oils and greases)	Ferrous sulphate	Co-precipitating agent
	Proprietary organic flocculants, surfactants	Flocculants and dispersants
	Alcohols	Wetting agent
	Amides	Wetting agent
	Carboxylic acids	Dispersants
	Aldehydes and ketones	Dispersants
	Sulphonates	Dispersants
	Amines	Flocculants
	Iron salts	Flocculants
	Magnesium salts	Flocculants

Purpose	Additive	Effect
	Silica	Flocculants
Sorption, bulking, or structural modification (removal of interfering substances from reacting surfaces, immobilise organic species, free water control, viscosity control)	Activated carbon	Sorbent for organics, especially VOCs, organo-metallics and some metals
	Organoclays	Sorbent for organics
	Rubber particulate	Sorbent for organics, especially SVOCs
	Fly ash	Sorbent for some metals and organics, pozzolanic reaction with alkalies, bulking agent
	Rice hull ash	Sorbent for organics, especially VOCs, reacts with alkalies to form soluble silicate
	Natural clays	Sorbents for some metals, bulking agent, viscosity control
	Expanded minerals	Sorbents for some metals, bulking agent
	Diatomaceous earth	Sorbents for some metals, bulking agent
	Blast furnace slag	Pozzolanic reaction with alkalies, bulking agent, reducing agent, structural modification
	Silica fume	Pozzolanic reaction with alkalies, bulking agent, structural modification
	Wood chips	Sorbent, bulking agent
	Ground corn cob	Sorbent, bulking agent
	Cement kiln dust	Pozzolanic bulking agent
Catalyst	Calcium chloride	Accelerates set
	Calcium aluminate	Accelerates set
	Calcium sulphate	Accelerates set
	Glycols	Accelerates set
	Sugar	Accelerates set
	Amines	Accelerates set
	Organic acid salts	Accelerates set

Purpose	Additive	Effect
	Lime	Supplies additional calcium for reaction, reacts with certain interfering organics, anti-inhibitor, controls biological status
	Sodium silicate	Reacts with interfering metals, catalyst, fixes metals
	Iron compounds	Counters effect of tin, lead arsenates, sulphides by reaction
	Triethanolamine	Accelerates set
	Calcium formate	Accelerates set
	Phosphates	Accelerates set
	Bentonite	Sorbs oils, organics, anti-inhibitor
	Cement kiln dust	Accelerator (in some cases)
Retardation (retardation of setting to allow for better processing control)	Sugar	Retards setting at low levels
	Sugar derivatives	Retards setting
	Zinc hydroxide	Retards setting
	Copper hydroxide	Retards setting
	Lead hydroxide	Retards setting
	Calcium chloride >4%	Retards setting
	Magnesium salts	Retards setting
	Tin salts	Retards setting
	Phosphates	Retards setting
	Lignosulphonic acid salts and derivatives	Retards setting
	Hydroxy carboxylic acids	Retards setting
	Polyhydroxy compounds	Retards setting

Purpose	Additive	Effect
Free water control	Slag	Bulking agent, pozzolan
	Fly ash	Bulking agent, pozzolan
	Concrete water reducing additives	Reduce water requirement where applicable
	Cement kiln dust	Bulking agent, pozzolan
Miscellaneous	Biocides	Counter biological activity
	Organic polymers	Fill pores, improve microstructure, improve durability
	Air entrainment additives	Improve durability
	Wood resins	Improve durability

Appendix B – Case studies

The following provide examples of CIS implementation from Australia and internationally.

- Video of Platypus gasworks remediation:
  - Excavation, CIS treatment and reuse
  - https://www.youtube.com/watch?v=LOD0lk4jAzE
  - Excavation and stabilisation of 30,000 tonnes of contaminated soil (gas works waste) by the addition of portland cement. 90% of waste reused onsite.
  - Processing water captured from the excavation-site in a purpose-built treatment plant prior to disposal to sewer.
  - Construction of a barrier wall to provide permanent seal between the stabilised contaminants and Sydney Harbour.
- Hunter River, Newcastle:
  - https://www.ch2m.com/corporate/worldwide/assets/ProjectPortfolio/australia/CH2M-HILL-Hunter-River.pdf
  - Dredging of 400,000 m^3 of contaminated sediment for treatment via cement stabilisation prior to placement in a purpose built facility.
- Katoomba Gasworks, Chiswick - *Use of Immobilisation Methods to Remediate metals and PAHs in Soil*, Baltpurkins K, Cole K, Hunt J (Ecoforum presentation, 2008).
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- http://cement.org/waste/Remediation%20of%20Oil%20Refinery%20Sludge%20Basin.pdf
- http://www.researchgate.net/publication/237616887_RCRA_Closure_of_Refinery_Sludge_Basin_Using_In situ_Solidification_and_Containment

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