STATE OF PRACTICE REPORT
UK STABILISATION/SOLIDIFICATION TREATMENT AND REMEDIATION - PART VI: QUALITY ASSURANCE AND QUALITY CONTROL

ASR Perera[a], A Al-Tabbaa[a] and D Johnson[b]
[a]Department of Engineering, University of Cambridge, Cambridge, UK
[b]S/S Remediation Consultancy, Nottingham, UK

Introduction

Quality assurance (QA) is a wide-ranging concept referring to the policy, which prevents problems from occurring and which covers all activities and materials which affect the quality of the outcome, in this case the treated S/S material. Quality control (QC) deals with the specific actions taken consistently to monitor the effectiveness of the system. Therefore adequate QA/QC is vital in S/S treatment and remediation projects in order not to jeopardise the performance of the treated S/S material due to incorrect or inconsistent actions adopted during the tenure of a given project.

Another view on QA/QC is given by LaGrega et al. (1994). They state that a QC plan describes the specific procedures by which the implementation of sampling and analytical procedures designed to result in reliable data are documented. They present a QA plan that describes the procedure by which the QC implementation is audited to ensure that the work and documentation is being conducted in accordance with established QC procedures.

The USEPA Guide for QA/QC procedures for submission of data for the land disposal restrictions program (USEPA, 1991) states that "the overall effectiveness of a QC program depends on operating in the field and laboratory in accordance with a program that systematically ensures the precision and accuracy of analyses by detecting errors and preventing their recurrence or measuring the degree of error inherent in the methods applied". Although the above statement only refers to one aspect of QA/QC, it indicates the importance of consistency and thoroughness that is required.

Although QA/QC should cover all activities, the general tendency of compliance verification is achieved by examining materials tested during all stages of the process. However, as the scope is much wider it must be considered as such, rather than limiting it to this area, although this may be the main area investigated. As QA/QC spans across a broad area it will be useful to consider the key issues at different stages. This could be achieved by broadly categorising the stages as prior to-, during- and after- application.

Although QA/QC is being adopted in certain stages of the S/S treatment and remediation process, and in particular in sampling and testing (Sherwood, 1993; Shi et al., 1995a&b), there is currently no adequate guidance available providing a standardised approach for S/S treatment and remediation. This aspect is very important in any type of work, and is essential for S/S processes which are still facing issues relating to their reliability especially in the long-term. This essential QA/QC programme should be adopted from the beginning of the works and should continue until completion. Having said that, such a programme is insufficient; as it should actually be well documented and well implemented if its benefits are to be reaped. The USEPA (1997) recommends that QC procedures, which cover the control of batch proportions, control of mixing time and post-treatment testing, should be an item on the list of typical pre-construction submittals provided by the contractor. It further suggests that the specifications should specify how re-testing and reprocessing would be addressed in the eventuality of QA/QC test failure.

Integration of the various elements of S/S treatment and remediation projects into a proper quality assurance QA/QC programme is essential to ensure that there is a systematic and consistent approach to the whole S/S treatment and remediation process from conception to completion. Those elements include the treatability study, testing procedures and the design, construction and monitoring of the works on site.

In relation to above having an environmental audit will also prove to be useful to ensure proper functionality. The USEPA has defined environmental auditing as a 'systematic, documented, periodic and objective review by a regulated entity of facility operations and practices related to meeting environmental requirements (Federal Register, 1986). Even these audit programs, which are put in place to observe the proper functionality of other systems, are required to have a process that include quality assurance procedures (LaGrega et al., 1994). This is required to ensure the accuracy and thoroughness of the environmental audits themselves if they are to be deemed effective. These audits should cover all aspects of the work mentioned in this paper.

This report looks at these QA/QC issues which are relevant to the various stages in the S/S treatment and remediation process. These are divided into 'prior to application', 'during application' and 'after application'. This is similar to Usui's (2002) categorisation in which he stated that to ensure sufficient quality of the stabilised column by cement deep mixing (CDM) method, adequate QA/QC are required before, during and after construction.

QA/QC Prior to Application

Once a project has been decided on, the QA/QC programme should be built around the main objectives of the works and also as part of the objectives. Projects, especially those involving field work, require a QA/QC procedure to be incorporated as part of the work plan (Day, 1997; prEN 14679, 2003). The procedure should detail the key QC issues that will be addressed throughout the project, the methods and frequency of their checks and also define the procedure for dealing with non-conformance (BS EN ISO 9000, 2000; EA, 2004). A proper record keeping system should also be observed as this would enable the identification of any discrepancies at an early stage and would also enable access to them for later use if the necessity arises.

The location of treatment and where the treated material will end up should both be investigated, prepared as necessary and thereafter maintained to ensure that they remain fairly consistent. In the laboratory this means checking the laboratory working and curing conditions, and maintaining them. In the field, the site to be treated needs to be investigated sufficiently to ensure that any variability is understood and that there are proper controls to tackle it. Thereafter it should be ensured that the site preparation is carried out in accordance with requirements. For contaminated sites the investigation could be performed in accordance with a suitable standard such as BS 10175 (2001), to ensure that the samples are representative of the material to be treated. Where large variation is present, several samples should be taken for the treatability study and should not be combined.

For highway earthworks involving treatment with lime and/or cement to improve fill and to stabilise capping materials, guidance on investigation is given in the HA 74/00 (Highways Agency et al., 2000). In addition, when the final disposal location is to landfill, checks will also need to be carried out on the landfill or at least conditions will need to be obtained from the landfill owner. This is important as the curing conditions will have an influence on the performance of the material and these conditions will need to be considered at the treatability study stage. In all cases the time period between sampling of material and laboratory assessment should be kept to a minimum, as constituents and properties of the original material could change with time. The samples, especially those that could be affected by oxidation, should be kept air-tight and Mitchell (1986) recommends storing them at below 4ºC. The time period between the treatability study and the field remediation should be kept as short as possible to minimise any potential changes in the contaminants present in the contaminated material caused by weathering effects on the site.

Thereafter the QA/QC of source material will be one of the key issues at this stage. Source material will include all binders, fillers and additives that are going to be used in the project. These should be properly characterised and should comply with relevant quality standards (Harris et al., 1995a&b). This is normally certified by the supplier and should also conform to ISO 9000. The material quality standards for common materials in use are available in the form of BS standards. For example the quality standards for cement, building lime and ground granulated blastfurnace slag (for use with Portland cement) are BS EN 197-1 (2000), BS EN 459-1 (2001) and BS 6699 (1992) respectively. Other binders such as kiln dust and fly ash may be more variable in quality and appropriate technical specifications are required for these materials. Pulverised fuel ash, in particular, is used in many applications in both standardised (BS EN 450, 1995; BS 3892, 1996 & 1997) and non-standardised forms (e.g. conditioned ash).

In addition to the supplier guarantee, the material, when received, should be checked periodically according to a set plan to ensure that the material in hand conforms to the standards. Where standards are not available then they should be checked against a benchmark sample to ensure they remain consistent. Also where possible it is advisable to use the same supplier to supply materials throughout the project. All these procedures are necessary as they ensure that the materials used in the given treatment process remain consistent throughout the project, as slight changes in some materials could significantly affect their performance. This control should apply even at the stage of conducting treatability studies.

It should also be noted that the water used and the contaminated material to be treated would also need to be considered as a source material. These too would need to be kept consistent as changes in water quality especially changes in temperature and pH could affect the treatment. The water, which must be clean and potable, should comply with BS EN 1008 (2002) (as used for the making of concrete). The contaminated material treated during the project should also be comprehensively characterised in the first instance to develop the formulations, to establish whether inhibitory substances are present and to determine material handling requirements (Harris et al., 1995b). The checks should even continue thereafter to ensure that the contaminated material lies within the ranges that were acceptable at the treatability study. Otherwise the design formulation used might become less effective and might need to be changed. In fact regular checks should be carried out on all the material to ensure conformity especially when taken for use.

When conducting the above investigations on the material, the sampling technique itself should be in accordance with the relevant standard if available. Where a standard is not available it should be conducted in a diligent and consistent manner.

Storage of materials, both the material to be treated and the binders, also need to be controlled. The longer the period of storage the higher the care should be. This is performed in order to prevent materials from deterioration, damage and contamination or at least to minimise the impact. The materials will usually be stored in containers that will not deteriorate with time or in the case where the contaminated material requires storing the containers should not affect the contaminants. Some materials will also require further controls such as being stored in air tight conditions and kept at a temperature below 4ºC. Binders should be stored under cover and above ground in order to minimise contact with damp earth. Cement quality deteriorates when exposed to the atmosphere. Quicklime reacts with moisture present in the air, producing heat and additionally expands so that bags stacked above each other could become unstable and topple. Also adopting a first-in first-out policy when utilising materials from storage would minimise any adverse affects as the standing period of the material in storage is minimised. The QA on the material will be achieved by conducting characterisation tests as appropriate.

Other relevant aspects include controlling temporary storage locations such as transportation, final disposal site in ex-situ applications and where possible some control over in-situ locations, although this is much more difficult. Obviously a distinction needs to be made between laboratory conditions and field conditions. In laboratory conditions the control is generally easier as conditions remain fairly stable over long periods of time.

QA/QC During Application

During the treatment application QA/QC procedures are more diverse as the work involved depends on whether it is a laboratory-based, ex-situ field or in-situ field application, and could be significantly different. Furthermore, even within a similar category, e.g. ex-situ field treatment for landfill disposal, the approach during treatment could be different. Hence the QC procedure for this stage should be developed with the assistance of the designer of the S/S process and also the regulator where needed. The latter is essential particularly when decisions need to be made about post-treatment monitoring and testing requirements.

This section is divided into the different stages of a treatment including blending, ex-situ mixing and placement and in-situ mixing and placement.

Blending:
In some cases the binders are blended in stages prior to the addition of the water and prior to contact with the material to be treated and then either stored temporarily or used directly for treatment. Here the materials in question are weighed and blended together using some form of mixing. Controls should be in place to ensure the accuracy of the weighing, order in which the weighing and blending is performed, blending time and rate, homogeneity of the mixing etc. An example of such a QA/QC procedure can be found in Shi et al. (1995a), where the dry cementing additives were blended, trucked to the site and temporarily stored prior to the treatment and disposal. In this study several quick tests were used to determine the effect of the mixing procedure and transportation on the homogeneity of the blended material. Companies supplying blended binders should have a QA scheme conforming to BS EN ISO 9000.

In addition to blending of materials, some might have to undergo a form of pre-treatment prior to use. This process is normally undertaken in order to modify some of the initial properties of the material so that its performance, especially during treatment, is enhanced. Some common methods of pre-treatment include screening, processing to re-grade, dewatering, combining with high-surface area material, blending to dilute contaminants in hot-spots, phase separators, in-situ biodegradation and addition of additives. These summary points have been taken from EA (2004), which also examines their associated benefits and issues. When undertaking any of these or other pre-treatment techniques as required, controls should be put in place to ensure conformance.

Ex-situ mixing and placement:
Pre-blended materials or individual materials, which should ideally have been protected from moisture and direct sunlight, should be weighed as required for one application and then added to the mixture along with the material to be treated and also the water (where necessary). Here again the sequence of addition should be kept consistent. Some mixers work continuously rather than as a batch and therefore this stage involves continuous weighing and mixing. Obviously the controls needed for the latter process will be higher.

Once mixed the treated material will be disposed of or re-used. Generally, samples will be taken from the mixing unit, from the point of exit and from the final placed location for testing. Care is required in taking these samples in a safe manner. In cases where the treated material requires transportation a sample needs to be taken from the vehicle prior to depositing.

The samples collected should generally be subjected to two types of tests for verification of quality, namely quick tests on the fresh treated S/S material and tests after the samples had been cured for a given length of time. The time and rate of mixing, method of transport from the mixing unit to the placement site (if any) and the placement method, including compaction method, should be part of the QC plan. In a study conducted by Shi et al. (1995b) the mixing was carried out in batches for three minutes and then transported by a positive displacement pump for approximately 50m prior to discharging into a prepared cell. Compaction was achieved by using a pencil vibrator. Bulk density, moisture content, cone-slump and K-slump tests were performed to assess the quality of the S/S material.

In-situ mixing and placement:
Here the mixing of the binders will be similar to that of the ex-situ mixing detailed above. The binders will then be transferred to the equipment, which supply the blended mixture to the contaminated material, and mixed in-place. Contaminated material in the form of

slurries in pits could be mixed in-place by backhoes and contaminated material in the form of contaminated soil could be mixed in-place using augers. In the former, QC procedures should be set in place to ensure proper supply and mixing. Fresh samples should be taken from different locations and depths, and tested to ensure that requirements are met. Also as the process is visible, at least at the surface, it provides a visual QC check as well. In the latter case, involving the use of augers, the whole treatment phase will be below ground and hence the control of the treatment is performed by indirect measures. However additionally, and prior to treatment, the positioning and verticality of the shaft must be checked (Hioki, 2002).

During the in-situ auger treatment the controls will be the monitoring of the amount of binder dosed, mixing rotation speeds and penetration and withdrawal speeds. These should be adjusted during the execution procedure to ensure the required quality (Usui, 2002). The new advancements in terms of mixing apparatus, alignment control devices and integrated systems for real-time monitoring during treatment have led to improvements in the quality control and this in turn has helped enhance the reliability of the technique (Porbaha, 1998). Samples to assess the quality of the binding mixture should be taken from the auger outlets before and after treatment. However, core samples may also be required to assess the fresh treated material itself and this will be obtained from selected points in the treated ground.

When forming a stabilised layer, the Lime Stabilisation Manual (BLI, 1990) lists the factors that influence the performance of a lime stabilised layer and hence require control to ensure the uniformity and acceptability of the completed layer. These are the consistency of the material to be stabilised, quantity of reactive lime (available lime), moisture content, efficiency of mixing, thickness of layer, degree of compaction, surface level and regularity, and end product tests. Similar factors will apply for other end-use applications involving lime and/or cement, such as the Highways Advice Note HA 74/00 (Highways Agency et al., 2000) for the treatment of fill and capping material. This type of work would generally be carried out in accordance with the Specification for Highway Works and tested in accordance with BS 1924 (1990).

In relation to soil stabilisation work, Sherwood (1993) stated that regular checks need to be carried out during the construction process to ensure that the requirements are being met and also production control tests need to be carried out to monitor the work in progress to ensure a consistent product. These are then said to be followed up by compliance tests on the final product to observe the performance. He then describes the tests that may need to be conducted to check the compliance of the materials and discusses the various factors that influence the selection of a given test. These are considered under the categories of preliminary trial, sampling and testing frequency, storage and handling of the stabiliser, control of the moisture content, control of the stabiliser content, mixing efficiency, control of compacted density and routine strength determination.

The objective of sample testing conducted at this stage is to ensure compliance for verification of remediation. Additional monitoring during the treatment process will sometimes be needed to check factors which may be affected as a result of the process. This may include, among others, monitoring of air quality, ground vibrations, ground movement and pore water pressure.

QC checks will also be periodically conducted on all equipment used during the project to ensure that they function at the required level. This will generally be achieved in the form of calibration.

QA/QC After Application

Checks carried out after the treatment are mainly for quality verification purposes. This is usually achieved by the testing of cured samples and by continued monitoring. Samples tested would be those that were taken at the time of treatment and those acquired from the placed location at a later date. Additionally, some types of testing could be conducted on treated material while in place. The tests that could be conducted on ex-situ samples were discussed in Perera et al. (2004). In-situ tests for quality verification include integrity tests, rotary sounding test and the vertical loading test (Usui, 2002). The objective of testing at this stage will normally be to check compliance or for characterisation testing of the material in its end-use. It could also be for 'forensic' testing for materials, which have not met the required specifications (EA, 2004).

Sampling:
The fresh samples acquired from the various stages in the application process, may require moulding. This will depend on the tests to be carried out and any subsequent curing until taken for testing. For QC purposes the moulds used should be of the same material and dimensions, and be prepared in the same manner. The material of these moulds should not deteriorate with time or be damaged during the moulding of the specimens. Moulds may be cast in accordance to BS EN 12390 (2000), which is normally employed for testing concrete. Moulding of fresh samples should also be carried out in a consistent manner, as this has a bearing especially on tests involving monolithic samples such as strength. There are standards available for conducting this for given tests (e.g. BS EN 196, 1992; BS EN 12390, 2000).

When acquiring samples from the field, sampling should be conducted in the manner specified. This would be based on the sampling strategy and sampling objectives of the project. Factors such as the sampling location, number of samples, frequency of sampling, sampling pattern, sample size and sampling technique will need to be considered (EA, 2004). Amongst others, these factors will be influenced by the type of process application and end-use, i.e. in-situ or ex-situ and disposal or re-use. Checks will be needed to ensure that the above factors were observed and thereafter that the acquired samples were preserved properly and transported to the location of testing. The quality of the acquired samples will be based on a number of factors such as the quality of the coring equipment, coring technique, sampling tools and skill of the workman. Hence these need careful monitoring in order to minimise any compromising of the quality of the sample. It has been stated that in in-situ treatment using augers sample should be taken throughout the depth (CDIT, 2001) and should include both column centres and areas of overlap (EA, 2004) in order to verify the continuity of the material and these samples should be used for conducting relevant tests. CDIT (2001) also suggested that samplers of a relatively large diameter (e.g. 86mm) should be used in order to obtain good quality samples. Similar to the above, in other areas of treatment core samples should also be obtained to be representative of the treated material and these then should be tested as required. In addition to sampling of the main area of interest, i.e. the treated material, sampling will also be required of general monitoring activities such as water quality and air pollution monitoring.

Matsuo (2002) listed the conventional quality assurance procedures adopted for earth works in Japan which apply to all types of soil mixing work. The first point referred to the sampling frequency and sampling location in the column. It stated that one sampling was conducted for every 250 improved columns with the sample being retrieved from mid height of a soil layer. The other points referred to the obtaining of sub samples from the main sample, the test conducted and performance criteria required. These are a) acquiring three test pieces from the top, middle and bottom part of the sample for conducting unconfined compressive strength, with the average being taken as one data value unless doing so is not advisable; b) the average value is subject to comparison with the design strength; and c) all data should be larger than the design strength.

Monitoring:
Monitoring will be carried out at all stages of a project. In this section the emphasis is on post-completion monitoring. However, except for the work item itself and timescale involved the basic principles at all stages will be similar.

Monitoring will generally cover two areas, namely monitoring the treated material itself and monitoring the surrounding materials and areas. The treated material is monitored to check whether it would be effective for a timescale based on its end-use. This may involve direct measures such as observing swell or cracking, or indirect measures which would involve sampling and testing. The surrounding materials and areas require monitoring to check whether any changes that have been incurred due to the treatment process have had any effect on them. For example water quality of a downstream watercourse, ground movement after in-situ treatment activities etc.

Once the decision has been made on whether monitoring is required, the monitoring requirement will be incorporated into the monitoring programme. This will be based on various factors, including the concerned regulatory body. It is reported that in the case of the EPA and State regulated sites in USA, monitoring requirements vary based on the nature of the contaminants, their level of hazard and local ground water regime (BCA, 2001). The frequency and duration of monitoring and the number of variables monitored will also vary from project to project. Landfill site leachates are said to be monitored for 30 years after closure, initially on a quarterly basis and after five years may be reduced to twice a year or even yearly provided the conditions are favourable (BCA, 2001). The Highways Advice Note 74/00 (Highways Agency et al., 2000) suggests a modest system of monitoring be installed for large sites of slope repair and suggests monitoring will be necessary for about 2 years to monitor the performance of the repair.

Similar to the requirement for the application equipment, all monitoring equipment needs to be maintained and checked periodically to ensure that they are functioning properly.

Maintenance:
Maintenance may also be required, based on end-use or even as a regulatory requirement, to ensure that the treated material will continue to perform effectively and where necessary to isolate it from potential receptors. To achieve the former, the treated material may require protection from events such as those causing disturbance or weathering. The necessary maintenance activities should be developed at the initial stage and be well documented. Checks will need to be carried out to ensure that the requirements are met. In some cases maintenance is not easy to carry out especially when the site is part of a major development. Furthermore, care should be taken to ensure that no changes in the end-use have taken place or where stipulated no changes will take place until the designated time has lapsed. An example is where excavation is carried out into the treated material for the purpose of installing services. Where changes have taken place more checks will be needed to ensure that the original maintenance objectives are still upheld. Where compromised, additional checks will be required to ensure that the contingency plan will be carried out. Examples of maintenance include the installation of barriers to protect groundwater.

Testing:
Samples obtained at various stages of the project will require some form of testing for measuring the desired property. The range of tests and their frequency should be decided at the beginning of the project, and the schedule should take into account such factors as the number of replicates. The schedule should also be sufficiently flexible to incorporate extra tests if required. The testing programme could be developed for both physical and leaching tests based on approaches such as those outlined in DD ENV 12920 (1998), which refers to the suitable choice of leaching test to be used to ensure that a chosen leaching tests is representative of the in-service conditions. For

stabilisation of earthworks the minimum frequency for testing and tests required are given in the Notes for Guidance on the Specification for Highway Works (Highways Agency et al., 2001).

All tests should be conducted in a manner prescribed in the relevant standards (see Perera et al., 2004) or designated procedures. Where the exact stipulated procedure is unable to be followed then any changes made should be documented and the opted procedure should be followed throughout the project. This will remove any bias from the results when comparisons are made. The tests should be conducted on the stipulated days and where, due to practical reasons, this was not possible the tested date should be clearly documented.

Wherever possible, especially when the testing equipment belongs to the project (project co-ordinators) the same equipment should be used under the same conditions for testing the samples. This will minimise errors in results arising from the use of different equipment. Furthermore, these equipment need to be calibrated periodically to ensure that their functioning is within acceptable limits. If faults were found, these should be rectified and documented properly. When the project does not have control over the testing equipment, a reputable laboratory should be used and the same laboratory should be used throughout the project. Given typical testing regimes, more than one laboratory may sometimes need to be selected, to cope with the total range of tests to be conducted. It should be ensured that all the laboratories follow proper QA/QC procedures and are consistent with the method of testing. Proper documentation should be obtained from them and the requirements of the project should be made very clear.

Analysis:
Analytical methods would be required to analyse various substances prior to, during and after the treatment application. Analysis of water quality and leachate from leaching tests are some that would require analytical methods. Most of these methods would generally have guidelines on the number of replicates required. The equipment type that is being used should be kept consistent and should be able to cope with the desired detection limits. The standards for calibration should be made up in accordance to the specifications from acceptable reagents and should cover the range of concentrations expected from the samples.

Analysis of samples should be carried out diligently by trained workers to ensure the best possible precision and accuracy is obtained from the equipment. The equipment itself should be maintained properly and calibrated periodically.

Some Applications/Case Studies

Topolnicki (2002) reported on three different deep soil mixing (DSM) applications in Poland to illustrate the importance of quality control issues.

1) Pad and strip foundations with strongly varying loads were designed as shallow foundations supported on DSM columns of 800mm diameter. The number of columns in each cluster under the pad foundations ranged from 3 to 14 based on a maximum design load acting on a single column of 512kN and allowable settlement difference of 5mm over a 6m span. Based on the initial soil investigation results, which included soil profiles and parameters evaluated from classical borings and penetration tests, 6m length columns were assumed sufficient in the design at one pad foundation location. However, additional soil investigation conducted during the construction stage, as required by the quality assurance plan, revealed that 6m would have been insufficient and the fresh DSM columns were extended to a depth of 8.5m. This case underlined the role of adequate soil investigation data and on-site control of works.

2) A foundation slab was supported on DSM columns, based on 3D finite element calculations which allowed slab-soil interaction and elastic behaviour of columns to be investigated. As the soil was very heterogeneous and contained organic layers, significant differences in column strength were expected, hence a maximum factored design compression stress of 0.86MPa was used and a special mixing procedure was adopted. A general safety factor of 2.5 was applied to the maximum factored design stress which meant that a strength of at least 1.9MPa was required at 28 days. When the 32 standard cubic samples, which were extracted from the fresh DSM columns, were tested for uniaxial compression it was found that three samples had achieved lower strength values than prescribed (1.9MPa), even though they were higher than the design stress of 0.86MPa. It was also found that these samples had been left unprotected during a very cold night and had become partially frozen. This was not duly reported. This case illustrated that classical evaluation procedure of sample strength data, in this case based on 95% confidence which is normally prescribed for ordinary concrete under Polish standards, should not be mechanically used for DSM, but recognised that a new evaluation procedure for DSM strength data is actually needed.

3) DSM columns in groups were found in some cases to be capable of fulfilling all technical requirements with respect to stability and settlement of bridge supports in place of large diameter piles. A typical single column from a cluster under a bridge support was to have a characteristic maximum load of 382kN and the predicted settlement for the whole support was to be 9.5mm. Two loading tests were conducted on a single DSM column to check the load-settlement characteristic and to confirm the applied design method and the predicted settlement. The observed total settlement corresponding to the design characteristic load and maximum applied load (which was 150% of the former load) was 3.28 and 8.22mm respectively. The test results were reanalysed with the same calculation method in order to check the settlement prediction. The calculated settlement corresponding to the 3.28mm was 6.0mm, thus giving evidence that the

applied calculation approach is on the safe side and hence that the predicted settlement for the whole support could be considered as upper bound estimate. Other settlement observations obtained during further construction work would also be used for future back analysis.

Eggen (2002) reported on the stages of QC of lime-cement column installation in Norway using the dry method of DSM. Initially a soil investigation is carried out before installation by conducting sampling for geotechnical parameters, CPTU for finding layers and sounding tests for finding hard layers or rock. Samples of clay/silt taken would also be used for making lime/cement-mixed samples to conduct laboratory studies to ensure that the expected reaction with the soil is achieved, thus having control over the stabilisation. Furthermore, it is stated that if the site had been subject to previous investigation then any available old information could also be taken into consideration. The next stage is the control of the installation and mixing process. This entails ensuring the quality of the material (cement and lime), accuracy of the cement and lime blending, effectiveness of the mixing procedure (verticality, overlapping, rotation, stroke, rise etc.) and monitoring (measuring pore pressure). Thereafter the columns are tested on-site with CPTU and POPS. Also samples taken from the columns are tested in the laboratory.

Druss (2002) reported on the North American practice of QA/QC applicable to the wet method of DSM. One aspect mentioned is that when sampling of cured in-situ material by coring the sample quality must be ensured using good core recovery and with minimum disturbance. In order to achieve this, it is suggested to utilise experienced drillers, experienced drilling inspectors for monitoring/logging, large diameter cores 3” or greater, triple tube coring equipment, very coarse diamond coring bits, side discharge bit to minimise sample washout, appropriate drilling mud, lubrication on the inner surface of the sample tube and to seal core samples immediately to prevent moisture loss. The quality control and evaluation was conducted over several stages and are given below.

- Compressive strength and unit weight of wet grab samples and samples of uncured soil-cement obtained from selected depths.
- Conducting various tests and assessing composition of cored samples.
- Vertical alignment at specified frequencies.
- Observation shaft (5’ diameter) for direct observation of the product in-situ.
- Test pits for direct observation, extraction of block samples and for conducting plate load tests.

Barker, et al. (1996) described in detail the investigation, planning and execution of the remediation undertaken at the Ardeer landfill in Scotland. Initial site investigation and risk assessment suggested that only the groundwater outside the landfill posed long-term low level risk to the flora and fauna of the surrounding environment. Based on these findings remediation at the site was to neutralise the low pH waste within the landfill in order to reduce the movement of metals in the groundwater beneath the landfill. This was to be achieved by conducting in-situ stabilisation. Laboratory studies undertaken established the desired mix for use in a trial study prior to the main work. Lime, Portland cement and fly ash were used to develop the slurry mixes. The performance of the mixes was evaluated using acid neutralisation capacity and the ‘French leaching test’. The permeability was also measured and all mixes had to satisfy the strength (UCS) requirement of 100kPa at 7 days. The chosen mix was to be optimised for final composition and slurry to waste ratio during site trials itself. Site trials were conducted based on the Colmix process which was developed to create columns of stabilised soil in the ground. The site equipment chosen was to provide the most economic means of treating a mass block of ground and comprised a quadruple auger equipment, which gave the necessary stability and torque for penetration. Other supporting equipment included two bulk silos for storing the OPC and PFA dry powder, screw feeds, slurry mixer, agitator and two ram pumps (and one reserve). The lime was stored in bags for the trial and was fed to the mixer manually. The slurry was transferred to the four augers via four pipes. The correct dosage was achieved by computer control such that each slurry was evenly distributed to each column. The computer monitored the volume injected, torque, time and drilling speed.

The technical specifications for the project were set out for various activities and these are outlined below:
1) Testing of fresh slurry as supplied to the Colmix augers to check whether requirements were met. These were monitored for the following parameters: a) density by mud balance (target 1.58), b) viscosity by marsh cone (target 43s), c) stability < 5% after 2 days, d) pH > 12 and e) acid neutralisation capacity > 5 meq H+/g at pH 9 after 14 days. The frequency of these tests was also stipulated. Tests a), b) and d) were to be carried out at least three times in a full working day with the first being at the start of the day. Test c) at least once a day and test e) four times during the course of the trial.
2) Construction of the columns was controlled by rate of dosage, drilling and withdrawal/compaction. Rate of dosage was initially 230litres/linear meter of column with a restriction of a minimum of 200litres/linear meter. Rate of drilling was initially controlled by the computer to achieve the above dosage. The withdrawal/compaction was initially set at 0.5m/min but allowing a maximum of 2.0m/min.
3) Column sampling at the earliest possible time after construction using the Geoprobe instrument to monitor pH. The values were obtained along the column length at 1m from the top, mid point and 1 m from the bottom. The check was to ensure that the pH was greater than 9.
4) Sampling from augers: on completion of the column the auger redrilled a selected column to mid height and lifted without rotation. The samples obtained in this manner from the augers were moulded in triplicate for testing. Moulds were 100mm in diameter and 300mm long. The rate of sampling in this manner was to be one column per day. The tests performed were: pH at the

time of sampling >9, 7-day UCS >100kPa, 28-day UCS >200kPa and 14-day ANC >2meq H+/g at pH 9. Additionally two more moulded samples were taken on every fifth day for testing the 28 -day permeability $<1x10^{-7}$m/sec and leachability.

5) Field samples were obtained from the stabilised waste after at least 28 days of completion of the trials and tests were carried out on the 100mm diameter samples. Tests were carried out for checking UCS >200kPa (20 Nos), ANC >2meq H+/g at pH 9 (4 Nos), Permeability $<1x10^{-7}$m/sec (4 Nos) and leachability (4 Nos).

The trial study area consisted of about 10% of the total area to be treated and it included the area with the lowest pH and highest metal contamination. In total 261 columns were built with 152 constructed with the original slurry mix and the remaining 109 using another slurry mix developed during the laboratory studies.

The site trial assessments concluded that the overall results based on the parameters checked were judged to be satisfactory, as almost all of the specified criteria were met.

During the actual site work some modifications were made to improve the overall efficiency. These included a) additional silo for storage of lime, b) agitator was replaced with another to achieve more flexibility between mixing and drilling, c) construction of columns to be continuous rather than alternate and d) speed of penetration and withdrawal to be 0.8 and 1.0 m/min. Samples were continually taken during this stage, but at a reduced rate to that of the trial study, and tested to confirm continued compliance. An additional 2407 columns were installed during this time.

Post construction monitoring was to be carried out for a period of 18–24 months after completion. The monitoring was to include sampling from wells to determine water quality and using studies on Intertidal Meiofauna to act as a guide to the health of the estuary adjacent to the landfill.

References

Al-Tabbaa, A. and Perera, A.S.R. (2002a). State of practice report UK stabilisation/solidification treatment and remediation: Binders and technology – Part I: Basic Principles.

Al-Tabbaa, A. and Perera, A.S.R. (2002b). State of practice report UK stabilisation/solidification treatment and remediation: Binders and technology – Part II: Research.

Al-Tabbaa, A. and Perera, A.S.R. (2002c). State of practice report UK stabilisation/solidification treatment and remediation: Binders and technology – Part III: Applications.

Barker, P., Wyllie, M. and Esnault, A. (1996). Investigation, Planning and execution of the remediation of the Ardeer landfill, Scotland. Symposium International, Exemples majeurs et recents en geotechnique de l'environnement, Paris.

BCA (2001). Cement-based stabilisation and solidification for the remediation of contaminated land. The findings of a study mission to the USA. British Cement Association.

BS 1924 (1990). Methods of test for stabilised soils. British Standards Institution, London.

BS 6699 (1992). Specification for ground granulated blastfurnace slag for use with Portland cement. British Standards Institution, London.

BS EN 196 (1992). Methods of testing cement. British Standards Institution, London.

BS EN 450 (1995). Fly ash for concrete. Definitions, requirements and quality control. British Standards Institution, London.

BS 3892 (1996 & 1997). Pulverized-fuel ash. Part 1 (1997) - Specification for pulverized-fuel ash for use with Portland cement, Part 2 (1996) - Specification for pulverized-fuel ash to be used as a Type I addition and Part 3 (1997) - Specification for pulverized-fuel ash for use in cementitious grouts. British Standards Institution, London.

BS EN 197-1 (2000). Cement. Part 1: Compositions, specifications and conformity criteria for common cements. British Standards Institution, London.

BS EN 12390 (2000). Testing hardened concrete. British Standards Institution, London.

BS EN ISO 9000 (2000). Quality management systems. Fundamentals and vocabulary. British Standards Institution, London.

BS 10175 (2001). Investigation of potentially contaminated sites. Code of Practice. British Standards Institution, London.

BS EN 459-1 (2001). Building lime. Part 1. Definitions, specifications and conformity criteria. British Standards Institution, London.

BS EN 1008 (2002). Mixing water for concrete. Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete. British Standards Institution, London.

Buxton Lime Industries (1990). Lime Stabilisation Manual.

Coastal Development Institute of Technology (2001). Deep mixing method: Principle, design and construction. Japan.

DD ENV 12920 (1998). Characterisation of waste. Methodology for the determination of leaching behaviour of waste under specific conditions. British Standards Institution, London.

Day, S., Ward, L., Deming, P.W. and Remmert, R. (1997). Quality control for vertical barriers. Training Seminar Manual. 1997 International Containment Technology Conference and Exhibition. Florida State University.

Druss, D.L. (2002). North American practice - QA/QC wet method. Proceedings of the Tokyo Workshop 2002 on Deep Mixing, pp. 150-151.

Eggen, A. (2002). Qa/Qc current practice: Nordic practice dry method. Proceedings of the Tokyo Workshop 2002 on Deep Mixing, pp.xx-xx

EA (2004). Guidance on the use of stabilisation/ solidification for the treatment of contaminated soil. Science Report SC980003/SR1, Environment Agency.

Federal Register (1986). Environmental Protection Agency's environmental auditing policy statement, Vol. 51, No. 131.

Harris, M.R., Herbert, S.M. and Smith, M.A. (1995a). Remedial treatment for contaminated land, Vol. 7: Ex-situ remedial methods for soils, sludges and sediments.

Harris, M.R., Herbert, S.M. and Smith, M.A. (1995b). Remedial treatment for contaminated land, Vol. 9: In-situ methods of remediation. Construction Industry Research and Information Association (CIRIA), Special Publication 109.

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.

Hioki, Y. (2002). The construction control and quality control of dry method (dry jet mixing method). Proceedings of the Tokyo Workshop 2002 on Deep Mixing, pp. 124-138.

LaGrega, M.D., Buckingham, P.L. and Evans, J.C. (1994). Hazardous Waste Management, McGraw-Hill Inc.

Matsuo, O. (2002). Determination of design parameters for deep mixing. Proceedings of the Tokyo Workshop 2002 on Deep Mixing, pp. 75-79.

Mitchell, J.K. (1986). Practical problems from surprising soil behaviour. Journal of Geotechnical Engineering, ASCE, Vol. 112, No. 3, pp. 259-289.

Perera, A.S.R., Al-Tabbaa, A., Stegemann, J. and Reid, J.M. (2004). State of practice report UK stabilisation/solidification treatment and remediation – Part IV: Testing and performance criteria.

Porbaha, A. (1998). State of the art in deep mixing technology: Part 1. Basic concepts and overview. Ground Improvement, Vol, 2, pp. 81-92.

prEN 14679 (2003). Execution of special geotechnical works - Deep mixing. CEN/TC 288 – WG10, Draft. pp. 11-47.

Sherwood, P.T. (1993). Soil stabilisation with cement and lime. State of the art review. Transport Research Laboratory, HMSO.

Shi, C., Stegemann, J.A. and Caldwell, R.J. (1995a). Quality analysis/quality control tests for field stabilisation/solidification – Part 1: Dry cementing additives. Waste Management, Vol. 15, No. 4, pp. 265-270.

Shi, C., Stegemann, J.A. and Caldwell, R.J. (1995b). Quality analysis/quality control tests for field stabilisation/solidification – Part 1: Untreated waste, sodium silicate solution and solidified waste. Waste Management, Vol. 15, No. 7, pp. 507-513.

Topolnicki, M. (2002). Quality control of wet deep soil mixing with reference to Polish practice and applications. Proceedings of the Tokyo Workshop 2002 on Deep Mixing, pp. 167-175.

USEPA (1991). Guidebook for quality assurance/ quality control procedures for submission of data for the land disposal restrictions program. Office of Solid Waste, USEPA.

USEPA (1997). Chapter 5. Solidification/stabilisation. EP 415-1-261.

Usui, H. (2002). Quality control of cement deep mixing method. Proceedings of the Tokyo Workshop 2002 on Deep Mixing, pp. 116-123.