STATE OF PRACTICE REPORT
UK STABILISATION/SOLIDIFICATION TREATMENT AND REMEDIATION
Part IV: TESTING & PERFORMANCE CRITERIA

ASR Perera[a], A Al-Tabbaa[a], JM Reid[b], JA Stegemann[c]
[a]Department of Engineering, University of Cambridge, Cambridge, UK
[b]Viridis, Berkshire, UK
[c]Department of Civil & Environmental Engineering, University College London, London, UK

INTRODUCTION

Stabilisation/solidification (S/S) is a treatment technique which contains contaminants within a final solid matrix, usually based on cementitious or pozzolanic binder materials, so as to prevent the contaminants from entering the environment at unacceptable rates. The various types of binders used and the different approaches adopted in their application to obtain the end material were reported previously together with related work carried out in the UK (Al-Tabbaa and Perera, 2003 a, b, & c).

Whether in preparation for full-scale treatment, or to verify the effectiveness of treated material in-situ, it is necessary to assess the performance of a stabilised/solidified (S/S) material in order to judge its improved properties and the effectiveness of the binder matrix in containing contaminants. This is achieved by carrying out various tests, the results of which may be compared against performance criteria. It is appropriate to establish a testing regime that addresses the relevant issues for the management scenario (e.g., disposal or utilisation) being considered (Stegemann and Coté, 1990; 1991; Hinsenveld 1992; 1993). Performance criteria are also usually developed in conjunction with the objectives of the treatment and the management scenario of the end material.

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

Physical tests are used to predict mixing behaviour, reagent needs and volume increases, and compare treated and untreated materials in terms of their strength and durability. Chemical tests are used to determine the leaching behaviour of the S/S material (Harris et al., 1995).

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

TEST METHODS

Various test methods have been adopted in research and practice to assess the efficiency of S/S processes (Conner, 1990; Stegemann and Coté, 1990; 1991; LaGrega et al., 1994; van der Sloot et al., 1997). Such assessment could be generally categorised as:

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

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

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

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

In choosing the methods for inclusion in this review, use was made of the MONOLITH database (available through http://www.concrete.cv.ic.ac.uk/iscowaa/NNAPICS/intro.html), which was developed as part of a European Commission funded project that had the objective of collecting existing data concerning cement-based S/S materials from the literature, and developing models to examine trends and relationships in the resulting data set (Stegemann et al., 2001). It should be noted that collection of data for MONOLITH focussed on measurements of setting time, unconfined compressive strength and leaching in single batch extraction tests (WTC, 1990), including particularly measurement of pH and acid neutralisation capacity, which represent common and useful measurements of handling, durability and leachability. Thus, the information about use of other tests contained in MONOLITH was collected incidentally. Nevertheless, inspection of the literature indicated that the tests collected in MONOLITH were reasonably representative of common practice.

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

Leaching Tests

Leaching tests are conducted to examine mass transfer from a solid (the S/S material) to a liquid (termed the "leachant" before contact with the solid, and the "leachate" afterwards). Depending on the characteristics of the contaminated material and the surrounding environment, the leachant may flow through the contaminated material, maximising contact between the leachant and solid, and washout of contaminants, or flow around it, minimising contact between the leachant and solid, such that leaching occurs by diffusion of contaminants through the connected porosity of the sample. Hence the leachability (ability of the material to leach contaminants) is dependent on the physical and chemical properties of the contaminated material and the leachant (LaGrega et al., 1994).

There are several test methods in existence for conducting leaching tests, which are applicable to both raw and treated materials (although some tests are applicable mainly to monoliths). As these are defined by different experimental variables, the selected method itself will have an affect on the results. Further, the method of leachate analysis adopted also has a bearing on the results. As recommended by DD ENV 12920 (1998) and others (e.g., Stegemann and Coté, 1990), a range of leaching tests may be required to develop an understanding of the leaching behaviour of a material. WTC (1990), LaGrega (1994) and van der Sloot et al. (1997), among others, have identified the following important variables that distinguish leaching tests:

- *Sample preparation*: Depending on the form of the material and the type of test selected, the sample may require some preparation in the form of liquid/solid separation, drying, sub-sampling, particle size reduction, surface washing, compaction/remoulding, conservation and curing.
- *Leachant composition*: The leachant (e.g., water, acid, landfill leachate, groundwater, or simulated versions of these) will be selected depending on the application. In particular, leachant and/or leachate pH is often controlled (and should always be measured).
- *Mode and method of contact*: Depending on the form of the sample and the leaching test, conditions which may affect the mass transfer rate, such as agitation method, flow direction and rate, vessel type, headspace considerations, and contact with atmosphere must be given due consideration.
- *Liquid-to-solid ratio (L/S)*: L/S is generally measured as leachant volume to sample dry mass with the ratio varying depending on the objective or type of test, solubility of the components of interest and detection limits.
- *Leachant renewal*: Some tests require the leachant to be continuously or intermittently renewed to maintain a driving force for leaching.
- *Contact time*: The duration of the test influences the amount of contaminant released. In a batch leaching test, it is prescribed, or is a function of flow rate in a dynamic test.
- *Temperature*: Tests are generally conducted at room temperature, although different temperatures may be specified. The properties of the material and mechanisms of leaching are temperature dependent.
- *Leachate-solid separation*: An appropriate form of separation such as centrifugation, filtration (using membrane or glass fibre filters) will be adopted to obtain the leachate for analysis.
- *Analysis of the leachate*: Parameters of interest in leaching tests must include pH, without which it is impossible to interpret the results of the test, and can also include virtually any chemical species. Heavy metals, toxic and persistent organic compounds, and radionuclides, are the most common contaminants of concern, but other parameters, such as nutrients, bulk matrix components, conservative cations and anions, total organic carbon, or interfering compounds may be of interest. Attention also needs to be paid to leachate sample storage and preparation prior to analysis, method of calibration and analysis of recovery, and quality control, as these are essential for good results and for allowing comparison of results from different methods. Sample preparation and analytical procedures may be specified in the leaching procedure by citing standard methods or protocols.

Although several leaching test methods exist, many are variations on the same basic principle with modifications in the specific testing conditions. A number of systems have been developed for classifying leaching tests. The system proposed by van der Sloot et al. (1997) is based on (i) equilibrium or semi-equilibrium tests, (ii) dynamic tests and (iii) specific tests focusing on chemical speciation. An earlier system (WTC, 1990; Conner, 1990; Lewin et al., 1994) classifies leaching tests as either extraction tests or dynamic tests based on whether the leachant is renewed (in the case of the latter) or not (the former). Extraction tests include all tests that contact a specific amount of leachant with a specific amount of material for a specific amount of time (WTC, 1990). Dynamic tests include all tests that continuously or intermittently renew the leachant to maintain a driving force for leaching and generate information as a function of time while attempting to preserve the structural integrity of the material (WTC, 1990). This latter classification method will be used in this document.

Extraction Tests

Extraction tests are the most common tests and they have been subdivided by WTC (1990) into several categories, of which two types are most relevant for S/S materials:

***(1) Agitated extraction tests*:** An extraction test can be agitated to maintain a homogeneous mixture and promote contact between the solid and the leachant, thereby accelerating attainment of steady state conditions. To decrease physical barriers to mass transport, granular or crushed samples are used with the leachant at a specified L/S. They measure the chemical properties of the system and not the rate-limiting mechanisms. The common agitated extraction tests include:

(i) The toxicity characteristic leaching procedure (TCLP) (USEPA, 2003a) is a commonly used standard single batch leaching test, which was developed by the United States Environment Protection Agency (USEPA) as a rapid regulatory compliance test for determining whether a waste is suitable for disposal in a landfill with municipal waste. Because of the presence of organic acids in this scenario, the test uses acetic acid buffered to pH 4.93 (or 2.88) with sodium acetate, to a maximum buffering capacity of 2 meq/g of wet waste, at a L/S of 20:1, for 18 hours. The test has been criticised because it does not take into account the characteristics of a S/S material, or management scenarios other than municipal waste landfill disposal. The test is conducted on granular material, and therefore does not give credit for reduction in leachability due to production of a monolithic material. More importantly, since the maximum buffering capacity is often exceeded by a cement-based solidified material, the test conditions can result in an arbitrary final leachate pH. Since the final leachate pH is critical for solubility of contaminants, a combination of tests that measure contaminant solubility at different pHs is more informative.

(ii) The extraction procedure toxicity test (EP-tox) (USEPA, 2003b) was a USEPA regulatory compliance test, which was commonly used until superseded by the TCLP. It is also a standard single batch leaching test, which uses 0.5N acetic acid to maintain the leachate at pH 5, with a maximum acid addition of 2 meq/g of wet waste, at a L/S of 20:1 for 24 hours. The test makes provision for testing of monolithic samples, but it also has the drawback that the final leachate pH is arbitrary.

(iii) The synthetic precipitation leaching procedure (SPLP) (USEPA, 2003c) is a standard single batch compliance test, which was developed as an alternative to the TCLP for situations where disposal is outside municipal waste landfills. It uses an acid mix containing sulphuric/nitric acid (60/40 w/w) for an initial leachant pH of 4.2 or 5 at a L/S of 20:1, for 18 hours. In practice, applied to S/S material, this initial leachant pH makes little difference to the final leachate pH, which reflects that of the alkaline S/S material.

(iv) ASTM D3987 (ASTM D3987-85, 1999) is a standard compliance-type test first issued in 1981 and last revised in 1985. The intention of the test is to provide a rapid extraction procedure for industry, but not to simulate site-specific conditions (WTC, 1990; van der Sloot et al., 1997). The test uses distilled/deionised water at a L/S of 20:1 for 18 hours. Thus, the final leachate pH reflects the pH of the material being tested.

(v) DIN 38414 S4 (DIN-NORMEN, 1984) is a standard batch leaching test, which has been widely used for regulatory compliance purposes in Germany and Austria, as well as for general assessment elsewhere. It uses distilled/deionised water at a L/S of 10:1 for 24 hours, which allows the test material to establish the pH. This test will be superseded for regulatory use by the EN 12457 batch leaching tests and other tests recently developed under CEN TC/292.

(vi) The National Rivers Authority (NRA) leaching test (Lewin et al., 1994) is a standard single batch compliance test, which was developed and recommended by the National Rivers Authority for the purposes of general assessment of the leachability of mainly inorganic contaminants from contaminated land in the UK (Lewin et al., 1994). This method was developed as an alternative to more aggressive tests such as the TCLP. It uses distilled/deionised water left to stand over night (expected pH 5.6), at a L/S of 10:1, for 24 hours. In practice, this initial leachant pH makes little difference to the final leachate pH, which reflects that of the alkaline S/S material. This test will also be superseded by BS EN 12457, developed, by CEN/TC292 (see below).

(vii) BS EN 12457 (BS EN 12457: Parts 1 to 4, 2002*)* describes a series of batch leaching tests for granular wastes and sludges, developed by CEN TC/292 based on standard procedures DIN 38414 S4, AFNOR X-31 210, NEN 7343 and ONORM S 2072, primarily to support the requirements for compliance testing within the European Union (EU) and European Free Trade Association (EFTA) countries. The intent of these tests is to identify the leaching properties of waste materials. However, the standards have been developed to investigate mainly inorganic constituents and do not take into account the particular characteristics of non-polar organic constituents or the consequences of microbiological processes in organic degradable wastes. Each part specifies a distinct procedure and the annexes to the standards provide useful information on the selection of the appropriate procedure, reference documents and guidance on the limitations of these procedures. The procedure for Part 1 and 3 is only applicable to wastes and sludges having a high solid content: the dry matter content ratio shall be at least higher than 33%. All parts use distilled/deionised water and have a total contact time of 24 hours. The operating conditions for each part are summarised in Table 1. It should be noted that Part 3 is carried out in two stages. The high L/S tests may be considered to represent a form of accelerated leaching (Heasman, 2002).

(viii) The acid neutralisation capacity (ANC) test (Stegemann and Coté, 1991) is a measure of the ability of

a material to neutralise acid. This is a key variable for long-term material behaviour, because it affects precipitation of metals and maintenance of matrix physical integrity (Stegemann and Coté, 1990). The test involves mixing subsamples of a material with increasing quantities of mineral acid for 48 hours, prior to measurement of leachate pH to obtain a titration plot (Stegemann and Coté, 1990; 1991; WTC, 1991). Analysis of contaminants in the leachate can be used to assess their availability at pH values of interest. This approach is similar to that used in other availability tests, such as NEN 7431 (NNI, 1995) and prEN 14429 (2002).

These availability tests are themselves agitated extraction tests. Although not yet in common use, prEN 14429 has been developed from the ANC and NEN 7431 to investigate contaminant availability as a variable distinct from total contaminant concentration. The test involves a 24-hour extraction of granular material at controlled pH.

Modification of the ANC to use acetic acid, as a way of optimising binder addition to pass the TCLP was proposed by Isenburg and Moore (1992), but is less useful for understanding leaching behaviour, in part due to the development of a buffer system that alters the titration curve.

(2) Sequential chemical extraction tests**:** Increasingly aggressive leachants may be used to obtain information on the mechanisms of contaminant binding in a material. Most sequential chemical extraction tests for metals are based on a method developed by Tessier et al. in 1979, which divides the contaminants into 5 fractions: 1) ion-exchangeable, 2) bound to surface oxides and carbonates, 3) bound to iron and manganese oxides, 4) bound to organics and 5) residual. The test was originally proposed to examine respeciation of contaminants due to treatment, but has fallen into disuse except as a research tool because of concerns with definition of speciation and reproducibility (Stegemann and Coté, 1990).

Dynamic Tests

Dynamic tests are not as commonly used as extraction tests. They can also be divided into several categories (WTC, 1990). The serial batch test, which is the most common type, and two others are briefly summarised below:

(1) Serial batch tests**:** These are similar to agitated extraction tests, except that the leachant is replaced after a specific time until the desired number of leaching periods have been achieved. The temporal release of leachable constituents can be inferred by constructing an extraction profile using the data obtained. Typical tests include the multiple extraction procedure (MEP) (USEPA, 2003d), sequential batch extraction (ASTM D4793-93, 1999 and ASTM D5284-93, 1999), NEN 7349 (NNI, 1995b) and DIN 38414 S4 (DIN-NORMEN, 1984) which gives a procedure for multiple extractions in addition to the single extraction method stated earlier.

(2) Flow around tests**:** These are generally performed on monolithic samples. Leachant is continuous or intermittently renewed, to flow around the sample, providing the driving force to maintain leaching by diffusion. For these tests, the volume of leachant, and the leachant volume to sample surface area ratio are prescribed. Typical tests include the ANSI/ANS 16.1 test (ANS, 1986), NEN 7345 (NNI, 1995c) and the CEN monolithic tank test (CEN/TC292, in prep). The latter tests use an effective diffusion coefficient determined from the results of the test to estimate contaminant release under simplified disposal conditions.

(3) Flow through tests**:** These are performed on porous monoliths or granular material, with the leachant continuously or intermittently flowing through the material, to measure contaminant leaching under advective conditions. Typical tests include the ASTM Column Extraction Method (ASTM D4874-95, 2001), NEN 7343 (NNI, 1995d) and the European standard column test (prEN14405, 2002) being developed by CEN/ TC292. These tests employ slow upward leachant flow to allow attainment of steady-state conditions.

(4) Chloride permeability **(ASTM C1202-97, 2002):** is a test conducted to measure the resistance of a monolithic cement-based material to the penetration of chloride ions, by diffusion. In relation to S/S materials, the mobility of chloride ions may be related to the mobility of contaminant ions, although the relationship may be complex.

The presence of a large number of standard leaching tests has resulted in the different tests being applied to similar types of matrices, limiting comparability of the results (van der Sloot et al., 1997). It has therefore been recognised that effort is required to harmonise the leaching test procedures that could be adapted for different matrices and to validate the use of existing tests in other technical fields (van der Sloot et al., 1997). In order to achieve this, the European Standards Organisation CEN under the management of Technical Committee (TC) 292 is developing a range of standard leaching tests for the characterisation of the waste (Heasman, 2002). Some of these tests have been described earlier. These comprise tests for granular wastes and sludges, and tests for monolithic wastes and will be in the form of batch extraction tests and monolithic tank tests respectively. These tests, of which the tests for granular wastes and sludges are already available as BS EN, are expected to be adopted by UK regulators.

Leaching tests can be designed to inform predictive modelling of the leaching behaviour of the waste form. This is recognised in DD ENV 12920 (1998) and in the ASTM Accelerated leach test computer program (ASTM, 2001), which compares test data with 4 basic mathematical models that describe:

- Diffusion through a semi-infinite medium (low cumulative fraction leached);
- Diffusion through a finite cylinder (high cumulative fraction leached);
- Diffusion plus partitioning of the source term; and
- Solubility-limited leaching.

Primary Physical Tests

Most of the physical tests applied to untreated or treated S/S materials have been adopted or adapted from test methods used for other materials such as concrete (BS EN 12350, BS 1881 and BS 4550), soils for civil engineering purposes (BS 1337) and stabilised materials for civil engineering purposes (BS 1924) and similarly from ASTM standard test methods in volumes 4.01 (cement; lime; gypsum), 4.02 (concrete and aggregates), 4.08 (soil and rock) and 11.04 (environmental assessment; hazardous substances and oil spill responses; waste management). Typical applicability of the tests discussed below to either untreated or treated S/S material is shown in Table 2. The most commonly used physical tests were found to be three performance tests:

Unconfined compressive strength
Unconfined compressive strength (before and after immersion) is used as a measure of the ability of a monolithic S/S material to resist mechanical stresses (Stegemann and Coté; 1990; 1991). It relates to the progress of hydration reactions in the product, and durability of a monolithic S/S material, and is therefore a key variable. It is one of the most commonly used tests and there are numerous standard methods for its determination, all of which involve vertical loading of a monolithic specimen to failure (ASTM C109/C109M-99, 2001; ASTM D1633-00, 2002; BS 1881: Part 116, 1983; BS EN 12390: Part 3, 2002; BS 4550: Part 3(4), 1978; BS EN 196: Part 1, 1995; BS 1377: Part 7(7), 1990; BS 1924: Part 2(4.1) and 2(4.2), 1990). Standard methods vary mainly with regard to the specimen shape and size. Since these variables have an effect on the test result, they must be clearly reported. Measurement of strength after immersion, as well as before, is important to ensure that a specimen has set and hardened chemically rather than merely dried, and to ensure that deleterious swelling reactions do not occur in the presence of excess water. Because of its simplicity, unconfined compressive strength measurement is also suitable for use as a compliance test.

Hydraulic conductivity
Hydraulic conductivity indicates the rate at which water can flow through a material, which is a key variable for environmental behaviour. The method for determination of hydraulic conductivity is given in ASTM D5084-00 (2002) and BS 1377: Parts 5(5) and 6(6) (1990). A wide range of hydraulic conductivity tests is given in Head (1992). S/S materials normally have a low hydraulic conductivity to prevent advection of contaminants. Therefore, a falling head test method is used, in which the volume of water passed through a saturated monolithic specimen under pressure in a given period of time, is measured. Stegemann and Coté (1991), however, demonstrated poor reproducibility of this method on a variety of S/S materials and suggested use of a constant head/flow pump method.

Oxygen permeability (Kollek, 1989) is sometimes measured for S/S materials, if it is desired to measure permeability without concurrent sample changes due to leaching. An intrinsic permeability, which should be independent of the fluid used to conduct the test, can be calculated from either hydraulic conductivity or oxygen permeability.

The chloride permeability test purports to be a measure of chloride ion diffusivity, rather than permeability in the sense of these other tests (see Dynamic Tests, above).

Weathering resistance
Freeze/thaw and wet/dry durability tests are conducted to examine the capability of a monolithic S/S material to withstand weathering due to temperature and moisture fluctuations (ASTM D4842-90, 2002; BS 812: Part 124 1989; BS 1377: Part 5(7), 1990; BS 1924 Part 2(4.8), 1990, and ASTM D4843-88, 2002). These tests monitor the weight loss of a monolithic S/S material over a stipulated number of repeated cycles of freezing and thawing, or immersion and drying. Mechanical or chemical changes to the matrix are not measured. The freeze-thaw test is considered to be the more severe of the two tests (LaGrega et al, 1994) and also found to be the least reproducible (Stegemann and Coté, 1991).

Sodium or magnesium sulphate soundness (BS EN 196: Part 3, 1995; ASTM C88-90a, 2002) can be considered an indirect measure of weathering resistance, as it measures the ability of a monolithic material to withstand expansive crystallisation within its porosity.

Other Physical Tests

Review of the MONOLITH database (Stegemann et al., 2001) yields up a variety of additional, less commonly applied, tests, which include basic information tests and performance tests.

Initial Consumption of Lime (ICL) (BS 1924: Part 2(5.4), 1990): is a test for cohesive untreated materials to determine the percentage of lime which will be needed to bring about a desired degree of improvement in the properties of a soil. It is the percentage of lime required to raise the pH of the soil to 12.4. The initial improvement, termed modification, makes the soil drier and friable enabling easy compaction and the improvement over time, termed stabilisation, yield increased strength.

Pulverisation (BS 1924: Part 2(1.5): 1990): is a measure of how well the binder and water has been mixed with the untreated material. It is a site control test carried out on soils that have been stabilised for earthwork purposes.

Particle size distribution (ASTM D422-63, 2002; BS 1377: Part 2(9), 1990): is carried out by sieving to determine the grading of the untreated material. This is required to ensure that the material is in accordance with the limits of any specification (Sherwood, 1993) as it affects the workability of the material and hence affects the compaction of the material to achieve the maximum density with a reasonable amount of work (Neville, 1997).

Bulk density (ASTM C642-97, 1997; BS 1377: Part 2(7), 1990; BS 1924: Part 2(2.1) and 2(3), 1990): is the mass per unit volume of the material. It can be used together with moisture content and specific gravity to calculate S/S material porosity and degree of saturation. These properties are related to durability and leachability, although the relationship is not simple. It can also be used to assess the homogeneity of the S/S material. Bulk density can also be used together with mass change factor to calculate volume increase due to treatment.

Specific gravity (ASTM C128-01, 2002; ASTM C642-97, 2002; BS 1377: Part 2(8), 1990): is a measure of the solid density of a material relative to the density of water. This property is generally needed to calculate other physical properties.

Water absorption (ASTM C128-01, 2002; ASTM C642-97, 2002; BS 1881: Part 122, 1983): is a measure of the volume of pore space in the material although the two quantities are not necessarily related.

Porosity (ASTM D4404-84, 2002; BS 7591: Part 1, 1995; International society of rock mechanics, 1985): is a measure of the proportion of the total volume of the material occupied by pores and is useful in understanding other test results.

Moisture content (ASTM D2216-98, 2002; BS 1377: Part 2(3), 1990; BS 1924: Part 2(1.3), 1990): is a measure of the amount of free water in a material and necessary for determining the water mass balance in S/S treatment, and in calculating the L/S ratio in leaching tests. Moisture content of S/S materials is often determined by drying at 60^{o}C to avoid driving off the water of hydration (WTC, 1991).

Moisture Condition Value (MCV) (BS 1377: Part 4(5), 1990; BS 1924: Part 2(2.2), 1990): is a measure of the compactibility of a soil for use in earthworks. It is used as an acceptance test for soils that are to be stabilised with lime or cement. The advantage of MCV as a control test is that an instant result is available, whereas it would take longer to obtain a value for the moisture content. It is particularly useful for cohesive material.

Dry density/moisture content relation (BS 1377: Part 4(3), 1990; BS 1924: Part 2(2.1), 1990): is a test often used when materials are to be used for earthwork purposes. This is particularly useful for granular materials, whilst MCV as mentioned above is often used for cohesive materials.

Slump (ASTM C143/C143M-00, 2002; BS 1881: Part 102, 1983; BS EN 12350: Part 2, 2000): is one of several tests which could be conducted to obtain a measure of the workability of a material. The test involves the measurement of the resulting slump, once the standard cone into which the material was placed is removed.

Flow (ASTM C939-02, 2002; ASTM C109/C109M, 2001; BS 1881: Part 105, 1984; BS EN 12350: Part 5, 2000): is another of several tests which could be conducted to obtain a measure of the workability of a material. These tests involve the measurement of the resulting spread of the material, once the stipulated mould confining the material is removed and other conditions set out are followed.

Setting time (ASTM C191-01a, 2001; BS 4550: Part 3(6), 1978; BS EN 196: Part 3, 1995, and ASTM C266-99, 2001): can be determined by the penetration of a needle into the hydrating sample to observe the early stiffening of a paste prior to strength development. Setting time can also be determined from the heat evolution curve, or by monitoring electrical conductivity. This property is important for determining the time available for placement of a material, and is useful to identify the effects of different contaminants and binders on hydration.

Heat of Hydration (ASTM C186-98, 2001; BS 4550: Part 3(8), 1978): is the amount of heat evolved upon complete hydration in a calorimeter, at constant temperature, or under adiabatic conditions (Neville, 1997). The heat of hydration of a S/S material mix can be compared with the heat of hydration of the binder system to assess the relative degree of hydration.

Bound water: is the percentage of water present in interlayer spaces or more firmly bound, but not that present in pores larger than interlayer spaces (Taylor, 1997). The quantity present at a given time may help indicate the degree of hydration. It is about 32% for fully hydrated pastes of typical cements (Taylor, 1997). Unfortunately, the method of determination is complicated, and an approximate estimate is obtained by equilibrating a sample, not previously dried below saturation, with an atmosphere of 11% RH (Feldman and Ramachandran, 1971).

Microstructural examination: of S/S materials can be performed by several techniques. The most commonly used techniques are scanning electron microscopy (SEM), usually with energy dispersive x-ray analysis (EDX) or electron probe micro analysis (EPMA) and x-ray diffractometry (XRD). These techniques allows better understanding of the mechanisms by which contaminants are bound to the matrix, and the effects of waste components on binder hydration. However, S/S materials are heterogeneous at microscopic scale, so obtaining representative samples is difficult. Thus, these techniques are more useful in research, or for observing known features and comparing different samples rather than for general investigation.

Shrinkage/Expansion (ASTM C151-00, 2001; ASTM C157/C157M-99, 2002; BS 1881: Part 5(5), 1970): Shrinkage may be caused by a decrease in volume of the solid phase during hydration, or be a result of moisture loss or carbonation. Expansion may be caused by swelling of the hydration material due to absorption of water, when freely available, by the cement gel (Neville and Brooks, 1993), or by delayed formation of high volume hydration material such as ettringite. Both may induce stresses in the material which can lead to its deterioration. The shrinkage or expansion is normally achieved by measuring the length change, under stipulated controlled conditions, which permits assessment of the potential volumetric change.

Penetration resistance (ASTM C803/C803M-97, 2002): is a test carried out to estimate the strength of a material from the depth of penetration by a metal rod driven into the material by a given amount of energy.

California Bearing Ratio (CBR) (ASTM D1883-99, 2002; BS1377: Parts 4(7) and 9(4.3), 1990; BS 1924: Part 2(4.5) and 2(4.6), 1990): is an empirical test used for estimating the bearing capacity of a material. It attempts to measure the resistance of the material to penetrative deformation. Unlike in other strength tests, the outcome of CBR is reported as a percentage of the value for a standard crushed rock material. It is widely used in pavement design for roads.

Tensile strength (US Bureau of Reclamation, 1992 and ASTM C348, 2001; ASTM C78-02, 2002; BS 1881: Part 118, 1983; BS EN 196: Part 1, 1995 and ASTM C496-96, 2002; BS 1881: Part 117, 1983; BS 1924: Part 2(4.4), 1990): is carried out to identify the tensile load under which cracking will occur. There are three types of strength tests, namely direct tensile strength, flexural strength and splitting tensile strength.

Modulus of elasticity: provides an understanding of the stiffness of the material, that is, the strain response to an applied stress. Two main test methods are available: static modulus of elasticity and dynamic modulus of elasticity. ASTM C469-02 (2002) and BS 1881: Part 121 (1983) are for the former and ASTM C215-02 (2002) and BS 1881: Part 209 (1990) are for the latter. The modulus of elasticity is not a constant for a material, but varies with the applied stress. The test conditions are thus critical to ensure that the results from different samples can be compared.

MANAGEMENT SCENARIOS AND PERFORMANCE CRITERIA

Whereas it is possible to perform testing of S/S materials in order to obtain a quantitative understanding of the material for evaluating technological options and management scenarios, the results from testing are often compared to performance criteria. Such performance criteria may be acceptance limits prescribed for a specific management scenario, e.g., landfill disposal, or they may be derived from a site specific risk assessment. Conformity with performance criteria may be a regulatory requirement, or simply a part of responsible practice by industry. Since environmental behaviour of S/S materials is the subject of on-going research, development of performance criteria, and assessment of data in comparison with performance criteria is not usually a straightforward matter.

S/S material can be considered for a variety of management scenarios, e.g., in-situ remediation of contaminated land, which may be subject to redevelopment, disposal or utilisation. Provided that it can be done safely, it is evident that utilisation of treated material is preferred over disposal, as it reduces the burden on landfills and conserves natural resources. However, a variety of different management options may be considered, since there may be practical limits to the treatment standard that can be achieved. The results obtained from the selected test methods will be used to compare against relevant performance criteria to determine if the properties for the desired scenario were met, or alternatively to determine which is the optimal scenario for the treated material.

WTC (1991) reported scenarios: WTC (1991) identified four utilisation and disposal scenarios, and presented a decision flow chart showing a hierarchy of testing levels and their relationship to the four scenarios. The four scenarios in order of decreasing performance requirements for the S/S materials were listed as unrestricted utilisation, controlled utilisation, segregated landfill and sanitary landfill. In addition, WTC (1991) states that S/S materials that do not satisfy these scenarios would need to be disposed in a secure landfill or subjected to a more effective treatment process. Unrestricted utilisation scenario would require the S/S materials to have negligible leaching potential and considered to be used in any way similar to a natural material; controlled utilisation scenario requires the S/S material to have a leaching potential acceptable for a specific usage; segregated landfill, which does not necessarily have an engineered barrier or leachate collection system, would accept S/S materials that fail to satisfy utilisation, after separation from other waste materials, provided that they fall within the limits of the landfill; sanitary landfill, accepts S/S materials for co-disposal with municipal garbage where they have failed to satisfy the other three scenarios, provided it is within the acceptable limits of the landfill. However, it should be mentioned that with the new regulations being set up (described below) the above landfill scenarios might no longer be viable.

Landfill disposal or re-use scenarios in the UK: The approach to developing acceptance criteria in the UK will depend on whether the treated material is to be landfilled or re-used. The introduction of the European Landfill Directive (LFD) (Council Directive 1999/31/EC, 1999) will require waste management in UK to change significantly to meet its requirements. Acceptance criteria for landfill will be set at EU or member state level as set out in European Commission Decision 2003/33/EC and must be applied by member states by 16 July 2005. The LFD gives the framework for (i) the classification of landfill sites, including a timetable for such classifications, (ii) the procedures for waste acceptance to be adopted at landfills and (iii) the types of waste for each class of landfill specified by waste acceptance criteria (EA, 2002a). The landfill sites are required to be classified as sites for hazardous, non-hazardous or inert waste.

Further, the LFD requires wastes that are not prohibited from being landfilled (prohibited wastes are set out in Regulation 9 of the 2002 Landfill Regulations) to be subject to treatment prior to landfilling, unless they are (i) inert waste for which treatment is technically not feasible and (ii) non-inert waste where treatment would not reduce the quantity or hazards. However, the selected treatment method is required to meet the three point test explained in the Guidance on the Waste Treatment Requirements of Article 6(a) of the Landfill Directive consultation draft (EA, 2001a). The requirement is that the treatment (i) must be a physical/thermal/chemical/ or biological process, including sorting, (ii) must change the characteristics of the waste and (iii) it must do so in order to reduce its volume or hazardous nature, facilitate handling or enhance recovery.

Treatment by S/S is likely to be necessary to ensure that many types of wastes meet the waste acceptance criteria leaching limits. Hence a considerable market may arise for S/S technology, to treat waste streams prior to disposal, especially for those containing recalcitrant contaminants such as heavy metals.

However, given the time frame involved the Directive requires member states to put in place national interim waste acceptance criteria (NIWAC) and procedures prior to the introduction of the full acceptance criteria. The NIWAC are provided by the Landfill (England and Wales) Regulations 2002. Documents such as the Guidance on National Interim Waste Acceptance Procedures (EA, 2002b) contains advice on the Environment Agency's interpretation of the regulations and best practice associated with them and specifies waste acceptance procedures as required by Regulation 12 of the Landfill Regulations 2002. New regulations will be introduced shortly to specify Europe-wide acceptance criteria based on leaching characterisation and compliance tests.

A summary timetable for NIWAC and full criteria is given in the EA (2002b) and it is shown in Table 3. However, in addition to the requirements of the Landfill Regulations 2002 the Environment Agency considers that for four provisions, stated in section 3.1 of the EA (2002b), the full criteria should be introduced immediately. Another date of importance is 16 July 2004, from which hazardous waste landfills can only accept waste classified as hazardous under the Hazardous Waste Directive (Council Directive 1991/689/EEC, 1991) that meet the relevant acceptance criteria.

The approach to risk assessment and risk management of land contamination is enshrined in the Guidelines for Environmental Risk Assessment and Management (DETR/EA/IEH, 2000). This document sets out the common principles for managing environmental risks to meet the government's environmental policy objectives. It recommends a staged approach consisting of (i) Problem formulation; (ii) Tiered risk assessment (risk screening, generic and detailed quantitative risk assessment); (iii) Options appraisal; and (iv) Risk management.

The approach is developed further, and forms the basis for, the Model Procedures for the Management of Land Contamination (DEFRA/EA, in preparation). Acceptance leach tests will usually be required to demonstrate that the release of contaminants, by dissolution or diffusion, from a stabilised waste form does not cause pollution or harm. The remediation criteria to demonstrate this will usually be derived from risk-based criteria set at a pre-defined compliance point (e.g. stream quality downstream of the site or groundwater quality in a monitoring borehole). The Environment Agency has published a framework for deriving such criteria for soil and groundwater **(EA, 1999)**, and other methods are available, that can make use of leach test data with or without the dilution and attenuation potential of the soil between the source and the compliance point. Secondary criteria may also be set, e.g. strength, permeability or durability criteria, to support the conceptual model of the waste form in its environment of deposition. In summary, the compliance tests will be selected, and justified, from the conceptual model, having regard to the risk driver, location of compliance point/s, site-specific parameters and end-use of the site.

Utilisation of S/S material in earthworks: For utilisation of S/S material in earthworks a different set of criteria is used. These are set out in Highways Advice Note HA 74/00, for treatment of fill and capping materials using either lime or cement or both (Highways Agency et al., 2000) and in Series 600 of the Specification for Highway Works (SHW) (Highways Agency et al., 2001). These criteria are for uncontaminated materials treated with cement or lime, but the same test methods criteria, in conjunction with chemical (leach) tests, and performance criteria would apply to any contaminated materials that had been treated by S/S methods if they are determined to be suitable for use.

Test methods and limiting values are given for the untreated soils and for the treated S/S material in the SHW, and a design methodology is given in HA 74/00 (Highways Agency et al., 2000). A summary of the tests and limiting values is given in Table 4. Guidance on the frequency of testing is given in HA 74/00 and in the Notes for Guidance on the SHW (Highways Agency et al., 2001).

It is apparent that a detailed methodology of investigation, design and monitoring is available. It requires considerable investment in sampling and testing to conform with these requirements. The SHW is designed for trunk roads and motorways, but is also often used for other road and earthwork projects. Potentially large volumes of material can be used in these contracts, so the investment in testing may be well worthwhile.

The following sections summarise performance criteria for some of the most common test methods, described earlier, bearing in mind the management scenarios for the S/S material where appropriate. However, it should be noted that the values given, which have been obtained from various sources, might defer from various practitioners preference for use in UK. But in circumstances where UK does not have their own set criteria some of these values have known to been adopted. These values from other sources also provide a basis for comparison with UK values, where available.

Contaminant Concentrations

Under the EU Landfill Directive (Council Directive 1999/31/EC), the acceptance limits for different categories of landfill are set at EU or member state level. The waste for disposal will be required to meet the general interim waste acceptance criteria given in Schedule 1(1) of the 2002 Landfill Regulations and the additional interim waste criteria set out for landfills accepting hazardous waste, non-hazardous waste and inert waste, giving details of the types of wastes that could and could not be accommodated in the specified landfills together with the conditions attached to them and the required levels that should be achieved from leaching tests and other criteria using prescribed test methods. The EA (2002b) set out the expected full criteria for landfills, to assist in the consideration of permits for new landfills, and to allow producers and operators to consider the implications of changing from interim to full criteria. The leaching limit values given are only for granular waste and are calculated for liquid to solid ratios (L/S) of 2 and 10 L/kg for total release, by subjecting the waste to the CEN standard two-part batch test BS EN12457: Part 3. These are shown in Table 5 for the acceptance of wastes in specified landfills and Table 6 gives the limits for other criteria. The Environment Agency is developing criteria for monolithic waste and until they are available 'depositors' of monolithic waste should agree on tests and limit values with the Environment Agency.

Contaminated land remediation criteria are selected on the basis of risk assessment. The acceptance criteria will be generic in some cases and site-specific in others and UK reflects the latter (Brian Bone, 2003).

Performance criteria for remediation of contaminated land have been evolving over the past two decades. Past UK practice has been to take guidance values for contaminated land assessment and remediation from:

(a) ICRCL 59/83 (Interdepartmental Committee on the Redevelopment of Contaminated Land 59/83, 1987), which was set up in UK, recommends trigger concentrations (for threshold and action values) based on the most appropriate use of the sites. This has now been officially withdrawn by DEFRA.
(b) Contamination Classification Thresholds for Disposal of Contaminated Soils (EA, 2001b), which recommends threshold values.
(c) The Dutch List (1994)(initially known as the "A B C List" but now modified to the New Dutch List) recommends optimum and action value concentrations for soil and groundwater, based on multifunctionality of the site, that is, improvement to a standard suitable for any possible use. However, although these criteria have often been used as screening criteria, they are not preferred for regulatory purposes in the UK (Brian Bone, 2003).

Although used in the past, these guidance values do not relate to the contaminated land provisions of Part IIA of the Environment Protection Act 1990. Thus, they are being superseded by the publication of soil guideline values (SGV) determined using the Contaminated Land Exposure Assessment (CLEA) model, and implementation of the Landfill Directive.

Methodologies available in the UK for deriving site-specific criteria include;

(a) Methodology for the derivation of remedial targets for soil and groundwater to protect water resources (EA, 2000a) which is accompanied by the software tool Remedial Targets Worksheet, and the software tool Contamination impact on groundwater: Simulation by monte carlo method (ConSim) (EA, 2000b). These have been published in order to standardise the approach throughout England and Wales, and represent the agency's recommended approach to assessing risks to water resources from contaminated land. The Remedial Targets Worksheet provides a framework for assessing the risks to controlled waters from land contamination and for deriving remedial targets where those risks are unacceptable (EA, 2001c). ConSim provides a tool for assessing risks that are posed to groundwater quality by leaching contaminants. It models contaminant mobilisation and transport and is intended to use commonly available site data.
(b) Contaminated Land Exposure Assessment (CLEA)(DEFRA/EA, 2002a,b,c,d). Together the reports provide a coherent and consistent scientific framework for assessing the risks to human health from land contamination. It relates only to direct human health risk and allows the derivation of guideline values for concentration of contaminants for their effect on human health. The model is owned by the DETR, hence it is likely to be the most readily accepted by the regulators (Reid and Clark, 2001). The CLEA model has been used to derive the SGV, but it will be used for deriving site-specific criteria.
(c) Method for deriving site-specific human health assessment criteria for contaminants in soil (SNIFFER, 2003). This provides a framework for deriving numeric targets to minimise the adverse human health effects of long-term exposure to contaminants in soil. This reflects the guidance in DEFRA/EA (2002c,d). Circumstances where it must not be used include: where SGV is available and is appropriate to be used, and where the circumstances under consideration are represented by CLEA model.
(d) Risk-based corrective action (RBCA) protocol commonly used in groundwater risk assessments (ASTM E1739-95, 2002; ASTM E2081-00, 2002) is a consistent decision making process for the assessment of and response to chemical release based on protecting human health and the environment. The RBCA tool kit for chemical release is designed to meet the requirements of the ASTM E2081-00 (2002). It combines contaminant transport models with risk assessment tools to calculate baseline risk levels and derive risk-based cleanup standards for a full array of soil, groundwater, surface water and air exposure pathways.
(e) Risk-integrated software for clean-ups (RISC) (BPRISC, 2003) is a risk assessment model for soil and groundwater application. The software (BP RISC) which is a spreadsheet based on the RBCA algorithms is used for evaluating human health risk and determining clean-up levels at contaminated

sites. It has the ability to calculate additive risk due to multiple pathways, compounds and receptors with monte carlo capabilities for probabilistic risk evaluation.

Acid neutralisation capacity (ANC)

The EA (2002b) details the pH range that should be used for evaluation of ANC. This is given under additional parameters for the acceptance of granular wastes in landfills and is shown in (Table 6). But it does not set out limit values.

The WTC protocol (WTC, 1991) has made suggestions on the limit for ANC for their four listed scenarios. The values were considered as 1 eq/kg of matrix to a final pH of 9 for utilisation and segregated landfill scenarios, and 3 eq/kg to a pH 9 for sanitary landfill. The higher value for the latter takes into account the fact that the material may be exposed to a higher amount of organic acid due to the biodegradation of municipal waste (WTC, 1991). However, it must be clarified that these were only early suggestions and hence not applicable to all scenarios.

Unconfined compressive strength (UCS)

The UCS requirement is end-use driven and as such would vary according to the end-use. However, some guidelines and suggestions on limits exist and some of these are stated below.

An immersed UCS of 350kPa at 28 days is suggested by USEPA guidelines for materials that are to be disposed of to landfill (USEPA, 1986) which takes into consideration events such as weight of overburden and land moving equipment. In the Netherlands (Mulder, 2002) and France (Bone, 2002) a UCS of 1MPa is suggested for disposal. However, a higher value of the UCS of 3500kPa has been suggested by WTC (1991) for disposal to sanitary landfill because compaction of municipal waste might subject the S/S material to higher stresses because handling, placement and covering operations are not tailored for S/S material. It has also been suggested that the UCS with immersion should not be less than 80% of the UCS without immersion (Sherwood, 1994 and WTC, 1991).

The UCS of cement stabilised material for utilisation in sub-bases and bases, under the British specification, for the stipulated four categories CBM1-4 (Sherwood, 1994) are required to have a minimum 7 day cube compressive strength of 4.5, 7, 10 and 15 MPa respectively (Department of Transport, 1986). In the Netherlands, the UCS requirement for stabilised material for use as sub-base layers is given at 3-5MPa, which is the requirement for raw materials. However, the American and South African specifications rank strength as not being the primary requirement for cement stabilised materials (Sherwood, 1994).

The CBR has been specified as required to achieve a minimum value of 15% at 7 days when tested according to BS 1924: Part 2, for utilisation as a capping layer (Table 4) (Highways Agency et al., 2001). For use as general fill, lower values are appropriate. Reid and Clark (2001) suggest a minimum CBR of 5% at 7 days, with swell of less than 5mm at 28 days, for use of material treated with lime and PFA as general fill. Further, a minimum of 70% has been specified under the category of stabilised sub-base according to the TRL Road Note 31 (Sherwood, 1994).

Permeability

The permeability limit is usually taken as 10^{-9} m/s for in-ground treatment (this value is usually used for clay liners and cut-off walls) (Al-Tabbaa and Evans, 1998) and utilisation (WTC, 1991). USEPA tend to use 10^{-9} m/s for disposal to landfill (Bates, 2002). On the other hand a higher limit value of 10^{-8} m/s is suggested for disposal scenarios in the WTC protocol (WTC, 1991).

Durability

S/S materials subjected to both freeze/thaw and wet/dry durability testing at 28 days are required to survive 12 cycles of the prescribed test procedures with a maximum of 30% corrected cumulative dry mass loss (WTC, 1991; ASTM D4842-90, 2002; ASTM D4843-88, 2002). The latter requirement is used as the criterion to distinguish between success and failure.

Where the S/S material is to be utilised in a road pavement in the UK within 450mm of the road surface, it has to pass the frost heave test (BS 812: Part 124, 1989). If the mean heave is 15mm or less, the material is non-frost susceptible.

SUMMARY OF AVAILABLE DATA

The NNAPICS project database (MONOLITH) incorporates 1506 literature references and properties of 7953 cement-based S/S material containing impurities. This database represents a large percentage of information available in the literature, and incorporates results of various physical and chemical properties which have resulted from various mix designs involving binders and contaminants, tested over different time periods and temperatures. The range of values for many of those properties was compiled from the NNAPICS database and are given in Table 7. As the figures show very wide ranges of results and extreme values have been included in the literature and this emphases the diverse nature of the materials tested and the properties of the resulting S/S material. Clearly these values need to be treated with caution as they depend on the test method used.

Summary of test methods and performance criteria used in the research projects, field trials and commercial projects carried out in the UK and described in Parts 2 and 3 of this series of publications (Al-Tabbaa and Perera, 2003 b and c) are given in Tables 8, 9 and 10 respectively. Table 10 also includes end use for each of the commercial projects.

CONCLUSIONS

This report has presented the range of test methods available for the assessment of S/S materials and also treatment. The most commonly used tests, namely leachability, UCS, permeability and durability, were detailed. It is also clear that there is a vast number of leaching tests available. It was also clear that performance criteria varies depending on the management scenario of the end S/S material.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding for STARNET by EPSRC. The authors are also grateful to the core members of STARNET for their contributions and in particular to Brian Bone for his contribution to the report.

REFERENCES

Al-Tabbaa, A. and Perera, A.S.R. (2003a). State of practice report, UK stabilisation/solidification treatment and remediation: Binders & Technology – Part I: Basic Principles. Submitted for publications to the Journal of Hazardous Materials.

Al-Tabbaa, A. and Perera, A.S.R. (2003b). State of practice report, UK stabilisation/solidification treatment and remediation: Binders & Technology – Part II: Research. Submitted for publications to the Journal of Hazardous Materials.

Al-Tabbaa, A. and Perera, A.S.R. (2003c). State of practice report, UK stabilisation/solidification treatment and remediation: Binders & Technology – Part III: Applications. Submitted for publications to the Journal of Hazardous Materials.

American Nuclear Society (ANS) ANSI/ANS 16.1 (1986). Measurement of the leachability of solidified low-level radioactive wastes by a short term procedure.

American Society for Testing of Materials (ASTM) Test Method C109/C109M (2001). Standard test method for compressive strength of hydraulic cement mortars, Vol. 04.01, pp. 83-88.

American Society for Testing of Materials (ASTM) Test Method C151-00 (2001). Standard test method for autoclave expansion of Portland cement, Vol. 04.01, pp. 156-158.

American Society for Testing of Materials (ASTM) Test Method C186-98 (2001). Standard test method for heat of hydration of hydraulic cement, Vol. 04.01. pp. 171-176.

American Society for Testing of Materials (ASTM) Test Method C191-01a (2001). Standard test method for time of setting of hydraulic cement by vicat needle, Vol. 04.01, pp. 181-183.

American Society for Testing of Materials (ASTM) Test Method C266-99 (2001). Standard test method for time of setting of hydraulic cement by Gillmore needles, Vol. 04.01, pp. 217-219.

American Society for Testing of Materials (ASTM) Test Method C348-02 (2001). Standard test method for flexural strength of hydraulic cement mortars, Vol. 04.01, pp. 227-232.

American Society for Testing of Materials (ASTM) Test Method C78-02 (2002). Standard test method for flexural strength of concrete (using simple beam with third–point loading), Vol. 04.02, pp. 35-37.

American Society for Testing of Materials (ASTM) Test Method C88-99a (2002). Standard test method for soundness of aggregates by use of sodium sulphate or magnesium sulphate, Vol. 04.02, pp. 38-40.

American Society for Testing of Materials (ASTM) Test Method C128-01 (2002). Standard test method for density, relative density (specific gravity) and absorption of fine aggregate, Vol. 04.02, pp. 75-80.

American Society for Testing of Materials (ASTM) Test Method C143/C143M-00 (2002). Standard test method for slump of hydraulic-cement concrete, Vol. 04.02, pp. 96-98.

American Society for Testing of Materials (ASTM) Test Method C157/C157M-99 (2002). Standard test method for length change of hardened hydraulic-cement mortar and concrete, Vol. 04.02, pp. 104-110.

American Society for Testing of Materials (ASTM) Test Method C215 (2002). Standard test method for fundamental traverse, longitudinal and torsional resonant frequencies of concrete specimens, Vol. 04.02, pp. 135-140.

American Society for Testing of Materials (ASTM) Test Method C469 (2002). Standard test method for static modulus of elasticity and Poisson’s ratio of concrete in compression, Vol. 04.02, pp. 255-258.

American Society for Testing of Materials (ASTM) Test Method C496-96 (2002). Standard test method for splitting tensile strength of cylindrical concrete specimens, Vol. 04.02, pp. 281-284.

American Society for Testing of Materials (ASTM) Test Method C642-97 (2002). Standard test for density, absorption and voids in hardened concrete, Vol. 04.02, pp. 334-336.

American Society for Testing of Materials (ASTM) Test Method C803/C803M-97 (2002). Standard test method for penetration resistance of hardened concrete, Vol. 04.02, pp. 422-425.

American Society for Testing of Materials (ASTM) Test Method C939 (2002). Standard test method for flow of grout for pre-placed aggregate concrete (flow cone method), Vol. 04.02, pp. 506-508.

American Society for Testing of Materials (ASTM) Test Method C1202-97 (2002). Standard test method for electrical indication of concrete’s ability to resist chloride ion penetration, Vol. 04.02, pp. 654-659.

American Society for Testing of Materials (ASTM) Test Method D422-63 (2002). Standard test method for particle-size analysis of soils, Vol. 04.08(I), pp. 10-17.

American Society for Testing of Materials (ASTM) Test Method D1633-00 (2002). Standard test method for compressive strength of moulded soil-cement cylinders, Vol. 04.08(I), pp. 161-164.

American Society for Testing of Materials (ASTM) Test Method D1883-99 (2002). Standard test method for CBR (California Bearing Ratio) of laboratory-compacted soils, Vol. 04.08(I), pp. 171-179.

American Society for Testing of Materials (ASTM) Test Method D2216-98 (2002). Standard test method for laboratory determination of water (moisture) content of soil and rock by mass, Vol. 04.08(I), pp. 218-222.

American Society for Testing of Materials (ASTM) Test Method D4404-84 (Re-approved 1998) (2002). Standard test method for determination of pore volume and pore volume distribution of soil and rock

by mercury intrusion porosimetry, Vol. 04.08(I), pp. 631-636.
American Society for Testing of Materials (ASTM) Test Method D4429 (2002). Standard test method for CBR (California Bearing Ratio) of soils in place, Vol. 04.08(I), pp. 658-661.
American Society for Testing of Materials (ASTM) Test Method D5084-00 (2002). Standard test method for measurement of hydraulic conductivity of saturated porous material using a flexible wall permeameter, Vol. 04.08(I), pp. 1010-1032.
American Society for Testing of Materials (ASTM) Test Method D3987 (2002). Standard test method for shake extraction of solid waste with water, Vol. 11.04, pp. 1-5.
American Society for Testing of Materials (ASTM) Test Method D4793 (2002). Standard test method for sequential batch extraction of waste with water, Vol. 11.04, pp. 56-65.
American Society for Testing of Materials (ASTM) Test Method D4842-90 (Re-approved 2001) (2002). Standard test method for determining the resistance of solid wastes to freezing and thawing, Vol. 11.04, pp. 66-69.
American Society for Testing of Materials (ASTM) Test Method D4843-88 (Re-approved 1999) (2002). Standard test method for wetting and drying test of solid wastes, Vol. 11.04, pp. 70-73.
American Society for Testing of Materials (ASTM) Test Method D4874 (2002). Standard test method for leaching solid waste in a column apparatus, Vol. 11.04, pp. 81-88.
American Society for Testing of Materials (ASTM) Test Method D5284 (2002). Standard test method for sequential batch extraction of waste with acid extraction fluid, Vol. 11.04, pp. 164-178.
American Society for Testing of Materials (ASTM) Test Method E1739-95 (2002). Standard guide for risk-based corrective action applied at petroleum release sites, Vol. 11.04.
American Society for Testing of Materials (ASTM) Test Method E2081-00 (2002). Standard guide for risk-based corrective action, Vol. 11.04.

American Society for Testing of Materials (ASTM) Test Method C1308-95 (2001). Standard test method for accelerated leach test for diffusive releases from solidified waste and a computer program to model diffusive, fractional leaching from cylindrical waste forms Vol. 12.01.
Bates, E.R., Akindele, F. and Sprinkle, D. (2001). Low cost stabilisation/solidification treatment for soils contaminated with dioxin, PCP and creosote. Proceeding of the Air and Waste Management Association's 94th Annual Conference and Exhibition, Orlando, Florida, USA.
Bates, E.R. (2002). USEPA, personal communication.
Bone, B. (2003). UK EPA, personal communication.
BPRISC (2003). Risk-integrated software for clean-ups. www.bprisc.com
British Standards Institution (1970). Methods of testing hardened concrete for other than strength, BS 1881: Part 5(5), pp. 17-27. British Standards Institution, London.
British Standards Institution (1978). Methods of testing cement. Physical tests. Strength tests, BS 4550: Part 3(4). British Standards Institution, London.
British Standards Institution (1978). Methods of testing cement. Physical tests. Tests for setting time, BS 4550: Part 3(6). British Standards Institution, London.
British Standards Institution (1978). Methods of testing cement. Physical tests. Tests for heat of hydration, BS 4550: Part 3(8). British Standards Institution, London.
British Standards Institution (1983). Testing concrete. Method for determination of slump, BS 1881: Part 102, pp. 1-3. British Standards Institution, London.
British Standards Institution (1983). Testing concrete. Method for determination of compressive strength of concrete cubes, BS 1881: Part 116, pp. 1-3. British Standards Institution, London.
British Standards Institution (1983). Testing concrete. Method for determination of tensile splitting strength, BS 1881: Part 117, pp. 1-4. British Standards Institution, London.
British Standards Institution (1983). Testing concrete. Method for determination of flexural strength, BS 1881: Part 118, pp. 1-3. British Standards Institution, London.
British Standards Institution (1983). Testing concrete. Method for determination of static modulus of elasticity in compression, BS 1881: Part 121, pp. 1-3. British Standards Institution, London.
British Standards Institution (1983). Testing concrete. Method for determination of water absorption, BS 1881: Part 122, pp. 1-3. British Standards Institution, London.
British Standards Institution (1984). Testing concrete. Method for determination of flow, BS 1881: Part 105, pp. 1-4. British Standards Institution, London.
British Standards Institution (1989). Testing aggregates. Method for determination of frost-heave, BS 812: Part 124, pp. 2-22. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Classification tests, BS 1377: Part 2(3), pp. 2–5. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Classification tests, BS 1377: Part 2(7), pp. 22–26. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Classification tests, BS 1377: Part 2(8), pp. 26–30. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Classification tests, BS 1377: Part 2(9), pp. 30–45. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Compaction related tests, BS 1377: Part 4(3), pp. 2–11. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Compaction related tests, BS 1377: Part 4(5), pp. 15–19. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Compaction

related tests, BS 1377: Part 4(7), pp. 20–26. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Compressibility, permeability and durability tests, BS 1377: Part 5(5), pp. 10–14. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Compressibility, permeability and durability tests, BS 1377: Part 5(7), pp. 18. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Consolidation and permeability tests in hydraulic cells with pore pressure measurement, BS 1377: Part 6(6), pp. 40–44. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. Shear strength tests (total stress), BS 1377: Part 7(7), pp. 19–22. British Standards Institution, London.
British Standards Institution (1990). Methods of test for soils for civil engineering purposes. In-situ tests, BS 1377: Part 9(4.3), pp. 31–33. British Standards Institution, London.
British Standards Institution (1990). Testing concrete. Recommendations for measurement of dynamic modulus of elasticity, BS 1881: Part 209, pp. 1-6. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Classification tests. Determination of moisture content, BS 1924: Part 2(1.3), pp. 3-6. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Classification tests. Determination of the degree of pulverisation, BS 1924: Part 2(1.5), pp. 10. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Compaction related tests. Determination of the dry density/moisture content relation, BS 1924: Part 2(2.1), pp. 11-19. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Compaction related tests. Determination of the moisture condition value (MCV), BS 1924: Part 2(2.2), pp. 19-20. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. In-situ density tests, BS 1924: Part 2(3), pp. 21-34. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Strength and durability tests. Determination of the compressive strength of cylindrical specimens, BS 1924: Part 2(4.1) and 2(4.2), pp. 35-41. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Strength and durability tests. Determination of the tensile splitting strength, BS 1924: Part 2(4.4), pp. 42-43. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Strength and durability tests. Laboratory determination of the CBR, BS 1924: Part 2(4.5), pp. 43-47. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Strength and durability tests. Determination of the in-situ CBR, BS 1924: Part 2(4.6), pp. 47. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Strength and durability tests. Determination of the frost heave, BS 1924: Part 2(4.8), pp.47. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material. Chemical tests. Determination of the initial consumption of lime, BS 1924: Part 2(5.4), pp. 54-56. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material, BS 1924: Part 2. British Standards Institution, London.
British Standards Institution (1990). Stabilised materials for civil engineering purposes. Methods of test for cement-stabilised and lime-stabilised material, BS 1924: Part 2. British Standards Institution, London.
British Standards Institution (1995). Porosity and pore size distribution of materials. Method of evaluation by mercury porosimetry, BS 7591: Part 1, pp. 3-9. British Standards Institution, London.
British Standards Institution (1995). Methods of testing cement. Determination of strength, BS EN 196: Part 1, pp. 3-17. British Standards Institution, London.
British Standards Institution (1995). Methods of testing cement. Determination of setting time and soundness, BS EN 196: Part 3, pp. 1-7. British Standards Institution, London.
British Standards Institution (1998). Characterisation of waste. Methodology for the determination of leaching behaviour of waste under specified conditions. DD ENV 12920. British Standards Institution, London.
British Standards Institution (2000). Testing fresh concrete. Slump test, BS EN 12350: Part 2, pp. 1-5. British Standards Institution, London.
British Standards Institution (2000). Testing fresh concrete. Flow table test, BS EN 12350: Part 5, pp. 1-5. British Standards Institution, London.
British Standards Institution (2002). Testing hardened concrete. Compressive strength of test specimens, BS

EN 12390: Part 3, pp. 1-12. British Standards Institution, London.
British Standards Institution (2002). Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. BS EN 12457: Part 1: One stage batch test at a liquid to solid ratio of 2 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction). British Standards Institution, London.
British Standards Institution (2002). Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. BS En 12457: Part 2: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 4 mm (without or with size reduction). British Standards Institution, London.
British Standards Institution (2002). Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. BS EN 12457: Part 3: Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction). British Standards Institution, London.
British Standards Institution (2002). Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. BS EN 12457: Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction). British Standards Institution, London.
CEN/TC292 (in prep). Characterisation of waste – Compliance leaching test for monolithic material. Work Item 00292010.
Council Directive 1991/689/EEC (1991). Hazardous Waste Directive. Text from the Official Journal of the European Communities L377 on 31 December 1991.
Council Directive 1999/31/EC (1999). European Union Landfill Directive. Text from the Official Journal of the European Communities L182/1 on 16 July 1999.
DEFRA and Environment Agency (2002a). Assessment of risks to human health from land contamination: an overview of the development of guideline values and related research. R&D Publications CLR7. Environment Agency, UK.
DEFRA and Environment Agency (2002b). Priority contaminants report. R&D Publications CLR8. Environment Agency, UK.
DEFRA and Environment Agency (2002c). Contaminants in soil: collation of toxicology data and intake values for humans. R&D Publications CLR9. Environment Agency, UK.
DEFRA and Environment Agency (2002d). The contaminated land exposure assessment model (CLEA): technical basis and algorithms. R&D Publications CLR10. Environment Agency, UK.
DEFRA and Environment Agency (in prep). Model procedures for the management of land contamination.
DETR/EA/IEH (2000). Guidelines for environmental risk assessment and management. The Stationery Office, London.
Department of Transport, 1986. Specification for highway works, Sixth Edition. HMSO, London 1986.
DIN-NORMEN. DIN 38414 S4 (1984). Determination of leachability by water (S4). German standard methods for examination of water, wastewater and sludge. Sludge and Sediments (group S)
Environment Agency (2000a). Methodology for the derivation of remedial targets for soil and groundwater to protect water resources. EA R&D Publication 20. Environment Agency, UK.
Environment Agency (2000b). Contamination impact on groundwater: Simulation by monte carlo method. Prepared by Golder Associates (UK) Ltd. Environment Agency, UK.
Environment Agency (2001a). Guidance on the waste treatment requirements of article 6(a) of the landfill directive. Version 2.1 External Consultation Draft. Environment Agency, UK.
Environment Agency (2001b). Guidance on the disposal of contaminated soils. Version 3. Environment Agency, UK.
Environment Agency (2001c). Remedial Targets Worksheet v2.2a. User Manual. Environment Agency Report NC/99/11. Environment Agency, UK.
Environment Agency (2002a). Landfill directive regulatory guidance note 2 (LFD RGN 2). Interim waste acceptance criteria and procedures. Version 4.0, November 2002, Environment Agency, UK.
Environment Agency (2002b). Guidance on national interim waste acceptance procedures. Version 1.2 External Consultation Draft. Environment Agency, UK.
Evans, C.W. (1998). Studies related to the in situ treatment of contaminated ground using soil mix technology. PhD Thesis, University of Birmingham.
Feldman, F.R. and Ramachandran, V.S. (1971). Differentiation of interlayer and adsorbed water in hydrated Portland cement by thermal analysis. Cement and Concrete Research, Vol. 1, No. 6, pp. 607-620.
Harris, M. R., Herbert, S. M. and Smith, M. A. (1995). Remedial treatment for contaminated land. Volume IX: In-situ methods of remediation, Construction Industry Research and Information Association Special Publication 109, pp 121-131.
Head K. H. (1992). Manual of soil laboratory testing, Vol. 3, Chapter 20: Triaxial consolidation and permeability tests, pp 1001-1027.
Heasman, L. (2002). The significance of leaching tests within European landfill directive. CLAIRE newsletter, summer 2002, pp. 8.
Highways Agency, Scottish Executive Development Department, The National Assembly for Wales and the Department for Regional Development, Northern Ireland (2000). Design manual for roads and bridges, Volume 4, Section 1 Part 6: Treatment of fill and capping materials using either lime or cement or both. Highways Advice Note 74/00. The Stationery Office, London.
Highways Agency, Scottish Executive Development Department, The National Assembly for Wales and the Department for Regional Development, Northern Ireland (2001). Manual of contract documents for highway works:
Volume 1. Specification for highway works

Volume 2. Notes for guidance on the specification for highway works.
The Stationery Office, London.

Hinsenveld, M.A. (1992). Sound and practical method to determine the quality of stabilisation. In: Proceedings of the first international NATO/CCMS conference on the evaluation of demonstrated and emerging technologies for the treatment and cleanup of contaminated land and groundwater (Phase II), (Budapest). USEPA Risk Reduction Engineering Laboratory (Cincinnati).

Hinsenveld, M.A. (1993). Sound and practical method to determine the quality of stabilisation. In: Proceedings of the fourth international KfK/TNO conference on contaminated soil. Arendt, F. et al (eds.) Kluwer (Dordrecht), pp. 1519.

Interdepartmental Committee on the Redevelopment of Contaminated Land 59/83 (1987). Guidance on the assessment and redevelopment of contaminated land. 2nd Edition. DETR Publications.

International Society for Rock Mechanics (1985). ISRM suggested methods for porosity/density determination using saturation and calliper techniques, Ed. ET Brown, International Society for Rock Mechanics, London.

Isenburg, J.E. and Moore, M. (1992). Generalised acid neutralisation capacity test. Stabilisation and Solidification of Hazardous, Radioactive and Mixed Waste, In: T.M. Gilliam and C.C. Wiles (Eds.), STP 1123, American Society for Testing and Materials, Philadelphia, PA, USA.

Kollek, J.J. (1989). The determination of the permeability of concrete to oxygen by the Cembureau method – a recommendation, Materials and Structures, Vol. 22. No. 129, pp. 225-230.

LaGrega, M.D., Buckingham, P.L. and Evans, J.C. (1994). Stabilisation and solidification. Hazardous Waste Management, McGraw-Hill, pp. 641-704.

Landfill (England and Wales) Regulations (2002). SI No 1559.

Lewin, K., Bradshaw, K., Blakey, N. C., Turrell, J., Hennings, S. M. and Flavin, R. J. (1994). Leaching tests for assessment of contaminated land: Interim NRA guidance, NRA, R&D Note 301, Bristol, UK.

Materials Characterisation Centre (MCC) (1981). MCC-5S Sox

Materials Characterisation Centre (MCC) (1984). MCC-1 Static leach test method.

Materials Characterisation Centre (MCC) (1984). MCC-2 Static, high-temperature leach test.

McKinley, J.D., Thomas, H., Williams, K. and Reid, J.M. (1999). Detailed chemical analysis of lime stabilized materials. TRL Report 424. Transport Research Laboratory, Crowthorne.

Mulder, E. (2002). TNO, personal communication.

Neville, A.M. (1997). Properties of concrete. Fourth Edition. Longman group UK limited.

Neville, A.M. and Brooks, J.J. (1993). Concrete technology. Longman group UK limited.

Netherlands Normalisation Institute (1995a). Leaching characteristics of earthy and stony building and waste materials. Leaching tests. Determination of the availability for leaching of inorganic components from granular materials. NEN 7341. Netherlands Normalisation Institute.

Netherlands Normalisation Institute (1995b). Leaching characteristics of earthy and stony building and waste materials. Leaching tests. Determination of the leaching of inorganic components from granular materials with the cascade test. NEN 7349. Netherlands Normalisation Institute.

Netherlands Normalisation Institute (1995c). Leaching characteristics of earthy and stony building and waste materials. Leaching tests. Determination of the leaching of inorganic components from buildings and monolithic waste materials with the diffusion test. NEN 7345. Netherlands Normalisation Institute.

Netherlands Normalisation Institute (1995d). Leaching characteristics of earthy and stony building and waste materials. Leaching tests. Determination of the leaching of inorganic components from granular materials with the column test. NEN 7343. Netherlands Normalisation Institute.

prEN14405 (2002). Characterisation of waste. Leaching behaviour test. Up-flow percolation test. CEN/TC292.

prEN14429 (2002). Characterisation of waste. Leaching behaviour test. Influence of pH on leaching with initial acid/base addition. CEN/TC292.

Reid, J M and Clark, G T (2001). The processing of contaminated land in highway works. TRL Report 489. TRL Limited, Crowthorne.

Sherwood P. T. (1993). Soil stabilization with cement and lime, HMSO.

Shi, C., Stegemann, J.A. and Caldwell, R.J. (1998), Effect of supplementary cementing materials on the specific conductivity of pore solution and its implications on the rapid chloride permeability test (AASHTO T277 and ASTM C1202) results, ACI Materials Journal, Vol. 95, No. 4, pp. 389-394.

SNIFFER (2003). Method for deriving site specific human health assessment criteria for contaminants in soil. SNIFFER report LQ01. Scotland and Northern Ireland Forum for Environmental Research, UK.

Stegemann, J.A., Butcher, E.J., Irabien, A., Johnston, P., de Miguel, R., Ouki, S.K., Polettini, A. and Sassaroli, G., Eds. (2001), Neural network analysis for prediction of interactions in cement/waste systems - Final Report, Commission of the European Community, Brussels, Belgium, Contract No. BRPR-CT97-0570.

Stegemann, J.A. and Coté, P.L. (1990). Summary of an investigation of test methods for solidified waste evaluation. Waste Management, Vol. 10, pp. 41-52.

Stegemann, J.A. and Coté, P.L. (1991). Investigation of test methods for solidified waste evaluation. Appendix B: Test methods for solidified waste evaluation. Environment Canada. Manuscript Series Document TS – 15.

Taylor, H.F.W. (1997). Cement chemistry. Thomas Telford, London.

The Dutch List (1994). Intervention values and target values – soil quality standards. Ministry of Housing, Spatial Planning and Environment, The Netherlands.

Tessier, A., Campbell, P.G.C. and Bisson, M. (1979). Sequential extraction procedure for the speciation of particulate trace metals. Analytical Chemistry, Vol. 51, No. 7, pp. 844-851.

U.S. Bureau of Reclamation (1992). Procedure for direct tensile strength, static modulus of elasticity, and Poisson's ratio of cylindrical concrete specimens in tension, Concrete Manual, Part 2, 9th Eds, pp. 726–731.

United States Environmental Protection Agency (2003a). Method 1311: Toxicity characteristic leaching procedure. SW846 On-line test methods for evaluation of solid wastes, physical chemical methods, URL: http://www.epa.gov/epaoswer/hazwaste/test/pdfs/1311.pdf

United States Environmental Protection Agency (2003b). Method 1310A: Extraction procedure (EP) toxicity test method and structural integrity test. SW846 On-line test methods for evaluation of solid wastes, physical chemical methods, URL: http://www.epa.gov/epaoswer/hazwaste/test/pdfs/1310A.pdf

United States Environmental Protection Agency (2003c). Method 1312: Synthetic precipitation leaching procedure. SW846 On-line test methods for evaluation of solid wastes, physical chemical methods, URL: http://www.epa.gov/epaoswer/hazwaste/test/pdfs/1312.pdf

United States Environmental Protection Agency (2003d). Method 1320: Multiple extraction procedure. SW846 On-line test methods for evaluation of solid wastes, physical chemical methods, URL: http://www.epa.gov/epaoswer/hazwaste/test/pdfs/1320.pdf

United States Environmental Protection Agency (1986). Prohibition on the disposal of bulk liquid hazardous waste in landfills – Statutory interpretive guidance. Office of Solid Waste and Emergency Response (OSWER) Policy Directive No. 9487.00-2A. EPA/530-SW-016, Washington DC.

University of Wisconsin (1978). Standard leach test, procedure C.

Van der Sloot, H., Heasman, L. and Quevauviller, P. (1997). Harmonisation of leaching/extraction tests. Elsevier.

Wastewater Technology Centre (1991). Proposed evaluation protocol for cement-based solidified wastes. Report EPS 3/HA/9, Environment Canada.

Wastewater Technology Centre (1990). Compendium of waste leaching tests. Report EPS 3/HA/7, Environment Canada.

Weitzman, L.H., Hamel, L.E. and Barth, E.F. (1990). Evaluation of solidification/stabilisation as a best demonstrated available technology for contaminated soils, EPA/600/52-89/013.

Table 1 Operating parameters for BS EN 12457

Part	1	2	3	4
Particle size (mm)	<4	<4	<4	<10
L/S ratio (L/kg)	2	10	2+8	10
Contact time (h)	24	24	6+18	24

Table 2. Typical use of the properties on untreated and treated S/S materials and also at the point of onset

Property	To assess suitability for treatment	Testing just after treatment	End product specification
Commonly utilised			
Leachability and pH	X		X
Unconfined compressive strength			X
Durability			X
Permeability	X		X
Others of relevance			
Bound water	X	X	X
Bulk density	X	X	X
Chloride permeability	X		X
California Bearing Ratio (CBR)			X
Dry density/moisture content relation	X?	X	X
Flow	X	X	
Heat of hydration	X	X	
Initial Consumption of Lime (ICL)	X?		
Intrinsic permeability	X		X
Microstructural examination			X
Modulus of elasticity			X
Moisture content	X	X	X
Moisture Condition Value (MCV)	X	X	X
Oxygen permeability	X		X
Particle size distribution	X		
Penetration resistance			X
Porosity	X	X	X
Pulverisation		X	X?
Setting time		X	
Shrinkage/expansion	X		X
Slump		X	
Soundness			X
Specific gravity	X	X	X
Tensile strength			X
Water absorption	X		X
Other chemical tests	X		X

Table 3. Summarised timetable (EA, 2002b)

	All new landfills	Existing hazardous landfills	Other existing landfills
NIWAC	Via permit	From 16 July 2002	When re-permitted, unless after 16 July 2005
Full Criteria	16 July 2005	16 July 2005	16 July 2005

Table 4. Tests and limiting values for stabilised materials for capping material from Specification for Highway Works (SHW) (Highways Agency et al., 2001).

Property	Test Method	Limiting Value
Untreated Material		
Grading	BS 1377: Part 2	Table 6/2 of SHW
Moisture Content (See Note 1)	BS 1377: Part 2	To be specified by the designer based on site investigation data on moisture content/dry density relation. Maximum value only required
MCV (See Note 1)	BS 1377: Part 2	To be specified by the designer based on site investigation data; minimum value only required. Default value of 7 generally used.
Plasticity Index	BS 1377: Part 2	Less than 20 (granular material and Class 7F) or greater than 10 (cohesive material)
Liquid Limit	BS 1377: Part 2	Less than 45 (granular and Class 7F); no limit for cohesive material
Organic matter	BS 1377: Part 3	To be specified by the designer based on site investigation data; value of 2% generally used as default value
Total sulfate content	BS 1377: Part 3	To be specified by the designer based on site investigation data; value of 1.0% often used as default value, but values as low as 0.25% may be necessary for some soils.
Total sulfur content	BS 1047	To be specified by the designer based on site investigation data.
Treated Material		
Pulverisation	BS 1924: Part 2	Table 6/1 of SHW; generally minimum of 30% for cohesive material and 60% for well graded material, silty cohesive material and pulverised fuel ash.
MCV immediately before compaction (See Note 1)	Clause 632 of SHW (BS 1377: Part 4)	To be specified by the designer based on site investigation data; upper and lower limits required. Generally, minimum value of 8.5 and maximum in range 12 to 14.
California Bearing Ratio	BS 1924: Part 2	To be specified by the designer based on site investigation data; a minimum value of 15% at 7 days, with a swell of less than 5mm at 28 days is usually required.
Moisture content (See Note 1)	BS 1377: Part 2	To be specified by the designer based on site investigation data; upper and lower limits required. Material should be wet of optimum moisture content.

Note 1: MCV is the preferred method of control for cohesive soils and moisture content for granular soils. The moisture content is related to the optimum moisture content derived from dry density/moisture content relation tests. One or other of these parameters should be specified, depending on the material, but not both.

Note 2: This table provides a summary of the requirements of the Specification for Highway Works. Users should check the SHW and HA74/00 for full details on the use of solidification/stabilisation techniques for highway earthworks.

Table 5. Leaching limit values for the acceptance of wastes in landfills (EA, 2002b)

	Hazardous waste to hazardous waste sites (set 1)		**Hazardous waste to non-hazardous waste sites (set 2)**		**Inert waste sites (set 3)**	
Components	**L/S = 2 l/kg**	**L/S = 10 l/kg**	**L/S = 2 l/kg**	**L/S = 10 l/kg**	**L/S = 2 l/kg**	**L/S = 10 l/kg**
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
As	6	25	0.4	2	0.1	0.5
Ba	100	300	30	100	7	20
Cd	0.6	1	0.06	0.1	0.03	0.04
Cr_{total}	25	70	4	10	0.2	0.5
Cu	50	100	25	50	0.9	2
Hg	0.1	0.4	0.005	0.02	0.003	0.01
Mo	20	30	5	10	0.3	0.5
Ni	20	40	5	10	0.2	0.4
Pb	25	50	5	10	0.2	0.5
Sb	2	5	0.2	0.7	0.02	0.06
Se	4	7	0.3	0.5	0.06	0.1
Zn	90	200	25	50	2	4
Cl	17,000	25,000	10,000	15,000	550	800
F	200	500	60	150	4	10
SO_4	25,000	50,000	10,000	20,000	560#	1,000#
TDS*	70,000	100,000	40,000	60,000	2,500	4,000
DOC**	480	1,000	380	800	240	500
Phenol index	-	-	-	-	0.47	1

* The values for TDS (Total Dissolved Solids) can be used alternatively to the values of Sulphate, Fluoride and Chloride.

** If the waste does not meet these values for dissolved organic carbon (DOC) at its own pH, it may alternatively be tested at L/S = 10 l/kg and a pH of 7.5 – 8.0. The waste may be considered as complying with the acceptance criteria for DOC, if the result of this determination does not exceed 1000, 800 and 500 mg/kg for set 1, 2 and 3 respectively (A draft method based on prEN14429 is available).

\# If the waste does not meet these values for sulphate, it may still be considered as complying with the acceptance criteria if the leaching does not exceed either of the following values: 1500 mg/l as Co at L/S = 0.1 l/kg and 6000 mg/kg at L/S = 10 l/kg. It will be necessary to use the percolation test (prEN14405) to determine the limit value at L/S 0.1 l/kg under initial equilibrium conditions, whereas the value at L/S = 10 l/kg may be determined either by a batch leaching test (BS EN 12457: Part 2 or BS EN 12457: Part 3) or by the percolation test (prEN14405) under conditions approaching local equilibrium.

Note: For inorganic parameters of concern not listed in the table the maximum leachable value obtained from the percolation test (prEN14405) can be used as the source term for those parameters in the risk assessment outlined in Schedule1(1) of the 2002 Regulations.

Table 6. Additional limit values for the acceptance of wastes in landfills (EA, 2002b)

	Hazardous waste to hazardous waste sites (set 1)	**Hazardous waste to non-hazardous waste sites (set 2)**	**Inert waste sites (set 3)**
Parameter	mg/kg	mg/kg	mg/kg
LOI*	10%	-	-
TOC**	6%	5%	30,000
PH	-	Minimum 6	-
ANC	Must be evaluated between the pH of the waste in question, pH6 and the pH of the site leachate	Must be evaluated between the pH of the waste in question, pH6 and the pH of the site leachate	-
BTEX	-	-	6
PCB’s (7 congeners)	-	-	1
Mineral oil (C10 to C40)	-	-	500

* Either Loss on Ignition (LOI) or Total Organic Carbon (TOC) must be used.

** If this value is not achieved (for soils in the case of set 3), a higher limit value may be admitted by the competent authority, provided that the DOC value of 1000, 800 and 500 mg/kg is achieved for set 1, 2 and 3 respectively at L/S 10 at its own pH or pH 7.

Table 7. Typical ranges of values for selected test methods (Stegemann et al., 2001)

Physical Property	**Minimum**	**Maximum**
Bound water (%)	6.8	19.6
Bulk density (as is) (g/cm^3)	0.466	2.86
Bulk density (dry) (g/cm^3)	0.145	1.18
Bulk density (saturated) (g/cm^3)	1.6	1.97
Chloride permeability (mg/kg wet wt)	2540	21110
Flow table spread diameter (cm)	10.5	13.6
Permeability (m/s)	$4x10^{-18}$	$3.66x10^{-6}$
Intrinsic permeability (m^2)	$2.2x10^{-17}$	$1.74x10^{-16}$
Modulus of elasticity (kPa)	10200	$2.1x10^{7}$
Moisture content (% wet wt)	0.263	98
Oxygen permeability (m/s)	$4.06x10^{-16}$	$5.33x10^{-15}$
Penetration resistance (kPa)	16000	52400
Porosity (%)	2	75
Setting time - initial (minutes)	25 (25)	2400 (1650)
Setting time - final (minutes)	11 (65)	12000 (2700)
Shrinkage/expansion (%)	$-9.3x10^{-5}$	7
Slump (mm)	180	220
Soundness (cm)	0.09	4.12
Specific gravity	0.905	5.189
Tensile strength (kPa)	3.4	10270
Unconfined compressive strength (kPa)	0	395000
Water absorption @80^0C (%?)	12.5	19.4
USEPA TCLP (mg/l)		
Leachate pH	1	12.78
As	4.92	17510
Ba	22.73	418.2
Cd	0.3155	45990
Cr (total)	2.718	58070
Cu	0.8202	6291
Hg	$9.79x10^{-3}$	1828
Ni	0.95	57930
Pb	3.918	46940
Zn	0.85	299100

Table 8. Summary of the tests performed in the research projects detailed in Al-Tabbaa and Perera (2003b)

Research Project	**Tests Utilised**
S/S with OPC	
- Effect of cyanide	Calorimetry, XRD
- Treatment of PFA and flue gas	Dimensional stability, UCS, rapid dynamic leaching, microstructural
- Effect of organics	Heat of hydration, setting, strength, microstructural
- Effect of industrial waste and organics	Differential thermal analysis (DTA), TCLP leaching, FTIR & NMR spectroscopy, XRD
- Effect of cement chemistry	strength, leaching, microstructural
- Effect of uniaxial pressing	MIP (porosity, pore size distribution, bulk density), DTA, static leaching, pH
- Treatment of metal nitrate salts	SEM & image analysis (porosity), density, non-combined (evaporable) water
- Effect of calcium chloride on treated synthetic waste	DTA, calorimetry, static leaching, pH
- Treatment of foundry dust	Setting time, UCS, ANC,XRD
S/S with Lime	
- Treatment of lead and iron nitrates	Shear vane strength, batch leaching, pH, conductivity
S/S with Organophilic Clays	Strength, setting, leachability, SEM/EDS, XRD
S/S with Blended Binders	
- OPC and PFA blends	Calorimetry, strength, microstructural
- Effect of acid addition	ANC
- Treatment of metal nitrates by zeolite and silica fumes blended cements	Setting, UCS, ANC, solubility of metal contaminants as a function of pH
- Treatment of IFA by sodium silicate blended cements	Setting, strength, microstructural
- Treatment of mine tailings	UCS, permeability, NRA leaching, pH, SEM, XRD
- Effect of carbonation	UCS, modified DIN 38414 leaching, NRA leaching, ANC, XRD, SEM, EDAX.
- Effect of binder variability on performance	strength
- Treatment of radioactive waste	UCS, physical coherence, pH, pore fluid extraction, leaching, microstructural analyses
S/S with Waste Material	
- S/S with spent bleaching earth	Strength, leaching/chemical analysis
Research with Laboratory-scale Augers	UCS, pH, TCLP leaching, NRA leaching

Table 9. Typical examples of tests performed and performance criteria used in some of the field trials described in Al-Tabbaa and Perera (2003c)

Field Trial	**Tests Performed**	**Performance Criteria**
Field treatment of electric arc furnace dust using sodium silicate activated blastfurnace slag	Bulk density, moisture content, permeability, UCS, freeze-thaw durability, leachate samples from cell, 3 types of batch extraction leaching tests, pH	
In-situ S/S site trial for organic contamination in West Drayton	UCS, durability, permeability, compressibility, TCLP and NRA leaching, pH	UCS ≥ 350 kPa soaked at 28day, Permeability ≤ 10^{-9} m/s, Durability – pass ASTM tests with max 30% mass loss, TCLP Leachability – up to 50 times drinking water standards TCLP leachate pH 7 – 11
CIRIA demonstration project – Geodur process	Moisture content, bulk density, particle size distribution, crushing & compressive strength, permeability, porosity, durability, NRA and draft CEN leaching, bulk chemical analysis.	Environmental Quality Standards values
Treatment of river dredgings and sewage sludge by lime	CBR, shear strength, MCV, swell, permeability, conductivity, NRA and dynamic flow-through leaching, pH, selected chemical species	CBR (lower bound) – immediately after compaction – 3%, after 7 days – 5% MCV prior to final compaction – 8.5 lower bound, 12 upper bound 28 day swell – 5mm upper bound
Greenwich/Blue circle demonstration project with special cement	UCS, leaching.	

Table 10. Typical examples of tests performed, performance criteria employed and end use in some of the commercial projects described in Al-Tabbaa and Perera (2003c)

Commercial Project	Tests Performed	Performance Criteria	End Use
Sealosafe plants 1974	UCS, permeability, durability, leachability: EP-Tox		Disposal
A13: Thames Avenue to Wennington highway scheme 1995	Physical and leaching tests	CBR (lower bound) – immediately after compaction – 3%, after 7 days – 5% MCV prior to final compaction – 8.5 lower bound, 12 upper bound 28 day swell – 5mm upper bound	Lightweight fill for use in embankments
Ardeer site, Scotland 1995	Strength, permeability, pH, ANC		Remediation of contaminated land for the prevention of further groundwater contamination
West Drayton site, Middlesex 1997	Leaching tests	Leaching: Dutch Intervention Values	Redevelopment of contaminated ground for housing
Pumpherston site, nr Edinburgh 1999	Density, UCS, in-situ penetrometer		Remediation of a contaminated site
Long Eaton site, Nottingham 2000	Permeability, bearing capacity	Permeability 10^{-9}m/s for passive barrier section, Permeability of reactive section comparable with in-situ soil, Minimum bearing capacity – 150kPa	Remediation and enabling works on a contaminated site for a new retail supermarket
Leytonstone site, London 2000	CBR, permeability		Redevelopment of a brownfield site for the construction of a school
Winterton Holme water treatment works site 2000	Strength, permeability, leaching tests		Disposal in landfill