SYNOPSYS
This is the first of a three-part report which presents the state of practice in stabilisation/solidification (S/S) treatment technologies in the UK. This first part covers ‘Basic Principles’ while the second covers ‘Research’ and the third ‘Applications’. This is part of the activities of an EPSRC funded Network on stabilisation/ solidification treatment and remediation (STARNET). The purpose of this work is to identify the knowledge gaps and future research needs in this field. This paper describes the details and basic principles of available binders and technologies in the UK. The introduction in the report includes background on S/S, legislation aspects, overview of STARNET and its activities and details of commonly used binder selection criteria. The report is then divided into two main sections. The first covers binders and includes cement, blastfurnace slag, pulverised fuel ash, lime, natural and organophilic clays, bitumen, waste binders and concludes with proprietary binders. The second part details implementation processes for S/S treatment systems starting with ex-situ treatment systems, such as plant processing, direct mixing and in-drum processing and finishes with in-situ treatment processes, such as mechanical mixing and pressure mixing.

BACKGROUND
Stabilisation/solidification (S/S) treatment methodologies have been widely used over the past three decades particularly in the United States (LaGrega et al, 1994; Conner, 1993) where it is now an established treatment methodology. S/S has been used to treat hazardous waste, residues from treatment processes and contaminated soils. Such methodologies have been mainly used to treat inorganic contamination but more recently some organic contamination has also been successfully treated (Conner, 1993; Al-Tabbaa and Evans, 1999). Initial treatments were carried out ex-situ but more recently in-situ treatments have also been applied (Harris et al, 1995a,b; Evans et al, 2001). Stabilisation, with chemical admixtures, for ground improvement purposes (Hausmann, 1999; Sherwood, 1993) is a technology which can be correlated with S/S treatments of waste and contaminated ground. S/S treatments have been carried out in the UK over the past 15 years.

Stabilisation/Solidification (S/S) treatments include a wide range of similar processes that usually involve mixing inorganic cementious binders, such as Portland cement, into the waste or soil to transform it into a new, solid, non-leachable material. The treated waste product encapsulates potentially hazardous contaminants, reducing contact between the waste and any potential leachant. In addition to encapsulation, various waste-binder interactions and chemical effects occur that lock contaminants into the product, further reducing the potential for pollutant transfer into the environment. Binders are usually selected according to some mix design criteria which depend on the application, which could be landfilling, redevelopment of a contaminated site or reuse of waste as aggregate in construction. Overviews of the basics of S/S technologies can be found elsewhere (LaGrega et al, 1994; Conner, 1993; Harris et al, 1995a,b; Evans et al, 2001).

LEGISLATION
The use of S/S treatment is compatible with UK and EU legislation. The recent EU Landfill Directive (European Council Directive, 1999) will have a significant impact on UK waste management. In particular, it will ban the co-disposal of hazardous and non-hazardous wastes and place bans or restrictions on the landfilling of liquid wastes and some other materials. The end of co-disposal in the UK and the associated requirements contained in the Landfill Directive mean that some form of waste treatment prior to landfill is likely to be increasingly required. An EU Technical Adaptation Committee (TAC) has the task of setting acceptance criteria for different classes of landfill and this will determine the degree of pre-treatment required. S/S technologies will almost certainly represent the most cost-effective treatment method available for major types of industrial wastes that are predominantly inorganic, and will likely be an option for organics as well.

The use of S/S is compatible with the Government’s approach to the remediation of contaminated land under Part IIA of the EPA 1990 (DoE, 1995) which is based on the principle of risk management and suitability for use. There is a legacy of contaminated industrial sites in the UK that require some form of treatment before they can be either redeveloped or otherwise re-used. This has become increasingly important in recent years, as greater environmental awareness and growing pressure on land resources have brought about the protection of greenbelt and agricultural land. The government has stated that it requires the construction of 2.4 million new homes by the year 2016, 60% on brownfield sites (Urban Environment, 1998). This has placed the onus firmly on the re-development of land originally used for industrial purposes. However, as a result of past usage, increased levels of pollution within the soil and
groundwater may preclude the site from immediate construction activity. Some type of ground remediation is therefore required, the choice of which is governed by performance, speed and economics. These requirements have promoted research into fast, effective and economical remediation techniques that enable future land commercialisation.

Immobilisation of contaminants in the ground using S/S treatment is emerging as viable and economic because of its advantages over other containment and remediation methods. None of the other remediation methods are completely effective and typical characteristics such as heterogeneity in soil and contaminant conditions, particularly in made ground soils, pose serious problems. Stabilisation/solidification is a remediation method, which without removal of the contaminants, prevents their further spreading and hence offers an immediate solution. It also offers rapid implementation of the treatment hence enabling immediate redevelopment of contaminated sites or reuse of waste materials. In addition, it is a cost-effective remediation method which is competitive with all other remediation methods including landfilling.

STARNET
STARNET is an EPSRC funded Network on ‘Stabilisation/Solidification Treatment and Remediation’. The overall aim is to build a Network of key participants who will work together to promote the development of research work on and implementation of UK S/S technologies. Its core membership includes leading UK scientists and engineers, organisations and regulators involved with S/S treatment technologies (Ground Engineering, 2001). This currently comprises Imperial College, Universities of Cambridge, Oxford, Greenwich, Newcastle, Birmingham and Surrey, TRL Limited, May Gurney Technical Services, British Nuclear Fuels, Environment Agency, Lafarge Cement UK, Buxton Lime Industries, MJ Carter Associates, Shell Research, CL:AIRE, CIRIA and SITA. Key scientific and technical issues for S/S technologies which will be addressed by the Network include:
(a) Binder selection;
(b) Technology selection;
(c) Testing and performance level;
(d) Long-term performance and environmental impact;
(e) Quality assurance and quality control issues; and
(f) Good practice guidance documents.
This three-part report deals with the first two issues. Future reports will deal with the remaining four.

COMMON BINDER SELECTION CRITERIA
Treatability studies are an essential part of an S/S treatment methodology during which the appropriate binder system is selected for a specific site and contaminants based on a set of design criteria. The design criteria used, in terms of specified properties or parameters and their target values, have usually depended on the properties of the end products required taking into account the nature of the material and contaminants being treated. In the US, some criteria were developed for the immobilisation of waste and have since been applied to the immobilisation of soils. Commonly used design criteria and typical target values have included:
(i) Unconfined compressive strength; >350kPa (soaked) at 28 days (USEPA, 1986);
(ii) Leachate pH; 7 to 11 (Conner, 1993; Harris et al, 1995a);
(iii) Leachability; using standard leaching tests such as the USEPA Toxicity Characteristic Leaching Procedure (TCLP test) (Federal Register, 1986), or the UK NRA leaching test (Lewin et al, 1994); acceptable limits are usually quantified using a multiplier of drinking water standards, commonly 100 (Conner, 1993);
(iv) Permeability; <10⁻⁹m/s (as for cut-off walls).
(v) Freeze-thaw and wet-dry durability; pass in the ASTM tests (ASTM, 1988; 1990);
(vi) Acid neutralisation capacity (ANC); using the Environment Canada test method (Stegemann and Coté, 1991). ANC is a measure of the stability of the chemical environment in the contaminated material, relating particularly to its ability to immobilise metals (Stegemann and Coté, 1990).
Microstructural analyses have also been used to examine the development of the hydration products and their interaction with contaminants.
Design criteria and target values should be selected to meet site-specific requirements, in terms of the required mechanical properties and acceptable levels of leaching.

BINDERS IN S/S TREATMENT SYSTEMS
This section provides general information on available binders in the UK; their properties, applications and advantages and disadvantages.

Cement
Cement, a material used since the time of the ancient Romans, is frequently employed as the binder in S/S of contaminated material, be it as a means of pretreatment prior to disposal to landfill or treatment of contaminated land. The two major raw materials used in the production of cement are clay or shale which provides the alumina and silica, and limestone or chalk which is the calcereous material. Various types of cements have developed over time but the most commonly used for S/S is ordinary Portland cement (OPC), with calcium aluminate cement (CAC) also being considered in some work (LaGrega et al, 1994, Conner, 1993). The manufacturing process involving these various types has been standardised throughout the world, therefore the resulting product composition lies within a narrow band and any variation is mainly attributed to the difference in composition of the individual raw materials.
Extensive literature exists regarding the chemical reactions that take place when cement combines with water, a process known as hydration, which describes all the chemical reactions. However, these reactions are complex and different workers emphasise different mechanisms. But whatever the model, it can be stated that the same basic reactions occur (Connor, 1993). The cement sets, hardens and gains in strength as a result of
these reactions. When water is added to cement each of the major phases hydrate, but the products formed, the rates of reaction and their contributions are different. In the case of OPC, the two calcium silicates, C₃S and C₂S, are the main cementitious compounds and are responsible for the strength developed after initial set. They both give the same reaction product which is calcium silicate hydrate (CSH) and crystalline calcium hydroxide (CH).

In cement-based stabilisation the contaminated material is mixed with the cement and water added. In some cases water if not needed as the waste itself contains sufficient water. In this process immobilisation is achieved by physical entrapment of the contaminants within the cement paste matrix and/or by the reaction of the contaminants directly with the compounds formed during hydration (Harris et al., 1995a). Cement-based stabilisation is best suited for inorganic wastes, in particular those containing heavy metals (LaGrega et al., 1994). For example the metal cations may be retained in the form of insoluble hydroxide salts within the hardened structure as a result of the high pH of the cement. Some of these metals are likely to be bound in the matrix due to chemical fixation, whereas others are immobilised due to physical encapsulation. Although inorganic wastes are best suited to OPC, some inorganic compounds strongly affect the setting, strength development and final strength of the binder (Taylor, 1990).

Organic contaminants can be more problematic by interfering with the hydration process. Thus the final strength is reduced and stabilisation impaired due to the reduction in the formation of the crystalline structure resulting in a more amorphous material (LaGrega et al., 1994). Additives, such as pulverised fuel ash (PFA) and ground granulated blastfurnace slag (GGBS), are sometimes used as partial replacement material for cement (Al-Tabbaa and Evans, 1998; Stegemann et al., 1997; Stegemann and Shi, 1997). Other binders such as calcium sulphaaluminate cement (CSA) have also been investigated (Blue Circle Industries, 2001).

Blastfurnace Slag

Blastfurnace slag is obtained from the manufacture of pig iron and contains silica, alumina and lime (Neville and Brookes, 1993). There are many types of slag mentioned in the literature, with little attempt to distinguish between them (Harris et al., 1995a). Further details to be included here from (Dunster, 2001). They are not the same as pozzolans, in that the nature of the reactions and the reaction products are different (Harris et al., 1995a). Hence, the ability to react with and bind contaminants also differs. Ground granulated blastfurnace slag (GGBS), which is the type most available in the UK, is classed as a latent hydraulic cement with compositions broadly intermediate between pozzolanic material and Portland cements (Taylor, 1990).

The hydration of slag is initiated when lime provides the correct alkalinity, but subsequent hydration does not rely on lime. Reactivity depends on factors such as bulk composition, glass content and the fineness of the grinding and the relationship between composition and glass content is quite complex (Taylor, 1990).

GGBS is available as a separate ingredient to be added to treatment systems at the point of mixing either alone or with other binders, and as blends in various proportions with Portland cement. Because these could be used as partial replacement material for cement, they bring about cost savings on treatment. Further, work by Allan and Kukacka (1995) has shown that blastfurnace slag in grouts with OPC and bentonite has stabilised soils contaminated with trivalent and hexavalent chromium, whereas normally the hexavalent chromium needs to be reduced to its less toxic and less mobile trivalent form prior to solidification.

Pulverised Fuel Ash

Pulverised fuel ash (PFA) is a synthetic pozzolana created by the combustion of coal. Generally two types of PFA exist, namely low-lime PFA and high-lime PFA. The UK ashes are generally classified as low-lime PFA. The material consists mostly of glassy, hollow, spherical particles called cenospheres. PFA can be described as a siliceous and alumina material which on its own possesses little or no cementitious value. However, in a finely divided form and in the presence of moisture it will chemically react with lime to form compounds possessing cementitious properties (Neville and Brooks, 1993). Lime is needed to promote the pozzolanic reactions. However, not all types of PFA exhibit good pozzolanic properties (Harris et al., 1995a). The reactivity appears to depend upon the nature and proportion of the glass phase present (Dhir, 1986). The stabilisation effect of PFA relies on the formation of calcium silicate gels which gradually harden over a long period of time to form a stable material (Harris et al., 1995a). Although slow to harden, the hydration products may be similar to those of OPC (Taylor, 1990), indicating PFA’s potential as a binder.

PFA-lime products containing waste possess favourable leaching characteristics, especially for wastes containing heavy metals, where the metal ions may be chemically bound to the hydrate complexes. It is thought that the unburned carbon content in PFA generally acts as a sorbent for certain wastes including organics (Barth et al., 1990; LaGrega et al., 1994). Thus, PFA may be suitable for the stabilisation of both inorganics and organics. However, in general PFA-lime solidified waste products are less durable and have higher leaching rates than those containing cement (Harris et al., 1995a).

PFA is frequently used together with cement, with the amount of replacement depending on the requirement of the end product whether concrete or an S/S product. When used as a replacement material, PFA affects both the solid and paste phases of OPC by producing a complex interaction within the fresh system (Dhir, 1986). PFA also plays a multiple role in the hydration of blended cement systems. The hydration itself is similar to that when the materials are considered separately except for certain variations. The hydration reactions are initially retarded by the presence of PFA due to Ca²⁺ and SO₄²⁻ from PFA combining to form additional gypsum which retards the C₃A hydration reaction (Dhir, 1986). However, PFA
can accelerate the hydration of the silicate phases, especially C$_2$S, because the surfaces act as additional sites for nucleation of CSH (Taylor, 1990). The pozzolanic reactions of PFA in the mix are promoted by the CH produced from the hydrating OPC. The CSH gel produced generally has a lower Ca/Si ratio than for OPC and this is attributed to the lowering of the Ca$^{2+}$ in the pore solution.

**Lime**

Although several forms of lime exist, generally it is only quicklime (calcium oxide) and hydrated lime (calcium hydroxide) that are used as binders. Quicklime, which exists either in granular or powder form, is produced from heating chalk or limestone, and hydrated lime, which is generally available as a fine, dry powder, is produced as a result of the reaction of quicklime with water. In dolomitic lime magnesium replaces some calcium and grey (hydraulic) lime produced from impure forms of calcium carbonate may contain some clay (Sherwood, 1993). The materials generally treated using these limes are fine-grained soils, ranging from clayey gravels through to clays, and some industrial byproducts such as fly ash (Buxton Lime Industries, 1990).

However for the purpose of S/S, lime is used to control the pH of the waste form so as to keep the metals in the range they are least soluble, with a compromise being needed on pH control when several metals are present (Conner, 1993). However, due to the difficulty in controlling the pH, lime is generally used with other reagents such as cement, FFA and carbonate ions. Additives such as hydrophobing agents, surfactants or silicates to improve properties and reduce permeability (Conner, 1993). Further, lime can also be used to treat wastes containing components such as alumina and silicates which react with the calcium in lime to give materials with cementitious properties (LaGrega et al., 1994). However, in general the main processes involving lime in S/S are lime/clay and lime/PFA processes (see above).

In the case of lime/clay processes the addition of lime to clayey soils initiates several reactions which alter the physico-chemical properties of these soils bringing about both immediate and long-term changes. When quicklime is added it initially reacts exothermically with the water to give hydrated lime. The dehydration of the system by reaction and by steam generation can result in benefits purely as a result of de-watering. Further, a decrease in the plasticity of clay is also associated with this reaction, which is caused by the flocculation of clay particles (Glendinning et al., 1998). This immediate modification occurs as a result of cation exchange of calcium ions for existing cations such as hydrogen and sodium ions on the clay minerals. The degree of cation exchange will depend on the mineralogy, soil composition and pore water chemistry.

In the longer term another reaction process occurs as a result of pozzolanic reactions, bringing about physico-chemical changes to lime-clay systems. This occurs when sufficient lime (quicklime or hydrated lime) is added to the soil. The lime added creates a high alkaline environment which promotes the dissolution of silica and alumina from the clay in the soil or in the impure hydrated lime. These dissolved components permit the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) gels by reacting with the calcium ions in the pore water, which in turn treat the contaminants in a manner similar to when using cement as the binder.

Although the basic reactions are widely reported (Glendinning et al., 1998; Sherwood, 1993) many issues still remain unresolved. These include the mechanisms that bring about the observed changes, the time-scale over which the reactions occur and whether the reactions occur sequentially or concurrently.

**Natural bentonite clays**

Bentonite is classed as a clay which is formed by the decomposition of volcanic ash. It is characterised by the clay mineral montmorillonite which is a dioctahedral smectite and is chemically classified as a hydro-alumino-silicate (Weinmann, 1998). The hydration of bentonite particles produces a suspension with a gel-like structure (Spooner et al., 1984). Bentonite has high water absorption potential, swelling properties and a significant cation exchange capacity (CEC) due to its large surface area, thus having a high capacity for the adsorption of contaminants. Further, it has a small particle size, which helps in reducing the permeability, high liquid and plastic limits, which provide a flexible material, and a high base exchange, which is advantageous when treating heavy metals. Bentonite has good adsorption characteristics for heavy metals, radioactive substances and polar molecules. Therefore, bentonite is a suitable material for the immobilisation of many contaminants. However, the presence of organic and inorganic chemicals in contaminated groundwater may have detrimental effects on the ability of bentonite to contain contaminants (Spooner et al., 1984). Although suitable as a binder in its own right, bentonite is generally used with other binders, especially cement, for treating contaminants.

**Organophilic clays**

Organophilic clays are produced from natural clays such as Wyoming bentonite by increasing their adsorptive capacity by chemical treatment. This is accomplished by various reactions such as adsorption, ion exchange and intercalation. The modification process is achieved by replacing the inorganic cations (sodium, calcium, magnesium), within the clay crystalline structure with organic cations, such as quaternary ammonium salts (LaGrega et al., 1994). These have an affinity for other organic molecules which are absorbed and then widen the interplanar distance in the presence of organic contaminants.

Although these clays can be used alone to remove certain contaminants, they are more effective in treating wastes when used together with conventional binders such as cement. In the latter scenario, the organophilic clays are ideally mixed with the waste first and allowed to absorb the organic contaminants prior to the addition of an S/S binder which is used to encapsulate the material within the monolithic mass (LaGrega et al., 1994). In some cases other reagents such as co-
precipitating, redox potential modifying and hydrophobic agents are added (Harris et al, 1995a).

**Bitumen**

Bitumen occurs in natural asphalt or can be obtained from petroleum and consists mainly of hydrocarbons. It can be in the form of a solid or viscous liquid. However, bitumen in its natural form is too viscous and has to be made more fluid prior to use in S/S. There are typically two such fluid forms of bitumen that are used, viz. cutback bitumen or bitumen emulsion (Sherwood, 1993). Cutback bitumen is a solution of bitumen mixed in paraffin and/or diesel and bitumen emulsion is a suspension of bitumen particles in water. In both cases the bitumen is deposited on the waste material. In the first, this occurs when the solvent evaporates and in the second, when the emulsion breaks down. Bitumen however acts as a binding agent and does not react chemically with the material like cement and lime. Therefore bitumen simply sticks to the particles and thereby forms a fairly water tight material. Sherwood (1993) classes bitumen as a primary stabilising agent along with cement and lime.

**Waste binders**

Certain materials that might be considered as waste have been investigated as chemical binders because of their capacity to sorb various contaminants and also their low cost. Examples of such materials which have been tested include granulated tyre, wood shavings, straw and used peat (Kershaw & Pamukcu, 1997, Ajmal et al. 1998, McKay & Porter, 1997).

**Proprietary Binders**

**Geodur**

The Geodur system was developed by the Swiss company Geodur CIS. Although the exact composition of the Geodur additive is not disclosed, it is known that the additive is synthesised from a number of compounds. This proprietary additive is usually used together with a cementitious binder to promote additional bonding when mixed with contaminated soil or industrial waste. Several chemical mechanisms are proposed, including formation of hydroxides, formation of complexes between Geodur ligands and the contaminants and chemical molecular binding of Geodur components with both inorganic and organic chemicals in addition to several physical mechanisms, including increased density and reduced surface area. This therefore results in immobilisation of contaminants together with increased strength and reduced permeability of the material. The composition of the Geodur additive and the design mix need to be varied to suit a given application and contaminant mix (Jardine and Johnson, 2000).

**Pillared clays**

Naturally occurring bentonite clays are used to produce these clays by the addition of special chemical reagents to push the clay layers apart. Pillaring agents such as iron and aluminium compounds can be used to increase the spacing, with the clay layers being held apart by the reactive polymer compounds which act as molecular ‘props’ within the intercalated layers into which large organic molecules can be sorbed (Lundie and McLeod, 1997). One such process, the EnviroTreat process (McLeod, 1998), uses special aluminium pillaring agents to achieve this effect. The modification process can be carried out in two stages and has a two fold effect. In stage one a series of reagents are introduced into the clay to create an organophilic environment for the fixation of contaminants such as PCBs and PAHs. These reagents together with the addition of cementitious materials combine to provide an effective permanent fixation of contaminants which include certain organics and inorganic compounds and heavy metals. The second stage involves the addition of pillaring agents which can generally open up the clay configuration, allowing the clay to act as a molecular sieve by treating groundwater when it comes in contact with the reactive reagents introduced in the first stage. The E-clays are a particular form of pillared clays patented by EnviroTreat. However, many different types of pillared clays can be used for a similar purpose.

**Limbase products**

Buxton Lime Industries have developed a product range termed ‘Limbase’. It is specially formulated quicklime for use in soil stabilisation, and is produced by using high purity limestone to yield high reactivity quicklime with the maximum available lime content. Limbase soil stabilisation has been used for over 20 years in UK to treat soils by the addition of lime, or lime and cement, by offering strength, volume stability, durability and reduced moisture content. However, it has now been shown that the strong impermeable material that is achieved by this process provides a medium for encapsulating contaminants, especially heavy metals, within the soil. The highly impermeable material induces macro-encapsulation of contaminants and also prevents the passage of water. This, together with the other mechanisms such as microencapsulation, adsorption and precipitation of insoluble salts, are the processes that are said to make this a highly effective treatment for contaminated soils (Buxton Lime Industries, 1996).

**EnviroOceM Family**

Lafarge EnviroOceM Solutions has developed a range of special cements – EnviroOceM Family (Blue Circle Industries, 2000). These have been developed to outperform Portland cement in S/S of soils and wastes. EnviroOceM sludge stabilisation products are fast setting rapid hardening powders.

**Interaction between binder and waste**

It is a well-known fact that binders interact with various materials, whether chemical compounds in the waste or the waste material itself. A considerable amount of research has been carried out mainly in the US on interactions between specific chemical compounds, specific waste materials and specific binders and recommendations have been produced in the literature on materials which affect S/S (Spooner et al., 1984; Conner, 1993; LaGrega 1994; USEPA, 1999). Compatibility between the binder and the waste is clearly a major aspect which needs to be taken into account in the selection of appropriate binders.
IMPLEMENTATION PROCESSES FOR S/S TREATMENT SYSTEMS

This section provides general information on available process technologies based on in-situ and ex-situ operations. In-situ (or in-place) operations refer to all processes taking place within the ground including locations such as lagoons while ex-situ operations refer to all processes taking place away from the original contamination location either on-site or off-site (Conner, 1993; LaGrega et al, 1994; Harris et al, 1995b; Evans et al, 2001).

Ex-situ S/S implementation processes

Commercial ex-situ mixing can involve one of three main methods: plant processing, direct mixing (area mixing and layering) and in-drum processing (Conner, 1993; LaGrega et al, 1994; Harris et al, 1995b; Evans et al, 2001).

Plant processing: In plant processing the contaminated material is mixed with the appropriate binder, and other additives if necessary and in some cases after some form of pre-treatment, and the treated material is then placed at its final disposal site. The mixing plant could be fixed (off-site) or mobile (typically on-site) and is designed specifically for this purpose or adapted from other applications such as concrete batching and mixing. A schematic illustration of a typical ex-situ S/S system is shown in Figure 1. The mixing is carried out with mechanical mixers using either batch or continuous processes. In a batch process the required amount of contaminated material and binder(s) are added and blended for a fixed amount of time. In a continuous process the contaminated material and binder(s) are added and blended continuously. The required contact time for this process is achieved by controlling the feed and mixing equipment. The final disposal location could be on-site or off-site. On-site would typically mean that the blended material is placed back in its original location, compacted using suitable plant and left to cure in-place.

Direct mixing: Direct mixing involves the transport of the contaminated material to a designated final disposal area, which could be on-site or off-site. The material is spread out in layers along with the binder(s) and is mixed in-place using appropriate mechanical equipment. The blended material is then compacted and left to cure in-place.

In-drum processing: In in-drum processing the binder(s) is added to the contaminated material which is placed in a drum or similar container which initially acts as the container for the mixing and then for setting and hardening. Once hardened the treated material along with the drum are disposed of together. Normally the mixing paddles are left in the drum after mixing and are also disposed of.

There are subtle differences between those three mixing methods. This is mainly based on the type of plant, contaminated material being handled and method of disposal. Generally, a batching plant, e.g. Belmix 50 as shown in Figure 2, is needed for the processing of the contaminated material, the installation of which could be fixed or mobile. The handling capacity of the fixed installation could vary from small to large and the mode of operation could be batch or continuous operation. Generally the smaller handling capacity installations are batch processing plants and as the plant becomes larger the process involved changes from batch to continuous feed. An example of a fixed plant is shown schematically in Figure 3 for the treatment of electric arc furnace dust.

However, the system may be different for wastes which are pumpable, and also in the case of contaminated soils and other such contaminated material, where the material will be stored as stockpiles instead of in silos. These fixed installations will normally have their own peripheral plant, equipment and storage, and would accept a wide range of contaminated material for treatment. The mobile plants on the other hand are becoming more popular with the increase in ex-situ treatment on-site. These usually comprise of a treatment unit with the chemical storage, metering, and mixing equipment necessary to mix the contaminated material with the binders and discharge to a holding or disposal area (Conner, 1993). The plant might comprise of components for the purpose of getting the contaminated material from its location, homogenising it and transporting it to the treatment unit. The plants for handling pumpable contaminated material and non-pumpable contaminated material are generally different from each other as can be seen in Figures 4 (a) and (b) respectively. However, there are mobile plants which accommodate both liquid and solid contaminated material with some modification being incorporated to suit either type.

The mode of delivering the material to the plant is different depending on the plant type, form of the contaminated material and available equipment. In the case of pumpable material the feed could be directly pumped, but the waste may need to undergo some modification if being taken to a fixed installation for treatment. For non-pumpable material the waste may be delivered to the receiving point of the plant by means such as backhoe, front loader, clamshell bucket or dumped directly by tipping lorries and then the material conveyed into the mixer (if the mixer is not the receiving point).

Several types of mixers exist for the purpose of mixing the contaminated material, binder and water. One such type is the pugmill and examples are shown in Figure 5. In such a mixer, if the process is being performed as a continuous operation then the residence time required for mixing is obtained by opening and closing the dam gate at the exit, or by controlling the drive speed. Further, there are variations in the design of the blades to achieve improved mixing.

Once treated, the material is pumped, in the case of pumpable material, directly to the disposal area, conveyed/deposited directly onto dumpster trucks which will transport it to the disposal site or conveyed onto stockpiles for collection and disposal. In the latter two scenarios the treated material may be disposed off in landfill, spread and compacted at a designated area or in some cases re-used as a construction material.

In most ex-situ S/S treatment cases pre-treatment in the way of screening is required to prevent the larger lumps from entering the system to avoid damage to the mixer type equipment. These may be crushed and
screened again or are kept separate for disposal to landfill.

Each of the methods described above has its own advantages and disadvantages. Plant processing is generally the preferred method for ex-situ mixing as it ensures adequate mixing and reduces release of particulates and vapours. It can also accommodate a high rate of production, typically ranging from several hundreds to several thousands of cubic meters per day. Direct mixing is suitable for treating contaminated soils or high solids content contaminated material, but is not suitable for treating liquid-like contaminated material. This method requires a relatively large land area and also poses the greatest risk in terms of the generation of dust, vapour and odour. In-drum processing is suitable for treating toxic and radioactive material and gives the added protection of being carried out in a container thus avoiding direct contact with the environment in the shorter term. However, the integrity of the drum is not considered in the longer term and hence might disintegrate with time in the disposal site. The rate of production is relatively low in this process when compared to the other two methods.

Another selection criterion is cost. A typical exercise carried out to depict the relevant costs involved in the treatment operation for different approaches such as in-drum, plant mixing pumpable and unpumpable, and area mixing showed to be £180, £31, £38 and £30 per tonne respectively (Harris et al., 1995a). This exercise assumed the same reagent mix comprising 30% Portland cement and 2% sodium silicate, and process capacities and production rates were varied to accommodate double, triple or quadruple set-up. The base machine for the augers can vary from small hydraulic excavator to large piling rigs. The grout withdrawal are applied to further break down the soil and/or improve the blending between the binder and the contaminated material. The major system components such as delivery of grout are automatically controlled to ensure precise delivery. All soil mixing applications in the UK for the purpose of S/S treatment have been performed using wet binders.

Typical examples of the different configurations of deep soil mixing augers and set-ups available in the UK are shown in Figures 7(a) to (d), which show augers by the contractors May Gurney Technical Services, Bachy Soletanche, Keller Ground Engineering and Hercules respectively.

May Gurney Technical Services carry out soil mixing operations using single hollow shafted augers which is manufactured in house, Figure 7(a), and are usually attached to modified piling rigs. Several such augers have been developed for various jobs and applications. These augers have been used to treat hotspots as mass blocks, to create containment systems involving reactive and passive barriers and also to incorporate other facilities such as ground improvement. Such scenarios are shown in Figures 8(a) to (d) (May Gurney Technical Services, 2001). The grout is mixed at a batching plant located centrally on site and the slurry is pumped from an agitator via dedicated pipes to each of the hollow stem augers and the slurry is injected to the soil through ports in the shaft at the auger tips.

Bachy Soletanche use the multiple overlapping counter-rotating continuous flight augers, Figure 7(b), the process usually referred to as the Colmix process (Wheeler, 1995; Bachy, 1999). The auger geometry can be varied to accommodate double, triple or quadruple set-up. The base machine for the augers can vary from small hydraulic excavator to large piling rigs. The grout slurry is pumped in the same way as in the May Gurney augers above.

Keller Ground Engineering utilise purpose built blending injection augers together with powerful high torque boring units (Keller Ground Engineering, 2001). The process involves rigorous rotary mixing and direct binder injection through ports along the blades of the auger rather than ports on the hollow shaft, Figure 7(c). Keller used soil mixing as part of the site remediation contract on a disused chemical factory in the North of England to neutralise the chemical waste found in the upper 4m of the ground which had arisen from years of production spills. In addition it also helped to provide
an increased uniform ground bearing pressure for this weak water bearing soil.

Hercules Grundlagning AB (Hercules) uses a single auger system to deliver and mix soil with dry binders (Hansson, 2001). There are two types of equipment set-up, an installer connected to a carrier or an installer with rear-mounted silo (Figure 7(d)). A purpose built single auger such as that shown in Figure 7(d) is used with either set-up. The binder is fed using compressed air from a bulk trailer to an intermediate storage tank and then transported from there to the carrier. It is then transported from the carrier using compressed air through a nozzle down the hollow auger shaft and out through port on its tip.

Deep soil mixing with dry binders has mainly been used for the improvement of soft uncontaminated soils but could have applications in the S/S of contaminated materials. The former application has been pioneered in Sweden and contractors like Hercules using the augers shown in Figure 7(d). Recently the first case of dry soil mixing for ground improvement was performed in the UK as part of the Channel Tunnel Rail Link Contract 400 (Hansson et al, 2001). A 800mm diameter mixing auger was used with rotational speed of around 200rpm and a withdrawal rate of 10mm/rev. As this system uses a dry binder it required the soil to contain a natural moisture content in excess of 20%.

Shallow mixing augers are single shafted, with a large diameter generally ranging from 1 to 4m and are used to mix contaminated material down to a depth of about 10m. Mixing augers usually consist of cutting and mixing sections of which a number of different designs have been developed by the different contractors. A typical example is shown in Figure 9(a).

Other augers available worldwide include those by the contractors Geo-Con and Seiko Kogyo which have been used in USA and Japan. These tend to be multi-shafted augers in a row, and have different blade designs for different soil conditions as shown in Figures 9 (a) - (c). Seiko Kogyo (Seiko Kogyo, 1999) designed three major styles of auger systems to be used in different soil conditions:

(i) the general purpose auger which is designed to be used in average soil conditions and consists of mixing paddles and short lengths of auger flights to move the soil both in the horizontal and vertical direction,

(ii) the cobbler auger which is similar to the above auger except that the spacing between the mixing paddles and auger flights are opened up to allow fairly large cobbles to be effectively mixed into the panel and

(iii) the mud auger is designed for use in soft cohesive soils and consists of short sections of auger flights.

In addition to the above various drill heads and cutting teeth to complement them have been designed for use in specific soil conditions.

In-situ S/S using augers is gaining commercial popularity especially in Europe and USA, as a rapid, cost-effective and safe methodology which uses well-established conventional techniques. An overview of the technology can be found elsewhere (Wiles; 1987; Harris et al, 1995b; Porbaha, 1998; Porbaha et al, 1998).

Shallow soil mixing also includes the use of Backhoe, blenders and mixers. The backhoe, an equipment readily available and commonly used in the construction industry, has been used for the in-situ mixing of wastes in lagoons and shallow contaminated soils for many years. In this process the reagent is introduced to the surface of the waste by pneumatic or mechanical conveyance, where it is mixed using the backhoe. The process maybe repeated until sufficient reagent is added to produce an acceptable solid. However this process, which is fairly crude, produces dust and the mixing is generally not very thorough. As a result of the latter, this method is not recommended for work where fixation is required (Conner, 1993).

Another variation to the backhoe is the in-situ blender (Figure 10(a)), where a mechanical excavator arm is fitted with a rotary mixing head where an aggressive mixing action can be produced with relatively slow rotational speeds. Similarly the binder is supplied separately but the lack of proper mixing and loss of reagent due to dust saw the development of more sophisticated binder feed and mixing systems which have been incorporated onto the backhoe arm (Conner, 1993). Figure 10(b) shows a schematic view of one such modified system in which the hollow tubes convey the binder below a sludge waste surface. This minimises dust and in turn maximises binder usage. The rest of the assemblage mixes the binder into the waste as it is moved. Another injection system is shown in Figure 10(c) where the end of each injection tube has a motor-driven mixer assembly to achieve better mixing. The reach and working depths in these systems are restricted by the size and power of the backhoe.

Other in-situ injection/mixer types suitable for shallow lagoons and contaminated soil areas include the two systems shown in Figures 10(d) and (e) (Conner, 1993). The first, Figure 10(d), has a hollow tube injector which is mounted on a tractor and pulled through the waste (like tilling a field). This is suitable for situations where high energy mixing is not required. The second system, Figure 10(e), which is also mounted on a tractor uses a rotary tiller to achieve more thorough mixing. This is suitable for situations requiring high energy mixing. Both these systems are suitable for stabilising high solids systems.

With liquid-like contaminated material, for example that present in lagoons, mechanical mixing is carried out in the location of the contaminants using appropriate equipment such as backhoes and draglines. The material once treated is left in place to set or once sufficiently hardened is excavated and transported to landfill, the former being the typical scenario.

O’Keefe Soil remediation in the UK uses specialised machinery to stabilise soils, especially clays, by direct mixing either in-situ or ex-situ once the soil is laid in place. The usual process is to spread the dry binder on the soil and then to use the machine’s mixing drum (Figure 11) to mix it into the soil, while the soil is cut and pulverised (O’Keefe Soil Remediation, 2001). Additional binders are then added and mixed in a similar manner, if required and the treated soil is then compacted. In order to overcome the problem of airborne dust, O’Keefe modified their machine. The modified machine, Wirtgen WR2500
(Figure 11), was extended in length to accommodate a four-tonne hopper in the middle to feed the lime right in front of the milling drum (Construction News, 1998). This modified machine was the first of its kind in the world with other similar machines being produced thereafter in other European countries (Construction News, 1998).

(ii) Pressure mixing: This method is similar to conventional grouting and involves injection of binders under pressure directly into the contaminated material. However, this method has not been developed on a commercial scale. This is due to the difficulty in ensuring even permeation of the treatment grout into the ground and the fact that depths in excess of 2m are usually required to ensure that there is sufficient overburden pressure to withstand the injection usually required (Harris et al, 1995b; Evans et al; 2001). This method is hence not discussed any further.

The selection of the appropriate S/S implementation process depends on a wide range of factors which include, amongst others, waste characteristics, material handling and processing, objectives, regulatory requirements, and economics (Wiles et al, 1989). Table 1 gives the principal advantages and disadvantages of ex-situ and in-situ implementation systems (Evans et al, 2001) with specific references to contaminated soils only. Ex-situ implementation was the method more commonly used until recently when a number of in-situ implementation techniques were used commercially in the UK.

CONCLUSIONS
This paper presented an overview of binders and technologies which are available for use in stabilisation/solidification treatments in the UK. It is clear that numerous binders and technologies exist which have been successfully used world-wide and in particular in the USA and France. It is also clear that many binders and technologies are site specific hence a considerable amount of research is needed to access the validity of certain binder and technologies on specific sites.

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 to the report and in particular to Murray Reid and David Johnson for their comments on the draft report.

REFERENCES:


<table>
<thead>
<tr>
<th>Advantages</th>
<th>In-situ process</th>
<th>Ex-situ process</th>
</tr>
</thead>
<tbody>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td>• recently developed in-situ equipment allows controlled reagent injection and mixing, as well as effective control of both volatile and particulate emissions</td>
<td>• a single plant at a central location can treat material from many sources thus minimising plant mobilisation costs</td>
</tr>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td>• little or no secondary spoil generation</td>
<td>• provides better control of reagent addition and mixing than in-situ</td>
</tr>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td>• low levels of noise and vibration</td>
<td>• quality control sampling is easier than in-situ</td>
</tr>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td>• allows treatment close to structures where excavation could cause damage</td>
<td>• suitable for site remediation at shallow depths, i.e., where groundwater or support of adjacent land is not an issue</td>
</tr>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td>• no requirements for excavation or ground control</td>
<td>• tolerant of unstable soil surface or soils with low bearing capacity</td>
</tr>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td></td>
<td>• may be included as an additional component of treatment processes such as soil washing</td>
</tr>
<tr>
<td>costs are typically lower for large and deep remediation projects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• the cost may be higher than for in-situ mixing for large remediation projects at substantial depths</td>
</tr>
<tr>
<td>costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• small sites may not accommodate in-situ mixing equipment and associated batching plants</td>
<td>• material may have to be excavated and transported to the treatment plant</td>
</tr>
<tr>
<td>costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• the bearing capacity of the ground must be sufficient to support the in-situ mixing equipment</td>
<td>• practical considerations regarding excavation may preclude treatment where depth of contamination is significant</td>
</tr>
<tr>
<td>costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• presence of underground services may complicate operations</td>
<td>• disposal arrangements must be made for cemented waste</td>
</tr>
<tr>
<td>costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• physical obstructions and clays, oily sands and cohesive soils may reduce auger penetration rate and depth of operation</td>
<td></td>
</tr>
<tr>
<td>costs for small remediation projects may be strongly influenced by plant mobilisation costs</td>
<td>• made ground may have to be excavated in advance of mixing</td>
<td></td>
</tr>
<tr>
<td>disadvantages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>disadvantages</td>
<td>• the cost may be higher than for in-situ mixing for large remediation projects at substantial depths</td>
<td></td>
</tr>
<tr>
<td>disadvantages</td>
<td>• material may have to be excavated and transported to the treatment plant</td>
<td></td>
</tr>
<tr>
<td>disadvantages</td>
<td>• practical considerations regarding excavation may preclude treatment where depth of contamination is significant</td>
<td></td>
</tr>
<tr>
<td>disadvantages</td>
<td>• disposal arrangements must be made for cemented waste</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Advantages and disadvantages of in-situ and ex-situ S/S implementation systems and their suitability to contaminated soils (Evans et al, 2001).
Figure 1. Schematic diagram of a typical ex-situ S/S system (Harris et al., 1995a).

Figure 2. Batching and mixing operation (Jardine and Johnson, 2000).
Figure 3. Schematic diagram of an electric arc furnace dust treatment plant (Conner, 1993).

Figure 4. Schematic diagram of a typical mobile treatment unit for (a) pumpable waste and (b) non-pumpable waste (Conner, 1993).
Figure 5. Pugmills with different blade designs (British Cement Association, 2001; Cheeseman, 2001).

Figure 6. Examples of constructed column using soil mixing augers: (a) overlapping configuration (SMW Seiko, 1997) and (b) barrier wall configuration (May Gurney Technical Services, 2001).
Figure 7. Examples of soil mixing augers available in the UK and owned by contractors: (a) May Gurney Technical Services (May Gurney Technical Services, 2001), (b) Bachy Soletanche (Bachy, 1999), (c) Keller Ground Engineering (Keller Ground Engineering, 2001) and (d) Hercules (Hansson, 2001).
Figure 8. Scenarios of soil mixing applications by May Gurney Technical Services: (a) active containment, (b) passive and active containment, (c) with development piles and capping, and (d) funnel and gate (May Gurney Technical Services, 2001).
Figure 9. Examples of other auger systems (a) shallow mixing auger (Geo-Con, 1991), (b) multi-shafted augers (Geo-Con, 1991), and (c) multi-shafted augers (SMW Seiko, 1997).
Figure 10. Examples of backhoes, blenders and mixers: (a) in-situ blender (British Cement Association, 2001), (b) schematic of an in-situ injection type backhoe system (Enrico Inc.)(Conner, 1993), (c) in-situ injection type backhoe system (Harmon Environmental Services Inc.) (Conner, 1993), (d) hollow tine injector mounted mixer (Conner, 1993), and (e) rotary tiller type mixer (Conner, 1993).

Figure 11. Wirtgen WR2500 soil recycling machine and variable depth granulating and mixing drum (O’Keefe Soil Remediation, 2001).