# Risks of Contaminated Land to Buildings, Building Materials and Services

A literature review

**Research and Development**

**Technical Report**

**P331**

ENVIRONMENT AGENCY

# Risks of contaminated land to buildings, building materials and services

A literature review

R&D Technical Report P331

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Research Contractor:
BRE (and M A Smith Environmental Consultancy)

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# EXECUTIVE SUMMARY

This literature review is concerned with the risks from contaminated land to buildings, building materials and services and provides a summary of relevant international literature that is available on the subject. The report is structured into five sections, as follows:

Section 1 Introduction
Section 2 Building materials in contaminated land
Section 3 Subterranean fires
Section 4 Building on fill
Section 5 Expansive slags

In 1994 the Building Research Establishment (BRE) published BRE Report, BR255, the performance of building materials in contaminated land. This was an extensive report covering the mechanisms of chemical attack by contaminants on building materials and aspects of risk management. In the intervening period there has been research reported on the performance of building materials in aggressive environments. Whilst not all of this research is specific to the contaminated land environment, other aggressive situations are relevant and guidance can be developed from these situations.

The sections on subterranean fires and risks posed by expansive slags cover specific problems. Whilst these risks are of concern they affect only a limited number of contaminated sites in the United Kingdom. In addition, the volume of literature that has been published on these aspects is small by comparison with aggressive attack on building materials. Geotechnical risks are not unique to contaminated ground. All sites should be assessed with regard to the presence of fill or other potential hazards. Consequently, the section on geotechnical risks provides only a brief resume of the current situation.

The review process comprised the following stages:

- Extensive searching of Chemical Abstracts, BRIX (building research index) and other databases has been undertaken. Papers gathered by BRE in recent years have also been included. Identification was made of several hundred potentially useful papers through these sources.
- A sifting process that used the abstracts of the papers to narrow this review to one hundred papers. These papers were ordered and reviewed (in addition, a number of others were already known to BRE, e.g. work by the Water Research Centre (WRc) and the Construction Industry Research and Information Association (CIRIA)).
- Preparation of this review included adding nearly 60 papers on top of those already cited in BRE Report BR255 (1994) all of which remain valid sources of reference.

The health and safety risks of landfill gas to building occupants are widely acknowledged. However, this review does not attempt to cover these issues as they are well covered elsewhere and guidance on protection of buildings and risk assessment has been developed.

The report has been structured so that each section can be used as a stand-alone document. References, tables and figures are grouped at the end of each section.

# Keywords

Buildings

Combustible Materials

Contaminated Land

Contaminants

Contamination

Concrete

Brick

Blocks

Mortar

Steel

Copper

Lead

Plastics

Reinforced Concrete

Rubbers

Sulfate

Sulfide

Acid

Chloride

Risk

Hazard

Subterranean Fires

Fill

Blastfurnace Slag

Steelmaking Slag

Steel Slag

# 1 INTRODUCTION

## 1.1 Background

In common with many other countries, the United Kingdom has a legacy of land contamination arising from industrial development and related operational practices. In some situations contaminants may pose a risk to human health, the environment and other receptors. The latter may include building and civil engineering structures. The UK has a policy and legal framework aimed at minimising the future incidence of contaminated land; ensuring appropriate action is taken when dealing with contamination so that it presents no unacceptable risks. The UK also aims to increase the amount of brownfield land that is reclaimed and recycled for beneficial use. Thus, the use of a consistent, predictable and clear approach to managing land contamination is required. Accordingly, the Department of the Environment, Transport and the Regions (DETR) and the Environment Agency have funded studies to develop a Handbook of Model Procedures for the management of contaminated land. Although, the Model Procedures cover the generic risks from contaminated land, there is a need for more detailed guidance on the assessment and management of risks to buildings, building materials and services.

The report is based on a review of published information available internationally. It:

- Reviews currently available guidance on the assessment and management of risks to buildings and other structures, building materials and services from land contamination.
- Is intended to provide information for use in developing guidance on risk assessment and management for building on contaminated land.
- Is intended to be used as both a stand alone document and to support the guidance once developed.

Parties involved in building on contaminated sites can use it for the purposes of gaining background information and obtaining further sources of reference. These parties include construction clients, developers, main contractors, 'specialist' contractors, consulting engineers, material producers, local authorities and regulators.

The literature review has shown that there is a considerable amount of information that can be used in the development of guidance on assessing and managing the risks to buildings. Much is known of issues such as sulfate attack on concrete and guidance is available on this issue. However, there is less literature available on other contaminants and on the issue of multiple contaminants and how they affect the performance of materials.

CIRIA (1995) has reviewed the hazards and risks to construction in the redevelopment of contaminated sites. The construction activities that were determined to be most likely to interact with contamination in the ground were as follows:

- Ground improvement, such as the need to assess if fills will accommodate the weight of structures;
- Foundation construction, including the materials used to construct the foundations;
- Services such as water and drainage, electrical cables and gas supply lines.

Advice is provided on reducing the risks from any hazards that remain in the ground after any remedial works. In terms of materials durability the ground conditions are important because of the following:

- Working conditions are usually less conducive to high quality workmanship.
- Material degradation in the ground is difficult to monitor once a building is constructed.
- Remedial measures for failure are difficult and usually expensive to implement and monitor.

CIRIA states that there are three basic methods of countering risk of degradation to materials, as follows:

- Remove or modify the critical media (i.e. the contamination).
- Provide a protective system.
- Select more durable materials.

In addition, careful attention must be paid to design (e.g. thickness of sections) as these can affect vulnerability to attack and to buildability as this will govern whether the necessary quality of construction can be achieved.

## 1.2 Scope and Structure of the Literature Review

### 1.2.1 Scope

This report deals with the risks to buildings, other structures and services arising from the following:

- Ground conditions aggressive to building materials
- Subterranean fires
- Unstable fill materials
- Expansive slags

The majority of the literature review is concerned with the performance of building materials in contaminated land. In 1994 an extensive review of the performance of building materials in contaminated land was published by BRE, as BRE Report BR255, 1994. This review included an extensive amount of literature on materials such as concrete, reinforced concrete, metals, plastics and rubbers in chemically aggressive environments. However, there is a limited amount of information that relates specifically to building materials in contaminated land. The most usable guidance is perhaps the performance of building materials in sulfate containing soils which is published in BRE Digest 363 (BRE 1996). This Digest contains guidance related to the performance of different types of concrete in response to differing sulfate concentrations and type. In effect BRE Digest 363 provides a risk assessment procedure for certain ground conditions.

Cairney (1995) has written on the risks to building materials in his book on assessing risks from contaminated land. In a similar manner to BR255 this publication was not able to uncover much in the way of specific data on the performance of building materials in contaminated land.

In developing guidance on materials in contaminated land it must be recognised that there is a considerable amount of general information on durability that could be reviewed. However, problems can occur for those producing guidelines. For example, there are instances where research reports contradict each others findings and where guidance is unclear on issues of contaminant concentrations and ground conditions. A classic example is whether the presence of chlorides inhibits or enhances sulfate attack on concrete.

The literature review has been undertaken through the following means:

- On-line database searching through STN International of Chemical Abstracts. The search focussed on research in the past five years (since publication of BRE Report 255 "Performance of building materials in contaminated land", 1994) on durability of concrete, plastics, metals and masonry.
- Searches involving the use of the key words 'contaminated land' and its effect on building materials produced little information, indicating the lack of research in this specific area. Therefore, the approach adopted was to have 'building' as the highest level key word. A range of generic material key words, such as 'concrete', 'cement', 'polymer', 'plastic', 'rubber', were used together with appropriate phrases such as 'degradation', 'deterioration', 'biodegradation' and 'biodeterioration'. In addition, more specific key words such as 'hydrolysis', 'acid attack', 'corrosion', 'permeation' were used depending on the context of the search. A similar approach was adopted in the searches carried out for BR 255.
- Such searching revealed nearly 250 papers that could potentially be used, but sifting of these papers using their abstracts reduced the total to about 100. The sifting was carried out by study of the abstracts and titles, only those papers that clearly considered building materials in aggressive ground or other relevant environments were subsequently ordered and reviewed. Papers from BRE's own literature databases, BRIX (Building Research Index) and FLAIR have supplemented this total as have other papers known to BRE (e.g. CIRIA reports and WRc publications).
- Separate searches on subterranean fires only revealed two Russian papers on the subject and these did not add greatly to the existing literature already known to BRE.
- Chemical Abstracts was not searched for geotechnical papers since they are unlikely to be stored on the database. It was considered that BRE's own databases contained all the relevant information.

The health and safety risks of landfill gas to building occupants are widely acknowledged (DETR 1991). However, this review does not attempt to cover these issues as they are well covered elsewhere and guidance on protection of buildings and risk assessment has been developed (BRE 1991, CIRIA 1995a, DETR 1997, CIRIA 1995b).

### 1.2.2 Structure

The literature review is structured into five sections, as follows:

| | |
|---|---|
| Section 1 | Introduction |
| Section 2 | Building materials in contaminated land |
| Section 3 | Subterranean fires |
| Section 4 | Building on fill |
| Section 5 | Expansive slags |

Section two forms the majority of the report for the reasons explained in the scope. The other parts are included due to the risks they pose to buildings. However, the available literature on these issues is not as extensive as that for the performance of building materials. The sections on subterranean fires and risks posed by expansive slags cover specific problems. Whilst these risks are of concern they affect only a relatively small percentage of the total number of contaminated sites in the United Kingdom. In addition, the volume of literature that has been published on these aspects is small by comparison with aggressive attack on building materials. The geotechnical risks are not unique to contaminated ground. All sites should be assessed with regard to the presence of fill or other potential hazard and consequently the section in this literature review is brief.

The report has been structured so that each part can be used as a stand-alone document. Tables, figures and references that are used have been included at the end of the relevant part of the report.

The sections of the report are structured to reflect the (draft) Model Procedures for the Management of Contaminated Land (DETR 1999). In particular the sections are subdivided in order to address issues related to the following:

- Hazard – identification and estimation,
- Procedure for risk assessment,
- Procedure for evaluation and selection of remedial measures, and,
- Implementation of risk management plan.

## 1.3 References (Section 1)

Building Research Establishment, ‘Construction of New Buildings on Gas Contaminated Land’, BRE Report BR212, 1991.

Building Research Establishment (BRE) Paul V, ‘The Performance of Building Materials in Contaminated Land’, BRE Report BR255, Construction Research Communications Ltd, Watford, 1994.

Building Research Establishment, ‘Sulfate and Acid Resistance of Concrete in the Ground’, BRE Digest 363, 1996 (new edition).

Cairney T, ‘Risk of Attack on Construction Materials, in the Re-Use of Contaminated Land’, Wiley, Chichester, 1995.

Construction Industry Research and Information Association, ‘Protecting Development from Methane’, CIRIA Report 149, London, 1995a.

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# 2 BUILDING MATERIALS IN CONTAMINATED LAND

## 2.1 Background

Building materials are often subjected to aggressive environments that cause them to undergo physical or chemical changes. These changes may result in loss of strength or other properties that will put at risk their structural integrity or ability to perform to design requirements. Aggressive environments include severe climates, coastal locations, polluted atmospheres and aggressive soils. The latter aspect is of particular concern in this review. Aggressive environments can result in increased maintenance requirements, a reduction in the service life of materials and buildings and ultimately risks to health and safety or the environment.

In aggressive soils the potential for contaminant attack depends on the following:

- The presence of water as a carrier of aggressive contaminants (except in the case of free-phase organic contamination).
- The availability of the contaminant in terms of concentration, solubility and replenishment rate of the aggressive solution.
- Contact between the contaminant and the building material.
- The sensitivity of the material to the contaminant, in other words the inherent durability of the material and the properties that cause it to react or not with the contaminant.

Other factors also influence whether or not deterioration will take place and the rate of deterioration (Al-Wakeel 1996). Identification and management of these factors are part of the risk management process. Risk factors include the following:

- The use of unsuitable materials, for example the wrong choice of cement or aggregates for mortar and concrete.
- Poor production or placing of concrete that leaves the concrete with a more open texture, lacking in cover to reinforcement or highly permeable.
- Placing a vulnerable material in an aggressive environment without appropriate protection or full protection from ground conditions.
- Lack of maintenance, as many materials require maintenance such as cleaning to remove aggressive substances.

The design of the building or its components will also dictate the potential for contaminants to attack building materials and therefore cause damage to the structure. Issues such as the thickness of walls and whether the material is part of a piled foundation, foundation strip or wall contribute to the degree of attack experienced. In general the thicker the building material, in whatever form, then the less likelihood there is for contaminant attack to cause damage to the component or structure. More slender elements are potentially more at risk and are likely to fail faster than thicker elements.

The potential for contaminant attack to cause damage to the structure also depends on whether contaminant ingress into porous materials such as concrete and masonry can be encouraged by both ground conditions and the structure design. A particular example is where ground floor slabs allow evaporation of water from their upper surface and therefore result in the capillary forces that draw contaminated groundwater from soils or fill. This has been known to cause

damage where ground floor slabs have been laid on sulfate contaminated fill.

The design of a new building and its location on site may be deliberately chosen to minimise the potential for contaminant attack. Where a site investigation shows that there is a hot spot of a particular type of contaminant that will attack building materials then this part of the site could be contained, treated, removed or left undeveloped apart from perhaps landscaping. However, to manage contamination in such a way would require flexibility in the development process of a site and this may not always be appropriate.

There are few standard methodologies or commonly used practices that are used to test the durability of materials in aggressive media. Perhaps the most complex material to test is concrete as it contains cement, aggregate and other components. The methods used to assess durability are often based on 'in-house' methods or are experiment specific. These tests also tend to be long term (up to several years) in order to estimate likely field performance. Zivica (1998) has developed a methodology for the assessment of the chemical resistance of cement based materials. This uses mathematical modelling to model the experimental observations and link these with the material properties and the nature of the aggressive media.

Exposure classes for concrete related to environmental conditions are given in the European Pre-Standard ENV 206 (CEN 1990a). These classifications are essentially qualitative, as shown in Table 1 (CEN 1990b).

Barry (1983) identified the susceptibility of 55 common construction materials to attack from more than 140 generic or specific chemical compounds. Similar corrosion charts, showing the effects of a large range of chemicals on concrete, plastics and rubbers, are given in reports by Committee 515 the American Concrete Institute (ACI 1985) and the Water Research Centre (Crathorne *et al* 1987). These lists are of limited value in determining the effect of contaminated land on building materials. They deal with the effects of single chemicals in concentrated solutions and do not consider the in-ground environment.

In some cases the type and quality of a building material that is used for a specific environment can be adjusted to suit the aggressive conditions, for example, this is possible in the case of concrete. However, in other cases there may be a limit on the durability that can be expected of the materials, or uncertainty as to the full range of conditions that are likely to be encountered. In these cases it has been suggested that protective coatings could be used for the protection of building materials. A guidance document on coatings for steel and concrete in a contaminated land environment has been produced (Garvin *et al* 1995).

The review covers the common types of materials used in the ground, either in the building structure or in services such as water or sewage pipes. The review does not cover materials such as timber that are not used generally for foundations or services and therefore in below ground situations. There may, however, be some need to consider their durability when used as fencing or temporary structures.

## 2.2 General Principles

### 2.2.1 Site Investigation for Contaminants and Building Materials

In order to assess whether or not there is a risk posed to building materials from substances in the ground and how to best manage that risk it is first of all necessary to determine the type, nature and concentration of potentially hazardous substances. This will normally be carried out using sampling of soils and ground water using trial pits and boreholes on site. The sampling of soils and ground waters should follow the same good practice principles as detailed in guidance documents (BSI 1999, CIRIA 1995). However, if the site investigation has not been designed to specifically include contaminants or ground conditions that will affect building materials then further specific supplementary site investigations may be required.

Recommended procedures for the analysis of sulfates and related ions in the ground are given in BRE Report BR279 (BRE 1995) and BS7755: Section 3.11. Figure 1 shows the various steps for the classification of sulfate in the ground. In recent editions of BRE Digest 363 (BRE 1996) the acid soluble sulfate content of the soil has been recognised as too harsh a means of assessing the sulfate conditions in the soil. The current recommended procedures are to use a 2:1 water:soil extract and carry out analysis of the extracted solution. The sulfate classification of the site can also be made on the basis of ground water analysis. The main difficulty in classifying sites on the basis of ground water alone lies in the difficulty of obtaining samples that are not diluted or contaminated with surface water.

In cases where there is an existing development it may be necessary to carry out sampling of the materials in a building. This may be required as a result of deterioration or contamination of the materials. There is no specific guidance on sampling of building materials in the ground. This is likely to be expensive as it will require excavation of the surrounding ground to access foundations or services. Advice on sampling concrete for assessment of its condition is given in BS1881: 1983 (BSI 1983).

In cases where existing buildings have been subjected to contaminant attack that threatens the integrity or lifetime of the building it is necessary to undertake some remedial measures. These measures depend on the type of building material and the form in which it is constructed. A general review of investigation of problems and remedial measures is included at the end of this section. However, there will be specific issues for different building materials and sites that will dictate that the measures chosen will be site specific. There is considerable knowledge of the repair of reinforced concrete in above ground situation, however, there is little specific information on below ground reinforced concrete structures.

### 2.2.2 Hazard Identification and Assessment

The identification of hazards from contamination is based initially on the site investigation report that details the following information:

- The contaminants that are present on the site - there are a number of contaminants that are known to attack certain materials.
- The nature of the contaminant - for example, calcium sulfate has a much lower solubility

than sodium or magnesium sulfate and is therefore generally considered a lesser concern with regard to chemical attack. Therefore, if the site investigation considers only total (acid soluble) concentrations in soils then the potential for chemical attack may be overestimated in the case of concrete.

- The concentration of the contaminants - in general the higher the concentration then the greater is the hazard.
- The potential mobility of the contaminants - sites with aqueous (soluble) and liquid phase contaminants and appreciable ground water flow will be more aggressive than low solubility and static ground water.
- The solubility of metal ions and salts - contaminants that are not soluble will not in general react with materials.
- The nature of the soil - more open textured and permeable soils will increase the potential for contaminants to reach the materials.

### 2.2.3 Risk Assessment

The processes of risk assessment for building materials are concerned with knowledge of the site conditions (the hazards) and determining whether the contaminants can react with or permeate the building materials. Risk assessment and risk management can be considered using a *source - pathway - receptor* model. In this model the source is a contaminant at some point in the ground, the pathway is the soil itself and the receptor is the building material.

The results of all the individual chemical analyses should be made available to the specifier in order to estimate the risks to the materials. For concrete, if classification is based solely on the basis of ground waters then it should correspond to the highest sulfate concentration recorded. If classification is based solely on a small number of soil samples and the results vary widely it is best to take more samples. When there are a larger number of results available then it is suggested that the site classification should be based on the mean of the highest 20% of the results (BRE Digest 363, 1996). For other materials it may be more appropriate to use the highest concentrations. For example, in the case of organic chemicals that attack certain types of plastic it may be necessary to consider the highest concentration in all cases.

### 2.2.4 Evaluation and selection of remedial measures

The risks can be managed by the evaluation and selection of appropriate remedial measures and a strategy for future monitoring. Remedial and protective measures fall into the following categories:

- Excavation and removal of the hazard (contaminated soil) from the site, thereby removing the risks to the materials. This form of remediation can be applied to existing or new buildings. For existing buildings it may be used where there are known problems of contaminant attack and it is necessary to removal soil for repair of the material in any case. The soil would be replaced with well compacted clean backfill.
- Treatment or stabilisation of contaminated soil in order to destroy, remove or render harmless the contaminant. There are a variety of treatment technologies that could be applied; selection of the measure will depend on the type of contamination and the nature of the ground. This form of remedial measure may be applied to new buildings or existing buildings.
- Containment of contamination may in some cases be appropriate to restrict the mobility of contaminants and therefore reduce the risk of contact with materials. In some cases a

simple cover system may suffice, otherwise cut-off walls may be required to restrict mobility. This form of remedial measure may be applied to new buildings or existing buildings.

- The specification of types of concrete, plastic, metals, steel and masonry that are resistant to the type and concentrations of contaminants on the site can often be an appropriate form of action. The specification should also take account of the nature of the ground and the permeability of the ground. This form of action would best be applied to new building situations. The cost of using a higher specification material should be compared with the cost of undertaking the other forms of remedial measures that are described above.
- Additional protection can be added to materials in order to prevent contact with contaminants. This could be applied to new buildings or as a remedial measure for existing buildings. Additional protection may take the form of sacrificial layers, surface coating, wrapping in plastic membranes, galvanising metal or the use of containment cut-off walls.

In general, the specification of suitably resistant materials is normally selected as the remedial measure where the concern is only over materials durability. However, where there are other risks, such as to human health, it is often necessary to undertake excavation and removal, containment or treatment.

It is important when considering how to provide services on contaminated sites that future maintenance and in particular the health and safety of those carrying out such works is considered. It should, as far as practical, be possible to excavate the services to carry out repairs, possibly 20 or more years in the future, without having to take special precautions to protect the workers. This will commonly require either clean backfill in the trenches or placing of services in a clean cover system.

The following sections contain information that is relevant to risk assessment for various building materials in contaminated land. This includes the contaminants that are known to attack materials, the quantification of the risks where it is known and the measures that can be taken to overcome those risks.

## 2.3 Concrete

There are a number of mechanisms by which contaminants attack concrete, including the following (BRE 1994):

- Hydrolysis of the hardened cement paste.
- Chemical corrosion as a result of exchange reactions between calcium in calcium hydroxide (free lime hydrate) and ions in the aggressive solutions.
- Expansive reactions as a result of chemical reaction or salt crystallisation.

### 2.3.1 Sulfate Attack

**Hazard**

Sulfate attack on concrete is characterised by expansion, leading to loss of strength and stiffness, cracking, spalling and eventual disintegration (BRE 1994, ACI 1991, Crammond 1993). There are three principle forms of sulfate attack, as follows:

- Formation of gypsum through reaction of calcium hydroxide and sulfate ions.

- Ettringite formation through reaction of tricalcium aluminate and sulfate ions.
- Thaumasite formation as a result of reaction between calcium silicate hydrates, carbonate ions (from aggregates) and sulfate ions.

Boxes 1 and 2 provide more information on these forms of sulfate attack.

**BOX 2.1: Gypsum and Ettringite**

Gypsum is formed as a result of a cation-exchange reaction between calcium in the cement hydrates and sulfate solution. Depending on the counter ion present in the sulfate solution, both calcium hydroxide and calcium silicate hydrate can be converted to gypsum. Removal of calcium hydroxide and its replacement by gypsum leads initially to an increase in the stiffness and the strength of the concrete, due to pore filling. However, this is followed by expansion, leading to cracking and deformation.

Calcium, sodium and magnesium sulfates react in the presence of calcium hydroxide with both calcium aluminate and calcium monosulphoaluminate hydrates to form ettringite (Biczok 1972, Lea 1970). The exact mechanism by which ettringite formation causes expansion in concrete is unclear. However, it is thought that expansion may be caused by the exertion of pressure on the pore walls of the concrete (Lawrence 1990, Mehta 1983).

**BOX 2.2: Thaumasite**

Thaumasite is a calcium silicate carbonate sulfate hydrate that can form in certain types of concrete and mortar, either alongside ettringite and gypsum or by itself (Crammond 1985). It is formed in the reaction of calcite, gypsum and calcium silicate hydrate. The breakdown of the calcium silicate binder during thaumasite formation results in a reduction in the strength of the concrete, which eventually deteriorates into a mush. Concrete that has suffered deterioration caused by thaumasite formation typically exhibits a white pulpy mass between the aggregate grains.

The thaumasite form of sulfate attack is potentially more serious than gypsum and ettringite. Ettringite formation is limited by the tricalcium aluminate content of the cement, but the amount of thaumasite is much larger as it is formed from the dominant calcium silicate hydrate fraction of the hardened cement paste.

The rate of thaumasite formation is generally low, unless the following environmental conditions are satisfied:

- high humidity;
- low temperature;
- initial reactive alumina ($Al_2O_3$) content between 0.4 and 1.0%;
- adequate supply of available sulfate and carbonate anions.

The recognition and diagnosis of thaumasite attack is detailed in papers by Hartshorn (1998) and Sims and Hartshorn (1998). Laboratory methods of identification include petrography, chemical analysis and mineralogical analysis. Petrography will identify most cement types, mineral additions and aggregates. The quality of the concrete can also be assessed with this technique. Chemical analysis is mainly intended to quantify the content of acid soluble sulfate in the concrete using conventional techniques. X-ray diffraction and scanning electron microscopy establish the mineralogy and the crystal phases that are present.

**Risk Assessment**

Concrete degradation increases with the concentration of sulfate. Although, the rate of degradation is not directly proportional to the concentration and the degradation levels off as the concentration of sulfate increases (Biczok 1972). The rate and extent of concrete degradation due to sulfate attack is also in part determined by the cation. Magnesium sulfate and ammonium sulfate together with sulfuric acid are more aggressive towards concrete than calcium and sodium sulfate (Lea 1970, Crammond 1985, Eglinton 1987). Experimental work has investigated these factors and some details are given in Box 3.

The rate and severity of sulfate attack also depends on the following variables (BRE 1991, Osborne 1989).

- The amount of water available - nature of the water table and mobility of ground water,
- The susceptibility of the concrete - cement type and content, type of aggregate, water:cement ratio, curing and quality (Osborne 1999),
- The rate of transport of the sulfate in the concrete - permeability,
- The form of construction.

**BOX 2.3: Performance in Sulfate Soils**

BRE is investigating the performance of various concrete mixes in sulfate-containing soils (average sulfate concentration of 2.5 g $SO_3$/l) in a 30-year field trial at Northwick Park, London (Harrison 1992, Harrison 1981). After 15 years only a few 'deliberately' poorly compacted Portland cement concrete showed any strength reduction. Indeed, the majority of concrete mixes showed a significant increase in strength between 5 and 15 years' burial.

Analysis of the sulfate content of the various concrete mixes showed that the sulfate concentrations increased in the outer layers over the 15 years. The levels of sulfate were far in excess (up to 30% by weight of cement) of the amount that could arise from the evaporation of ground water from the pores of the concrete after excavation. For such high levels of sulfate to be observed in the concrete the sulfate in the ground water must have reacted with the cement hydrates to form ettringite or gypsum. As no signs of expansion were observed, it was suggested that the reaction products had been formed 'through solution' and precipitated in voids without causing expansion.

The formation of thaumasite is associated with the presence of limestone aggregates in a reactive state. Generally, the reaction is more likely to occur if the fine aggregate is a limestone type (Crammond 1995). A study at BRE has identified three cases of thaumasite formation of which two were in the UK (Crammond 1995). Research carried out in Canada studied thaumasite attack in two structures (Rogers *et al* 1997). The temperature dependence of the thaumasite form of sulfate attack is unique as the reaction is faster at low temperatures in contrast to the higher rate of ettringite formation at higher temperature. The range of temperature at which thaumasite will form rapidly is 0 - 5°C (Bensted 1999). However, the reaction will take place up to about 15°C.

Concrete can be produced from different types of cement and aggregates. Cements form different end products as they hydrate and this affects their inherent durability (CEB 1989). The common types of cement used in building are Portland cement (PC), sulfate resisting Portland cement, blastfurnace slag cement and pulverised fuel ash cement and. The latter two cements are blended cements that contain Portland cement in combination with the replacement material. Other cements that are less commonly used are microsilica (blended with PC) and high alumina cement (HAC).

Resistance to high levels of sulfate can be achieved by the use of well made concrete containing blastfurnace slag (ggbs) or pulverised fuel ash (pfa). Concrete containing ggbs should have at least 70% ggbs replacement of PC (by weight), pfa concrete should have between 25% and 40% replacement of PC (Concrete Society 1991). Minimum cement contents and maximum water:cement ratios are recommended within Digest 363 (BRE 1996). In some sulfate soils sulfate resisting Portland cement (SRPC) should be used. This has a restricted tri-calcium aluminate ($C_3A$) level (<3%). This phase is the vulnerable phase to the gypsum and ettringite forms of sulfate attack and is responsible for the vulnerability of Portland cement in sulfate soils. A study by Miletic *et al* (1999) has recently demonstrated the benefits of using pulverised fuel ash in reducing sulfate attack. This study considered attack by ammonium sulfate on concrete. This study found that gypsum was the main cause of chemical attack and that the quantities of ettringite were small and the same for PC or PC/pfa concrete.

Rendell and Jauberthie (1999) have studied the resistance of concrete, using mortar samples, to ammonium sulfate and sulfuric acid. In the latter case a layer of dense gypsum was formed on the surface and it was considered that this would act as a barrier layer to the ingress of further sulfate ions. The ammonium sulfate attack resulted in the formation of less dense gypsum that did not resist the ingress of further sulfate ions.

**Remedial Measures**

The normal approach to managing the risks to concrete from sulfate contaminated soil is to specify a suitably resistant type of concrete. In general, soil excavation and removal, containment or treatment are not considered as remedial measures solely to overcome sulfate problems.

Guidance on suitable concrete for sulfate contaminated soil is given in BRE Digest 363 and BRE Report BR255. In the Digest, soils are classified into five classes of increasing concentration of sulfate in the soil or groundwater. A 2:1 water:soil extract is recommended for analysis. The recommendations include the type of concrete that can be used in the various classes of sulfate soils. In class 5 sulfate conditions, corresponding with the highest levels of sulfate, it is necessary to use a coating to provide additional protection to the concrete. A BRE Report, BR286, provides advice on coatings for concrete in aggressive soil conditions (BRE 1995).

It should be recognised that BRE Digest 363 is currently being updated (BRE 1999) and that a new version will be published in early 2000. This is a major revision that will take account of thaumasite form of sulfate attack, pyritic oxidation in clay soils, form of construction, more on surface protection/sacrificial layers and more consideration of brownfield soils. The Digest is likely to be published in two parts, the first of which will sulfate soils in the UK and the second part the recommendations for concrete. In general, the classes of sulfate soils remain the same. However, the reactive carbonate content of the aggregate has to be taken into account in determining the concrete specification. Three classes of reactive carbonate are considered and the recommendations centre around lowering the water:cement ratio and increasing the cement content. This results in stronger concrete with reduced permeability. The potential for sulfate ion ingress into the concrete is thus reduced by virtue of the denser concrete.

A significant change is the greater use of surface protection or sacrificial layers to protect concrete from thaumasite formation. Previously, class 5 sulfate soils were considered to require surface protection for ettringite and gypsum formation. For thaumasite formation classes 3 and 4 may require surface protection or sacrificial layers if there is a high reactive carbonate content.

In some forms of construction, for example concrete piles, it may be possible to provide a sacrificial layer of concrete. This would be sufficiently thick to ensure that contaminant attack remains restricted to the sacrificial layer for the entire design life. Shell piles are formed by a precast shell that is filled in-situ with fresh concrete.

Guidance has been produced on the risks of thaumasite formation in new concrete construction (DETR 1999). As this form of attack is potentially deleterious to all types of cement then minimising the risks can be difficult. There are a number of ways in which the risk of the thaumasite form of sulfate attack can be reduced whilst retaining aggregates with reactive carbonates. These measures include the following (DETR 1999):

- Concrete made from ggbs offers good resistance to thaumasite sulfate attack.
- Use well compacted concrete with a low water:cement ratio.
- Well made SRPC and pfa/PC concrete should be resistant.
- Surface coatings that are properly applied and are compatible with the substrate and

surrounding ground offer additional protections.
- Sacrificial layers can be used.

### 2.3.2 Chloride attack

**Hazards**
There are a number of ways in which chlorides can react with hydrated cement compounds in concrete. These are described as follows:

- Chlorides react with the calcium hydroxide in the cement binder to form soluble calcium chloride that is subsequently leached away, this increases the permeability of the concrete, leaving it more susceptible to the ingress of other chemicals (Ben-Yair 1974).
- Calcium and magnesium chlorides can react with calcium aluminate hydrates to form chloroaluminates that are similar to ettringite (Ben-Yair 1974, Gutt 1977). The formation of these chloroaluminates results in low-to-medium expansion of the concrete.
- If concrete is subjected to wetting and drying cycles caused by ground-water fluctuations, salt crystallisation can occur within the concrete pores, particularly in the capillary zone. If the pressure produced by crystal growth is greater than the tensile strength of the concrete, the concrete will crack and eventually disintegrate.

Examples of the performance of concrete in chloride environments are given in Box 4. This Box also covers the effect of chlorides on sulfate attack. It should be noted that chloride attack on concrete is not as severe as sulfate attack and the extent of degradation is unlikely to be the same as in sulfate containing soils.

**Risk Assessment**
Chlorides of sodium, potassium and calcium are generally regarded as being non-aggressive towards mass concrete (Biczok 1972). Concrete brine containers in salt mines have been known to remain in serviceable condition for 20 years in spite of being heated to 100$^{o}$C.

Guidance on acceptable limits of chlorides in concrete has generally been developed for chlorides that have been incorporated as chemical admixtures into the concrete mix. Depending on the type of concrete and the cement used up to 0.4% chloride is allowed in BS8110: Part 1. Bartholomew (1979), Table 2, has made a tentative classification of the degree of attack by external chloride. This classification does not relate to appropriate choice of concrete mix design or cement type in the same way that Digest 363 covers sulfate classification.

**BOX 2.4: Performance in Chloride Environments**

An investigation (Smolzcyzk 1969) into the effect of chloride solutions on Portland cements and PC/blastfurnace slag cement (75% slag), found that after two years:

- Samples stored in saturated NaCl or weak $CaCl_2$ solutions showed no loss of strength,
- Portland cement samples stored in strong $CaCl_2$ and $MgCl_2$ solutions underwent severe cracking and spalling and were totally destroyed within 16 weeks,
- $NH_4Cl$ was the most aggressive solution, causing a loss of strength for PC and ggbs in concrete.
- The use of slag increased the chemical resistance of concrete exposed to chlorides. Samples containing slag showed a loss of strength only in the $NH_4Cl$ solution, gaining strength in all the other solutions.

The performance of concrete produced using high alumina cement (HAC) and a blend of HAC and ggbs (BRECEM) has been investigated in a chloride environment. All samples were found to perform well in seawater in the spray, tidal and full immersion zones. The samples were both resistant to chloride ion ingress and to freeze/thaw action. BRECEM in general outperformed the neat HAC concrete mixes (Osborne and Singh 1995).

Chlorides are generally considered to improve the sulfate resistance of concrete, as a result of the following (Biczok 1972, Lea 1970, Kind 1956)

- Increased solubility of calcium sulfoaluminates (ettringite) in the presence of chloride ion.
- Reduction in the concentration of $Ca(OH)_2$.
- Conversion of the hydroaluminates to chloroaluminates, so retarding the formation of ettringite.

However, other work has shown that chlorides may enhance sulfate attack (Bartholomew 1979). Cement paste specimens immersed in solutions containing 0.4% sulfate ($Na_2SO_4$, $MgSO_4$ or $K_2SO_4$) and 3.5% NaCl were found to undergo greater expansion than samples immersed in sulfate alone. The degradation of concrete was caused by the combined contributions of both salts. The greater expansion in solutions containing mixtures of chlorides and sulfates was explained as follows:

- The formation of expansive reaction products.
- Enhanced crystallisation of ettringite in the presence of the chloroaluminates.
- Degradation of the cement binder.

It is seen that there is some confusion and more research would be required to determine if the chlorides enhance or retard sulfate attack.

## Remedial Measures

In general soils do not need to be excavated and removed, contained or treated in order to overcome potential problems of chloride deterioration of concrete. It would be normal for suitably resistant types of concrete to be specified.

Digest 363 advises that the chloride concentration should be considered as equivalent to $SO_4$ concentration ($SO_4$ equivalent of Cl = Cl x 1.35 g/l). However, this guidance is really intended to address the acidity of the soil and not chloride salts as covered here. Coatings could also be used to protect concrete from chloride ingress in contaminated soils (Garvin *et al* 1995). The use of sacrificial layers could also be considered for severely contaminated sites.

### 2.3.3 Acid Attack

**Hazards**

Concrete being an alkaline material is vulnerable to attack by acids. Prolonged exposure of concrete structures to acidic solutions can result in complete disintegration. Further discussion is provided in Box 5.

**BOX 2.5: Acid Attack**

Corrosive acids most frequently encountered in building practice are shown in Table 3. Acids can attack cement hydrates and thus degrade the cement binder. Cation exchange reactions between the calcium in the cement hydrates, particularly calcium hydroxide, and the ions in the attacking acid result in the formation of soluble salts that are subsequently leached out. The concrete becomes more porous and looses strength. Oxalic and phosphoric acid are the exceptions as the resulting salts are insoluble in water and not readily removed from the surface of the concrete (ACI 1991, Biczok 1972).

Acid attack is concentrated initially on the free lime (calcium hydroxide) constituent of the cement paste, but strong acids can also react with the calcium silicate hydrates and calcium alumino hydrates to form silica gel and the aluminium salt of the attacking acid (CEB 1989, Biczok 1972). Further degradation of the cement binder can result eventually in the total disintegration of the concrete. However, formation of the silica gel can also reduce the rate of acid attack by acting as a protective barrier to the transportation of the attacking acid to the concrete and removal of soluble reaction products (Grube 1989). Silica gel is not particularly strong and is easily separated from the concrete surface by mechanical impact, but if it is retained in place, then the rate of acid attack on concrete will not increase and may even decrease.

Sulfuric acid and, to a lesser extent, hydrochloric acid are regarded as being particularly aggressive as in addition to degrading the cement binder they also produce an expansive reaction (Biczok 1972, Chandra 1988). Neither ettringite or thaumasite are stable in acid conditions and therefore sulfuric acid attack produces gypsum as the reaction product (BRE 1999).

Laboratory studies of acid attack on concrete have been undertaken (Chandra 1988, Fattuhi 1988). However, a survey by Eglinton (1975) on the behaviour of concrete in acid soils and ground-water found no evidence of structural weakening of mass concrete exposed to the more common types of naturally occurring acid waters. Similarly, a private communication to the author describes an investigation of precast hollow concrete piles that had been standing for 20 years in ground soaked with sulfuric acid (pH between 2.0 and 3.0; sulfate content between 5.0 and 6.0% $SO_3$). In this case only superficial signs of deterioration were found.

Zivica (1999) has studied the acid resistance of concrete containing modified silica fume (MSF). This included mixes with PC, slag and MSF that improved the acid resistance in comparison with PC or PC/slag mixes. The improvement in performance was attributed to improvements in the composition of the concrete and reduced porosity and permeability.

**Risk Assessment**

The rate of acid attack on concrete depends on the following:

- The type of acid,
- The acid concentration (pH),
- The composition of concrete (type of cement and aggregate),
- The soil permeability,

- The ground-water movement (BRE1996, Harrison 1987).

British Standard BS 8110: Part 1 classifies an extreme environment as one where concrete is exposed to flowing ground water that has a pH of ≤ 4.5. The Standard warns that Portland cement concrete is not suitable for use in acidic conditions with a pH of 5.5 or lower. Specific recommendations related to acid conditions are not included, but requirements for concrete exposed to attack from acids of pH above 2.5 are given in BRE Digest 363. If the pH of the soil was less than 2.5 the use of concrete would not be advised and further remedial measures would be required.

Further guidance on the aggressiveness of acids is given in the draft recommendations of European Pre-Standard ENV 206, Table 1.

**Remedial Measures**
BRE Digest 363 allows site classification to be modified if acid conditions are present alongside sulfates. The sulfate classification may need to be advanced by up to three classes if the pH is less than 4.5, it is made ground or contains waste and the ground water is mobile. Therefore, a soil that could be classified as Class 2 on the basis of sulfate concentration alone may need to be advanced to Class 5 if the pH is low and the ground water is flowing across the site.

In general soil does not need to be excavated and removed, contained or treated in order to overcome problems with acid soils solely for the protection of concrete. The preferred option is to use suitable types of concrete that are resistant to the ground conditions, or to provide added protection to the concrete such as coatings or sacrificial layers. The main exception is when the pH of the soil is less than 2.5 and some remedial measures, for example chemical treatment, would be required prior to using concrete.

### 2.3.4 Magnesium attack

**Hazards**
Magnesium salts, with the exception of magnesium hydrogen carbonate, are destructive to concrete (Biczok 1972). Corrosion occurs from cation-exchange reactions where the calcium in the cement paste hydrates is replaced by magnesium. The cement loses binding power and eventually the concrete disintegrates. Box 6 provides a more detailed discussion of magnesium attack.

**Risk Assessment**
In Digest 363 it is recommended that Portland Cement/ggbs and Portland Cement/pfa concrete is not used where the magnesium concentration in ground water is greater than 1000 mg/l, or greater than 1200 mg/l in a 2:1 water:soil extract. In this case SRPC concrete should be used. These recommendations are given for classes 4 and 5, but no recommendation is provided for classes 1 to 3. ENV 206 appears to indicate that higher concentrations of magnesium could be allowed. Strong magnesium environments are considered to exist when the concentration is greater than 3000 mg/l.

**BOX 2.6: Performance in Magnesium Environment**

Magnesium salts act as weak acids and readily react with the calcium hydroxide in the cement paste to form soluble salts of calcium, which are subsequently removed (Biczok 1972). The formation of magnesium hydroxide lowers the pH of the cement paste and consequently hydrolysis is resumed. If sufficient magnesium is present then silica gel is formed (Biczok 1972, Lea 1970). The silica gel then reacts with the magnesium hydroxide to form a hydrated magnesium silicate. This silicate, in contrast to silica gel, has no binding power and consequently the concrete disintegrates.

Magnesium salts, particularly $MgSO_4$ and $MgCl_2$, are especially aggressive towards concrete as in addition to magnesium corrosion the anions react with the cement paste hydrates to form expansive reaction products.

Laboratory tests on concrete cubes have shown that magnesium sulfate is more detrimental to concrete than an equivalent sodium sulfate solution (Harrison 1992). Similarly, tests on concrete samples in concentrated chloride solutions found that samples immersed in magnesium chloride suffered the greatest degree of deterioration (Smolczyk 1969). Laboratory tests have also shown that concrete containing PC/ggbs and PC/pfa cements are more susceptible to deterioration than sulfate resisting Portland cement (SRPC) concretes in a magnesium environment (Biczok 1972, Lawrence 1990, Osborne 1989, Osborne 1992). The increased sensitivity of PC/ggbs and PC/pfa cements is due in part to their lower calcium hydroxide content, which reacts preferentially with the magnesium ions.

**Remedial Measures**

Guidance on the use of concrete in magnesium environments is given in ENV 206, Table 1, and in BRE Digest 363. In general it is unlikely that soil would need to be excavated and removed, contained or treated in order to overcome problems of magnesium contamination. It is preferable to specify a suitable type of concrete. Coatings or sacrificial layers could also be considered.

### 2.3.5 Ammonium attack

**Hazards**

Ammonium salts, like magnesium salts, act as weak acids and attack the hardened cement paste of the concrete (BRE 1994). Further information on ammonium attack is given in Box 7.

**Risk Assessment**

Guidance is not available on the concentration of ammonium that can be tolerated by different types of concrete. However, ENV 206 (Table 1) does provide some guidance on weak, medium and strong ground conditions. Strong conditions have concentrations of greater than 60 mg/l in soil or groundwater.

**Remedial Measures**

In general it would not be necessary to undertake soil excavation and removal, containment or treatment in order to overcome problems of ammonium contaminated soils where concrete is to be used. It is normal to specify a good quality concrete with a low permeability to resist ingress of ammonium ions. In cases where there is doubt over high ammonium levels then coatings or sacrificial layers could be considered for additional protection.

**BOX 2.7: Performance in Ammonium Environments**

Ammonium salts act as cation-exchange compounds, transforming the insoluble calcium in the hardened cement paste into readily soluble calcium salts that are subsequently leached away (Biczok 1972). During the reaction, ammonia is liberated and escapes as a gas. The removal of both reaction products results in an increase in the porosity of the concrete, leaving it vulnerable to further attack. Ammonium salts also act as weak acids and neutralise the alkaline hardened cement paste (Nagele 1984). The removal of the hydroxide ions results in softening and gradual decrease in strength of the concrete. In addition to the corrosive action of the ammonium ion, some further deterioration may be caused by the action of the associated anions. Sulfate and to a lesser extent nitrate ions can cause expansion. The deterioration associated with the anions is aggravated by the corrosive attack of the ammonium ions increasing the porosity of the hardened cement paste.

The chemical resistance of PC has been investigated by immersion of concrete cubes in 5% ammonium sulfate, nitrate and chloride solutions (Nagele 1984, Lea 1965). The sulfate form was the most aggressive towards Portland cement and PC/ggbs. The other forms of ammonium salt also caused deterioration of concrete samples, but at higher concentrations and to a lesser extent. The reaction was concentration dependent with greater deterioration at higher concentrations of ammonium.

It has been argued that resistance to ammonium attack can be increased by using cements containing ggbs and pozzolans (Biczok 1972). However, experimental results do not fully support this hypothesis (Guner 1984). Partial replacement of PC with ggbs did not improve the deterioration resistance of mortar bar samples exposed to ammonium sulfate, ammonium nitrate and di-ammonium phosphate solutions. Experiments using concrete made with cements containing natural pozzolan immersed in ammonium nitrate solutions also found that these were less resistant to ammonium ion attack (Akman 1987).

### 2.3.6 Chromium attack

**Hazards**

Attack by chromium as either hexa or tri valent species has been identified by a number of workers (Craig 1969, Eglinton 1987, Huang 1994). Further details on cases of chromium attack are given in Box 8

**Risk Assessment and Remedial Measures**

There is no guidance on the levels of chromate that could cause a risk to concrete. There have been few studies carried out into the risk of deterioration in chromate contaminated soils and as reported in this paper the evidence for deterioration is currently conflicting.

Soil would not normally be excavated and removed, contained or treated in order to overcome the risk of chromium to concrete. However, given the toxic nature of chromium soil treatment may be necessary for human health reasons.

**BOX 2.8: Performance in Chromium Environment**

Mechanisms of chromium attack have been proposed and include acid attack and salt crystallisation. In the former case the attack could more correctly be defined simply as acid attack. In the latter case crystallisation was related to filling of the pores of the concrete and the exertion of pressure in these pores. The concrete subsequently deteriorated due to the pressure.

Research carried out in the late 1960s demonstrated that chromium would affect the early strength development of concrete (Craig 1969). Since then a number of studies have considered the effect of chromium on concrete in buildings constructed on chromite ore processing residues. However, no effect on mature and well made concrete was suspected until deterioration was found in buildings in New Jersey, USA that had been built on the ore processing waste.

Various workers have investigated the deterioration of concrete on this site. In one study attack was attributed to absorption of acidic $Cr^{6+}$ which was considered to have caused damage over a long period of time (Eglington 1987). Whilst this form of attack would be classed as acid attack the pH would have to be less than 6, but the site had a ground pH of 8. The damage resulting to the concrete was therefore considered to be due salt crystallisation in the pores. The chromium is introduced to the concrete from the ground and if the concrete can subsequently dry out then the chromium salt forms and expands resulting in damage to the concrete (Raghu 1989).

Other studies were less certain of the role of chromium in the concrete deterioration (Poston 1995, Whitlock 1997). In a bridge structure built on chromium residues no signs of salt crystallisation were found after 30 years. This has resulted in the quality of the concrete at the New Jersey site being questioned and deterioration being attributed to the poor quality (Whitlock 1997).

### 2.3.7 Organic Attack

**Hazards**

Most organic substances do not attack hardened concrete, but they can affect the hardening of ‘fresh’ concrete. Hydrocarbons such as petrol, petroleum distillates in general, and lubricating oils that are entirely of mineral origin, do not attack concrete (Biczok 1972, Lea 1970). Lubricating oils that contain vegetable oils can cause gradual surface degradation. Vegetable oils can readily oxidise to produce acids and it is these acids that cause concrete degradation (Lea 1970).

Despite not readily attacking concrete the majority of hydrocarbons, due to their low viscosity and surface tension, are capable of permeating even dense concrete. If these hydrocarbons contain compounds that do deteriorate concrete then the resistance of concrete will depend on the concentration of the aggressive compound and the rate of ingress of the hydrocarbon. Further details are given in Box 9.

**BOX 2.9: Performance in Organic Environments**

Phenol is a weak acid and, as such, will react with the calcium hydroxide in the hardened cement paste to form calcium phenolate. The calcium phenolate crystallises in the pores of the concrete, causing deterioration as a result of physical expansion (Biczok 1972). In experiments with concentrations of phenol up to 25,000 mg/l concrete samples experienced strength loss comparable to class 2 – 3 sulfate conditions. However, the physical condition was generally good. This is not untypical of cases of mild acid attack on concrete.

Other organic acids are more likely to attack concrete. Acidic attack from lactic acid in milking parlours and acids in silage are known to cause considerable deterioration to concrete (Lea 1970). In silage organic acids such as acetic and butyric acids are formed and the temperature of the silage rises. Chemical attack on concrete is negligible as long as the pH remains above 5, however, attack can be considerable at a pH of less than 5. The chemical attack is likely to decrease if the cement content of the concrete increases (lea 1970).

Biczok (1972) shows that alcohol (for example methyl, ethyl and propyl alcohol and their homologues) do not attack hardened concrete but can absorb water from fresh, unhardened concrete, causing a reduction in strength. The rate of water absorption is concentration-dependent and is greater for ethanol than for methanol.

The effect of oil based pollutants on building materials has been assessed in a study in Kuwait as a result of oil well fires during the Gulf War (Husain 1999). The main concern was gas containing sulphur dioxide and carbon dioxide. It was suspected that these gases could result in sulfate attack and carbonation of concrete. It was found that the hydrocarbon concentration in building materials was higher at the surface and decreased significantly with depth (Al-Mutairi 1995). The depth that was achieved was dependent on the type of material. The potential for hydrocarbons to convert to organic acids by photo-oxidation was a concern and would require monitoring as the organic acids formed that could affect the long term durability of the materials.

Glycerine (the chief alcohol constituent of oil) and glycol ($C_2H_60_2$) act in a similar manner to weak acids, reacting with calcium hydroxide in the hardened cement paste to form soluble calcium salts. Biczok reports work by Vierheller that found that aqueous glycerine solutions with a glycerine content as low as 2% leached calcium hydroxide from concrete and mortars. The amount of calcium hydroxide leached increased as the amount of glycerine in solution increased. Solutions containing between 50% and 90% glycerine caused decomposition and destruction of concrete. Lea (1970) reports that most vegetable and animal oils are only slightly aggressive to concrete. Ggbs concrete is likely to improve the chemical resistance.

Turpentine has little effect on concrete but can cause considerable penetration. The same can be found for lubricating oils of petroleum, but many of these oils also contain vegetable oils that if continuously spilt on a floor can cause gradual deterioration of the concrete (Lea 1970).

## Risk Assessment and Remedial Measures

There is currently no guidance that provides advice on the performance of concrete in land contaminated by organic substances. Deterioration of concrete may not be a major issue but permeation by low viscosity liquids is likely to be more of a concern. There are also likely to be differences depending on whether the organic exists as a free phase compound (non-aqueous phase liquids) or is soluble in ground water.

It would not normally be necessary to excavate and remove, contain or remove organic contaminated soil in order to overcome the risks to concrete. However, soil remediation may

be required as a result of risks to human health or the environment and this would have the benefit of removing the risks to the concrete.

### 2.3.8 Microbial corrosion

**Hazards**

As well as being corroded by chemical agents, concrete can be attacked by micro-organisms such as bacteria, fungi and lichens. The actions of aerobic and anaerobic bacteria are thought to be responsible for most microbial corrosion of concrete used below ground. When soil conditions change from anaerobic to aerobic or vice versa the dormant bacterial strain takes over (Doran 1987). The combined action of these bacterial strains can result in the formation of sulfuric acid that is highly corrosive towards concrete. Also, sites are likely to contain both anaerobic and aerobic areas, and so migration of $H_2S$ across the site can lead to the formation of an anaerobic - aerobic cycle, and the formation of sulfuric acid. Box 10 contains more details of studies on microbial attack on concrete.

**BOX 2.10: Microbial Attack**

The most widely recognised damage of bacterial origin is the deterioration of concrete in sewers (Eglinton 1987). Examination of samples taken from sewers has found that significant populations of aerobic bacteria are associated with concrete showing signs of decay (Kulpa 1990, Saricimen 1987). Laboratory experiments under controlled conditions in a specially built environmental chamber have shown that concrete exhibiting the greatest decay contains the largest cell count of the major aerobic species (Sand 1991, Sand 1987).

The role of bacteria in lowering the pH of soil was investigated using clay known to contain sulfate and both aerobic and anaerobic bacteria (Doran 1987). The investigation found that when the clays were exposed to aerobic conditions a rapid reduction in pH and increase in soluble sulfates was observed. Experiments on clay samples exposed to anaerobic conditions were inconclusive because, it was suggested, of inadvertent exposure of the samples to air during collection. It seems that even this limited exposure to oxygen was sufficient to start oxidation. Alternating the aerobic and anaerobic conditions did not significantly affect the rate of reduction in pH, and if anything it caused a decrease in the amount of sulfuric acid formed.

**Risk Assessment and Remedial Measures**

At present there is no guidance on the use of concrete in environments containing bacteria.

### 2.3.9 Performance in contaminated land

**Hazards**

The variety and mixture of contaminants that are likely to be encountered in contaminated sites has raised concerns as to whether or not existing guidelines for aggressive soils, such as sulfate soils, are sufficient for industrially contaminated soils. There is little definitive guidance on managing the risks to concrete from contaminants other than perhaps sulfate, chloride, magnesium and acids. However, only in the case of sulfate is there an extensive remedial strategy that covers both ground concentration of sulfate and the specification of concrete. Details of BRE research on concrete in contaminated land are detailed in Box 11.

**BOX 2.11: Performance in Contaminated Land Environments**

The performance of concrete in contaminated land has been the subject of research at BRE in recent years. The experimental programme has included four levels of test, as follows:

- Accelerated laboratory tests involving the immersion of small mortar prisms in solutions of contaminants (duration of exposure 2-4 months);
- long term tests involving the immersion of 100 mm concrete cubes in solutions of contaminants (duration of exposure 5 years);
- long term exposure of 150 diameter x 300 mm concrete cylinders in a contaminated soil slurry (minimum duration of exposure 10 years);
- a field trial involving installation of concrete piles in a contaminated land site (minimum duration of exposure 10 years).

The results of small-scale mortar prism tests have been reported (Paul 1992). Other published papers have reported the methods used to assess deterioration of the concrete in the long-term tests (Garvin and Lewry 1996, Garvin 1995, Garvin *et al* 1996, Garvin *et al* 1998, Garvin *et al* 1999). Table 4 shows the mixes that were selected for the experimental programme. Table 5 shows the solutions that were formulated in order to assess potential deterioration of different concrete mixes in contaminated soil. The impact on the compressive strength of the concrete mixes is shown in tables 6 and 7.

The performance of concrete in the various solutions is most easily indicated by reference to cement type, followed by cement content. The Portland cement concrete (mixes 1 - 3) had the poorest overall performance. In particular mixes 2 and 3 had deteriorated to the extent of near complete deterioration in a number of solutions. The acidified solutions (B and F) did not cause the same degree of deterioration as near neutral solutions, however, the strength was much reduced.

The performance of the pfa, SRPC, BRECEM (a 50:50 mix of high alumina cement and ggbs) and the higher cement content ggbs concrete was good in most of the solutions. The exception being in acidified solutions where most of the concrete samples had lost about 20% of their 28 day strength.

The results have indicated that the solutions of multiple contaminants caused enhanced deterioration of some of the concrete cubes in comparison with the cubes exposed only to sulfate. There was some evidence that the more resistant concrete mixes had their strength development retarded.

## Implications for Risk Assessment and Remedial Measures

The series of experiments as described in Box 11 has demonstrated that there are potentially greater risks when using concrete on contaminated ground with mixtures of contaminants as opposed to sites where only one contaminant causes concern. The problem with managing these risks is primarily concerned with the range of contaminants present and the great differences in concentrations.

This experimental programme has been aimed at developing guidance that can be used by concrete specifiers. In general the guidance would be based on Digest 363 but with advice to increase the class from, for example 3 to 4, if one or more other contaminants is present. However, at present there is no definitive guidance on concrete in contaminated soils where mixtures of contaminants are present.

The use of coatings in order to protect materials in contaminated land has been suggested (Garvin *et al* 1995). Advice is given on the selection of coatings that will be able to reduce permeation into the concrete and will be resistant to the contamination.

In general it is not considered that soil has to be excavated and removed, contained or treated in order to overcome risks presented by contaminated land to concrete. However, soils may be remedied for other reasons such as risks to human health or water sources that would remove or reduce the risks to concrete.

## 2.4 Reinforced Concrete

Reinforced concrete technology is now over one hundred years old and it is used in many countries and structures around the world (Andrioli 1998). The reinforcement is used to improve the tensile strength of the concrete. However, there are many buildings and structures that have suffered damage due to corrosion of the reinforcing bars in the concrete.

**Hazards**

Corrosion of the reinforcement can be caused by a breakdown of the protective layer, either as a result of corrosive ions, for example attack by chlorides, or as a result of a reduction in the pH of concrete through carbonation or leaching of calcium from the hardened cement paste. Further details of reinforcement corrosion in aggressive environments are given in Box 12.

**BOX 2.12: Reinforced Concrete Deterioration**

Concrete normally provides steel with corrosion protection as the alkaline environment of hydrated cement (pH 12.6 to 13.5) leads to the formation of a protective layer at the steel/concrete interface (ACI 1985, BRE 1982a, BRE 1982b). The protective layer is generally regarded to be a tightly adhering film of $\gamma$—$Fe_2O_3$ that forms soon after placing the concrete (Sagoe-Crentsil 1989). The cement matrix also provides a physical barrier to the ingress of corrosion-inducing agents such as oxygen, water and chlorides.

The corrosion of steel in concrete is generally regarded as an electrochemical process. The pressure generated by the formation of the rust, which occupies a larger volume than the iron from which it formed, can far exceed the tensile strength of the concrete with the result that the concrete cracks and eventually disintegrates. The rate of corrosion is determined by the rate of oxygen diffusion through the concrete that is faster in relatively dry than in saturated concrete (ACI 1985). If the pH is high and no chloride is present the ingress of oxygen does not cause corrosion. Corrosion of the steel will only occur if the concrete carbonates or there is a deleterious material present. For oxygen to be consumed in the cathodic reaction it must be in the dissolved state. Therefore, the presence of water is a prerequisite for corrosion to take place. As the water content of the concrete increases then the rate of oxygen diffusion decreases. In totally saturated concrete diffusion is too slow for corrosion to take place even if the passive layer at the surface of the reinforcement has been destroyed (CEB 1989). Corrosion of steel has occurred in North Sea oil rigs well below sea level.

The presence of sufficient quantities of free chloride ions in the concrete can stimulate reinforcement corrosion even in highly alkaline conditions (BRE 1982a, BRE 1982b, Nixon 1980). Three mechanisms have been postulated to explain the effect of chloride ions on steel corrosion as follows (ACI 1985, BRE 1994):

- Chloride ions destroy the protective layer on the steel surface either by penetrating the film through pores and defects or by colloidal dispersion of the film that makes it easier to penetrate.
- Chloride ions are adsorbed on the metal surface, promoting the hydration of the metal ion and thus facilitating the dissolution of metal ions.
- Chloride ions react with the ferrous ions produced in an anodic reaction to form a soluble iron chloride (green rust). This diffuses away from the anode destroying the protective layer (Raharinaivo 1987).

The ingress of chloride ions produces 'pitting' corrosion as the passive film is destroyed over only a small area (CEB 1989, Arup 1983).

Considerable work has been carried out on chloride-induced corrosion of steel reinforcement, in relation to atmospheric and marine conditions (ACI 1980, CIRIA 1985/86, Page 1990), but less attention has been paid to reinforcement corrosion in buried structures.

In underground concrete the physical properties of the concrete, in particular their influence on diffusion of oxygen and chloride, play an important role in determining the rate and extent of corrosion of the reinforcement (Nixon 1980). The vulnerability of reinforced concrete structures at the soil/atmosphere interface has been shown in houses built on former salt ponds (Howell 1990). Reinforced slab foundations had been placed in direct contact with soil containing 1400 to 4300 ppm $Cl^-$ and 760 to 1700 ppm $SO_4^{2-}$. Cracking and spalling were detected in most cases just above the soil/concrete interface.

Asrar *et al* (1999) have studied the corrosion of reinforcement in concrete containing microsilica (MS). PC and SRPC concretes were manufactured with various quantities of MS. In tests the corrosion of reinforcing bars was suppressed in the presence of MS, and the chloride ion permeability reduced significantly. It was suggested that MS reduces the quantity of calcium hydroxide in the concrete and increases the CSH phase. Therefore, the concrete becomes less porous and has a lower permeability.

**Risk Assessment**

The critical chloride content can be defined as the chloride content at the steel surface that leads to deterioration of the concrete structure. The concentration of chloride that can initiate corrosion depends on various parameters as follows (BRE 1994):

- Alkalinity of the pore solution (Popovics 1983).
- Water content of the concrete.
- Proportion of water-soluble chloride (Nixon 1980).
- Temperature – higher temperatures promote corrosion.
- Metal counter ion (Hansson 1985, Tuutti 1982).
- Extent of carbonisation.

Corrosion of reinforcement by chlorides is controlled principally by the diffusion of chlorides in water-filled pores and the diffusion of oxygen in air-filled pores (CEB 1989). The rate of diffusion is controlled mainly by the quality of the concrete cover that is a function of permeability and thickness. Factors that affect the rate of corrosion are as follows (BRE 1994):

- Water:cement ratio (CEB 1989, Neville 1987).
- Cement content (CEB 1989).
- Cement type - ggbs and pfa cements have been shown to be more resistant to chloride diffusion than PC (Neville 1987, Page 1981, Smolczyk 1984, Hjorth 1984).
- Thickness of the concrete 'cover' (CEB 1989, Moersh 1995).
- Whether protective coatings are used for the concrete surface or the steel reinforcement (Moersh 1995).

On the basis of the examination of a large number of reinforced concrete structures in the UK BRE has shown that it is possible to relate risk of corrosion to chloride ion concentration in the concrete (by weight of cement) (BRE 1982a, BRE 1982b). The classification initially places the chloride ion content in one of three categories:

- Low - less than 0.4%
- Medium - between 0.4% and 1.0%
- High - more than 1%

On this basis and other research into the chloride-induced corrosion of reinforcement, British Standard BS 8110:Part 1 limits the percentage of chloride (expressed as % $Cl^-$ by weight of cement) in reinforced concrete as shown in Table 8. These values are slightly higher than those proposed by the American building codes. Code ACI 318-83 (ACI 1983, Berke 1995) limits the value of water-soluble chloride ion content to 0.06% in prestressed concrete, 0.15% in reinforced concrete exposed to chloride in service and 0.3% for all other reinforced concrete. For reinforced concrete that will be dry or protected from moisture in service the limit is raised to 1.00%.

The corrosion of steel in concrete can be followed using measurement of the electrochemical half cell potential (Salil 1995). ASTM C876-80 describes the measurement of the half cell potential (E) to the risk of corrosion as follows:

- E > -200 mV (10% corrosion risk)
- E -200 to -350 mV (intermediate risk)

- E < -350 mV (90% corrosion risk).

The design of reinforced concrete has to consider the whole system and not concentrate on one aspect of the material (Berke 1995). Reducing the w/c ratio or using a pozzolanic material may not be sufficient in aggressive environments in the long term. Indeed, some measures such as reducing the w/c ratio or increasing the cement content can result in increased drying and shrinkage of the concrete and result in cracking that would lead to routes for chloride ingress.

**Remedial Measures**

In general it would not be necessary to undertake removal, containment or treatment of soil to manage the risks from contaminated land to reinforced concrete. It is preferable to produce concrete that is of good quality and suitably designed to resist contaminant attack.

A number of measures can be included in the reinforced concrete with respect to reducing the potential for reinforcement corrosion, as follows:

- Provide suitable concrete cover, of depth and density, to the reinforcement (BSI 1985);
- Reduce the permeability of the cover concrete;
- Protect the reinforcing bar using epoxy coatings;
- Use cathodic protection in aggressive environments;
- Prevent drying shrinkage and cracking of the cover concrete by the use of admixtures or replacement materials such as ggbs.
- Use corrosion inhibitors, one example is nitrite based inhibitors that are chemical admixtures or surface applied treatments that compete with chlorides for sites on the reinforcing bars (Broomfield 1999).

The repair of damaged reinforced concrete is a specialised field, but one in which there is considerable experience. The most common approach to repairing damaged reinforced concrete is to remove the concrete to beyond the level of the reinforcement. The reinforcement can then be cleaned and the corrosion removed, a coating can then be applied if this is thought to be necessary. The concrete cover can then be built up using a suitable repair concrete.

Alternative methods of repair can be considered, as follows, these depend on the condition of the concrete and degree of deterioration:

- Desalination and realkalisation techniques using the application of electric currents between the concrete surface and the reinforcement. Chloride ions are moved outwards towards an electrolyte membrane where they collect. The concrete cover is re-alkalised during the process.
- Treatment of the concrete surface can be undertaken using suitable coatings. This should only be done when the surface is in good condition and the reinforcement is still covered. Coatings are therefore most likely to be used where future problems are being predicted as opposed to dealing with failure.

## 2.5 Asbestos Cement

Asbestos cement is a composite material in which 10 to 15% asbestos fibre is bound in a matrix of Portland Cement (PC) or autoclaved calcium silicate. Most asbestos cement is made with white asbestos (DoE 1991).

**Hazards**
Asbestos fibre is mechanically strong and highly resistant to heat and chemical attack (DoE 1991). The durability of asbestos cement is therefore largely controlled by the chemical resistance of the cement paste. Further details are given in Box 12.

**Risk Assessment**
As the problem of chemical resistance of asbestos cement is essentially a problem of the chemical resistance of the cement matrix, the mechanisms by which asbestos cement corrodes are much the same as those for concrete. Guidance on the use of asbestos cement pipe is given in British Standard BS 8010: 1985 (BSI 1988). It advises that a coated asbestos cement pipe should be used in conditions where the pH of the groundwater is between 6 and 5.5 and the sulfate concentration (expressed as $SO_3$) is between 2 and 5 g/l. In conditions where the pH is less than 5.5 and the $SO_3$ level above 5 g/l the standard recommends that specialist advice be sought.

**BOX 2.13: Asbestos Cement Performance**
The acid corrosion of asbestos cement differs from concrete degradation in that asbestos cement corrosion progresses and softens the matrix in only a thin layer, from tenths of a millimetre to a few millimetres deep (Nebesar 1983). The depth to which the material is softened depends on the following:

- The duration of the corrosive action,
- The concentration of the aggressive chemical,
- The convection conditions in the reaction environment,
- The solubility of the corrosion products.

Corrosion due to sulfates causes failure as a result of expansion leading to cracking and spalling of the cement surface. Asbestos cement is less permeable than most bulk concrete and therefore it is generally considered to be more resistant to corrosive influences. However, for certain chemical environments, for example sulfates, the experimental evidence does not support this hypothesis. Investigations into the sulfate resistance of asbestos cement pipes have found that once they are exposed to an aggressive sulfate environment they perform no better than other cementitious product (Mason and Blair 1962, Maui 1985). Mason and Blair showed that the durability of asbestos cement is directly related to the free lime content of the hydrated cement paste. They submerged samples of normally cured asbestos cement pipe (high free lime content) and autoclave-cured asbestos cement (low free lime content) in Medicine Lake, South Dakota (35 000 ppm $SO_4^{2-}$). After 10 years normally cured samples had been completely destroyed while autoclaved samples (with lower free lime content) showed no signs of deterioration.

**Remedial Measures**
Guidance on the durability of asbestos cement pipe has also been developed by manufacturers (Crathorne 1987 gives two references, TAC and Fibronit). Asbestos cement pipes are not recommended for the following conditions:

- Sulfate content (expressed as $SO_3$) of the ground-water is >5000 mg/l;
- Sulfate content (expressed as $SO_3$) of the soil is >20 000 mg/kg (2%);
- Soil/ground-water pH is <5.5;
- Free carbon dioxide content of the ground-water (in ppm) is 20 + 5.1 x carbonate hardness (as ppm $CaCO_3$).

There are no recommendations based upon removal, containment or treatment of contaminated soils where asbestos cement pipes are to be used. However, other methods of isolating the pipe from contaminated soil could be considered, examples are as follows:

- Laying the pipe in a trench with clean backfill.
- Routing the pipe away from the contaminated ground or area of the site with high levels of sulfate.
- Providing a sleeve or coating to the asbestos cement surface.
- Laying the pipe in a clean soil cover system.

## 2.6 Masonry

Brickwork or blockwork is a composite of two dissimilar materials, brick or blocks and mortar. The durability of brickwork structures depends on the durability both of the masonry units and the mortar (Grimm 1987).

### 2.6.1 Clay brick

Clay bricks are highly durable materials that have been used in buildings and other structures for centuries. Fired clay pipe material can also be considered as similarly resistant to contaminants. However, the permeability of both bricks and clay pipes will leave them at risk from salt crystallisation and in the case of pipes to contamination of the contents of the pipe.

**Hazards**
Dissolution of clay brick is potentially a serious cause of deterioration. The extent of dissolution depends on the solubility of the glass in the material. The acid nature of the glass phase means that while it has a low solubility in a neutral or acidic environment it can have an appreciable solubility in a basic environment. The three main reaction steps in the dissolution of the glassy matrix are as follows (BRE 1994):

- Ion-exchange reactions.
- Partial hydration of the glass surface.
- Dissolution of the glass surface.

Further details of clay brick deterioration are given in Box 14.

**Risk Assessment**
Engineering bricks are well fired materials glassy materials that are durable under aggressive underground conditions. For example, in sewers and similar conditions they have proven to be the most durable masonry lining.

The maximum dissolution of brick is usually only 1% except when attacked by hydrofluoric

acid, and so the extent of deterioration by dissolution is usually small.

A potentially more serious problem for brickwork is the crystallisation of soluble salts within the brick pore structure. The salts are transported by water to the interior of brick and can derive from the external environment or from the rehydration of the soluble phase of the brick. However, salt crystallisation is only likely to occur where there is a gradient from a wet interior to a drying surface. The potential for salt crystallisation in the ground is therefore low.

Bricks are not generally subject to attack from fungi and bacteria.

**BOX 2.14: Brick Performance**

Clay bricks are essentially a composite of crystalline phases embedded in a glassy matrix. The crystalline components are generally of low solubility, and so the corrosion properties are usually determined by the glassy phase, which in some cases can constitute as much as 60% of the brick (Hill 1960). A number of studies have shown that the most durable bricks are those with a low porosity and low microporosity (Robinson 1984, Somsiri 1985, BRE 1992).

British Standard BS5628: Part 3 (BSI 1985) provides an overview of the durability of masonry in aggressive conditions. The durability of masonry, both units and mortar, is described as being affected by the following:

- Exposure to the weather or other sources of water.
- Exposure to aggressive conditions from all sources including the ground.
- The adequacy of measures taken to prevent the masonry from becoming saturated both in terms of design and workmanship.

Aggressive contaminants, such as sulfate, can be prevented from entering the main wall structure from the ground by the use of appropriate damp proof courses (BSI 1985). However, brickwork below the ground will still be subject to exposure to sulfates and other contaminants below the dpc level.

Calcium silicate bricks are resistant to attack by most sulfate salts in the soil and ground-water (BSI 1987). The durability of calcium silicate bricks under salt crystallisation attack can be attributed to a combination of their low soluble salt content and their low porosity and coarse pore structure. However, the calcium silicate bricks may be attacked by high concentrations of magnesium and ammonium sulfate. They may also suffer severe deterioration if they are impregnated by strong salt solutions, such as calcium chloride or sodium chloride, and then subjected to frost.

The resistance of buried brickwork to sulfate attack is being investigated in a long-term durability trial, involving four half-brick walls built with calcium silicate bricks (Class 2-3 according to British Standard BS187: 1978) in 1:1:6 mortar (Saunders 1987). A visual examination of the four calcium silicate walls after 15 years' burial found no sign of deterioration either to the bricks or to the mortar.

## Remedial Measures

Soil removal, containment or treatment is not normally considered necessary in managing the risks to clay bricks in contaminated land. It is normal to ensure that the brick will not be attacked by contaminants in the ground through either dissolution or salt crystallisation.

Guidance is provided on the durability of clay bricks in aggressive environments in BS8301 where it is stated that bricks are particularly suitable for soil environments containing sulfates or acids (Carlsson 1988). BS5628: Part 3 provides guidance on masonry in aggressive

conditions. In cases where continuous exposure to foul water sources is predicted then the use of engineering bricks is recommended.

### 2.6.2 Concrete blocks

**Hazards**

Precast aggregate concrete blocks and autoclaved aerated concrete (AAC) blocks are commonly used in the construction of shallow foundations for housing and low rise buildings. Concrete blocks are potentially attacked by the same contaminants and ground conditions that affect dense concrete. Box 15 contains details of the limited studies that have been undertaken on concrete blocks in aggressive soil conditions.

**BOX 2.15: Concrete Block Performance**

Recent work has assessed the durability of various precast concrete blocks in sulfate solutions (Pettit 1996). In this research blocks were subjected to sulfate soil conditions. It was found that the blocks were resistant to sulfate class 3 levels. This was regardless of the type of cement used in the manufacture of the blocks. It was found that there was a positive benefit from allowing the concrete blocks to carbonate prior to immersion in the aggressive solutions. This finding is in agreement with other work where the benefits of some carbonation on sulfate resistance have been found for dense concrete (Arber 1961).

BS5628: Part 3 (BSI 1985) does not allow the use of aircrete and aggregate concrete blocks to be used in foul drainage. Therefore, concrete blocks are not generally suitable for acid soil conditions. In surface water conditions concrete blocks can be used with certain limitations.

The performance of concrete blocks in contaminated soils using both laboratory and field tests is the subject of current work at BRE.

**Risk Assessment and Remedial Measures**

In general the mechanisms of chemical attack on concrete blocks is likely to be the same as for dense concrete. BRE Digest 363 allows the use of precast and AAC blocks in class 1 conditions, and in class 2 and 3 providing the density is greater than 600 kg/m$^3$.

It is not normally considered necessary to remove, contain or treat soil in order to manage risks to concrete blocks. However, soil may be remedied for other reasons that may help to remove or reduce the risk to the blocks. At present there would be doubts over the use of concrete blocks where sulfate levels exceed class 3 sulfate levels (3 g/l) and this is a barrier to their use in developing contaminated sites. The current research on their performance in contaminated soil is therefore necessary.

Concrete blocks are not allowed in foul drainage and therefore their use in acid soils is questionable.

### 2.6.3 Mortar

Mortars are based on building sands (‘soft’ sands) mixed with cement and/or lime as a binder (BRE 1991). In the UK, the most commonly used cements are Portland cements and masonry cements. Masonry cements are a mixture of Portland cement and fine mineral filler (for example limestone) with an air-entraining agent.

**Hazards**
Mortar is subject to the same agents of deterioration as concrete where one of the main causes of the deterioration of mortar is sulfate attack (Harding 1986). The reaction between sulfate and the hydrated tricalcium aluminate in Portland cement results in the expansive formation of ettringite. At low temperatures the deteriorated sample may also contain thaumasite (BRE 1996, Crammond 1985, Halliwell and Crammond 1996). Further details are given in Box 16.

**Risk Assessment**
Sulfates can come from the environment adjacent to the brickwork or originate from the bricks themselves. Calcium, magnesium, sodium and potassium sulfates are present in almost all fired-clay bricks. Water can dissolve a fraction of these sulfates and transport them to the mortar, where they can react with the hydrated constituents of the cement binder.

**BOX 2.16: Mortar Performance**
The durability of building mortar under sulfate attack was investigated in a series of laboratory experiments at BRE (Harrison 1986). The sulfate resistance of mortar was found to be improved by the use of sulfate-resisting Portland cement and lime:Portland cement mortars with a cement content of at least 200 kg/m$^3$. Lime mortars were found in a recent study to be more durable to sulfate attack than PC mortar that was used in restoration work (Moricini 1994).

Halliwell and Crammond (1996) have studied the deterioration of brickwork mortar in underground retaining walls. Problems were experienced when the ground water conditions were changed and the masonry was subject to constant wet and cold conditions. The source of sulfate, however, was from the type of brick that was used. Whilst the sulfate was in the form of calcium sulfate when it was wet for a long period of time the sulfates transferred to the mortar joint. The 1:3-5 PC:sand mortar, although strong, was rapidly affected by thaumasite attack.

Microbially induced corrosion is recognised as being important to the performance of PC and lime mortars (Wilimzig 1996a, Wilimzig 1996b). Some bacteria can oxidise ammonia to the inorganic acids (nitrous and nitric acids). Mortar located in wet areas can contain high amounts of bacteria and fungi, as water is one of the main causes of growth of micro-organisms. Ammonia from the environment has been found to convert to nitrites and nitrates and then to nitric acid. This was then found to cause damage to mortar in buildings.

**Remedial Measures**
Guidance on suitable mortar designations for a number of environments is given in BS5628:Part 3 (BSI 1985). However, there are no specific guidelines for contaminated ground. BRE Digest 363 gives recommendations for both the composition and use of a general use mortar (lime:Portland cement) and sulfate resisting Portland cement that have resistance to attack by sulfates.

In general soils are not removed, contained or treated in order to manage the risks to mortar from contaminated soil.

## 2.7 Metals

There are a number of metals that are used in building either for piles, services, non-structural components and structural components. The most common types of metals used are steel, stainless steel, copper, lead, zinc, aluminium and cast iron. All these metals can deteriorate through corrosion processes and the mechanisms and types of corrosion are common to all metals.

### 2.7.1 Corrosion

**Mechanisms of Corrosion**
The common forms of corrosion are as follows (BRE 1994):

- Electrochemical – the most common form of corrosion in an aqueous medium.
- Chemical corrosion - occurs when there is direct charge transfer between the metal and the attacking medium. Examples of chemical corrosion are oxidation, attack by acids and alkalis, and the action of organic solvents.
- Microbial induced corrosion (Tiller 1984, Von Wolzongen Kultr 1934, Shrier 1976, Zhu 1995).

**Forms of corrosion**
Corrosion can affect metals in a variety of ways depending on the nature of the metal and the precise environmental conditions to which it is subjected (Carlsson 1988). The main forms of corrosion are as follows (BRE 1994, Davies 1996, Fontana 1983, Shrier 1976).

- Uniform corrosion is usually characterised by chemical and electrochemical reactions that corrode the metal evenly over the majority of its surface. This is the most common form of corrosion.
- Localised corrosion is caused by heterogeneities in the metal. The environment or geometry of the structure can cause certain areas of the metal surface to corrode at a higher rate than others. Forms of localised corrosion include crevice corrosion, intergranular corrosion or stray current corrosion.
- Pitting is an extreme form of localised attack that results in small holes (pits) that penetrate the metal and cause perforation.
- Selective dissolution occurs in some alloys where one component, usually the most active, is selectively removed.

The synergistic action of corrosion and mechanical actions can result in localised attack or fracture of the metal. The most common forms of combined chemical and mechanical attack are stress corrosion cracking and hydrogen embrittlement.

**Risk Assessment and Remedial Measures for Corrosion**
Corrosion in soil is predominantly an aqueous electrochemical process. However, conditions in soil vary from dry to saturated and, as a result, corrosion can range from negligible to rapid (Davies 1996, Hassani 1978, Lankes 1981). Variations in soil composition or structure can cause different environments to act on different parts of the same metal element that results in different electrical potentials at the soil-metal interface.

The heterogeneous nature of soil and the variety of factors that contribute to the operation of the corrosion cell make soil corrosivity difficult to predict. However, examination of the electrochemical mechanism shows that the conductivity of soil can be rate-controlling and, as a result (see Table 10), soil resistivity measurements have become one of the most widely used measurements of soil corrosivity (Uhlig 1971, King 1977, Knofel 1978, Miller 1981).

Booth *et al* (1971) developed a classification of soil corrosivity using resistivity and redox potential measurements. In cases where the two measurements placed the soil on the borderline between corrosive and non-corrosive, the classification used water content as a further criterion of corrosivity. If the water content of the soil was greater than 20% then the

soil was regarded as corrosive.

A number of other classifications have considered the combined effect of resistivity, redox potential, moisture content, pH, presence of carbonaceous materials, chlorides, sulfates, sulfides and carbonates. The most comprehensive of these 'complete' classifications are those devised by the German Gas and Water Association (DVGW) and the Ductile Iron Pipe Research Association (DIPRA) to measure the corrosivity of soil towards iron and steel (Collins 1983).

### 2.7.2 Cast Iron

Cast iron is a term used to describe ferrous metal alloys containing more than 1.7% carbon. It is comparatively cheap and easy to manufacture and therefore has been extensively used in the manufacture of pipes (Collins 1983). The main types of cast iron commonly encountered are 'grey' cast iron, in which most of the carbon is in the form of carbon flakes, and ductile cast iron, which uses graphite nodules.

**Hazards**

Traditionally, cast iron is regarded as having good resistance to corrosion by soils, the principal hazard being mechanical overloading (Collins 1983). More details are given in Box 17. However, corrosion can occur through the development of large-scale galvanic cells, caused by differences in salt concentrations, oxygen availability or the presence of stray electrical currents (Davies 1996).

Cast iron possesses no useful resistance to mineral acids. Hydrochloric acid will cause corrosion at any concentration and temperature. Dilute sulfuric, nitric and phosphoric acids are also aggressive. Similarly corrosive are well-aerated organic acids.

**Risk Assessment**

The corrosivity of salt solutions depends on the nature of the ions present. Salts of aluminium, iron and calcium hydrolyse to give acid solutions that if well aerated are corrosive to cast iron.

**BOX 2.17: Cast Iron Performance**

The resistance of cast iron pipes, both grey and ductile iron, to soil corrosion was comprehensively investigated in a nine-year study carried out jointly in the UK (Colchester), Germany (Varel), and France (Mont St Michel). More than 1000 specimens were buried in the three countries and excavated at two, five and nine years for examination. The characteristics of the three sites are given in Table 11.

A comparison of the maximum pitting depths found that the samples buried in soils containing appreciable quantities of chloride and sulfate (Varel and Mont St Michel) had corroded to a greater extent than those buried in soils containing only a small amount of the anions (Colchester). The results also showed that ductile cast iron had superior corrosion resistance to grey cast iron.

Cast iron is susceptible to corrosion by sulfate-reducing bacteria. In addition to localised pitting corrosion it undergoes a form of selective leaching known as graphitisation that reduces the mechanical strength of the material. Failure of cast iron pipes (6 mm thick) within a year and perforation within four years as a result of microbial corrosion are quite common (Tiller 1988). The intrinsic corrosivity of the sulfide films which can develop on ferrous metals is high (Table 12).

**Remedial Measures**
Guidance is available on the aggressiveness of soils based on resistivity and redox potential measurements. This could be developed into a series of recommendations for protection of cast iron components using coatings, burial trenches or isolation techniques. However, at present there is no definitive guidance and consultants will be required to develop their own specification for protection of such materials.

Guidelines, drawn up by the Water Research Centre (WRc) on the use of ductile iron pipes, state that highly acid soils (pH <5) are corrosive towards cast iron pipes even when they are protected by a system of zinc coating and loose polyethylene sleeving (Crathorne 1987, BRE 1994). The WRc guidance on the use of ductile iron pipes states that groundwater containing >300 ppm chloride may corrode even protected cast iron pipes.

It is normally necessary to isolate cast iron pipes from contaminated soils. Remedial measures could involve one or more of the following processes:

- Laying the pipe in a trench with clean backfill.
- Routing the pipe away from the contaminated ground.
- Providing a sleeve or coating to the pipe surface.
- Laying the pipe in a layer of clean soil cover system.

### 2.7.3 Steel piles

**Hazards**
The corrosion of steel requires the presence of both oxygen and water (except in the special case of anaerobic bacterial corrosion). In undisturbed natural soils the type and amount of corrosion of driven steel piles is generally so small that it is negligible irrespective of the soil resistivity and soil pH (Romanoff 1962). However, in disturbed soils corrosion rates can be high, see Box 18. This difference in the corrosion rate of steel in disturbed and undisturbed soil is thought to be due entirely to the differences in oxygen concentration.

**BOX 2.18: Steel Pile Performance**
The British Steel Corporation (Morley 1978) investigated piling recovered from underground exposure, and confirmed the findings of a previous United States study. Corrosion of steel piling in UK soils was found to range from 0.0 to 0.03 mm/year with a mean of 0.01 mm/year.

Piles in fill materials have been found to corrode at twice the rate of those in undisturbed natural soils (0.02 to 0.04 mm/year, with some piles showing corrosion rates as high as 0.06 mm/year) (Morley 1988). The formation of a galvanic corrosion cell between the upper portion of the pile in the fill and lower portion in the undisturbed soil is thought to be responsible for the additional corrosion. The heterogeneous nature of most contaminated land sites may well encourage the formation of such corrosion cells, and so cause an increase in the rate of corrosion of steel piling.

Steel, like cast iron, is susceptible to corrosion caused by the action of sulphur-reducing bacteria. However, there is no evidence in the literature to suggest that this is a problem with driven steel piles, except where they project above ground in installations (Morley 1978). One possible explanation for the lack of microbial corrosion on driven steel piles is that in undisturbed ground, bacterial mobility, nutrient replenishment and the symbiotic relationship with aerobic bacteria cannot be sustained at a significant level (Morley 1988).

**Risk Assessment**
Guidance on the use of steel piles in different environments is provided in British Steels Piling Handbook (British Steel 1997). This covers underground conditions where the lack of corrosion of steel piles driven into undisturbed soils has been noted. A maximum corrosion rate of 0.015 mm/side of the pile is allowable each year. In the case of landfill sites or industrially contaminated soils corrosion rates may be higher and additional protection will be required for the steel pile. The effective life of unprotected steel piling depends upon the combined effects of imposed stresses and corrosion rates. The end of the effective life is reached when any part of the pile reaches the maximum permissible working stress as a result of the loss of section due to corrosion. Guidance is provided in the Piling Handbook on how to calculate the effective life of steel piling in various environments. However, there is no specific guidance for contaminated soils.

**Remedial Measures**
Remediation of contaminated soil by removal, containment or treatment is not normally considered solely in order to protect steel piles. In cases where there are concerns over durability it may be preferable to use a more resistant type of steel or consider alternative types of piles. The use of coatings for steel has been suggested as a way of providing additional protection for aggressive soils (BRE1995). However, experience has shown some coatings can be severely damaged when piles are driven into made ground that contains hard materials such as waste brick or concrete or stone.

In aggressive environments, such as marine exposure or contaminated ground, it is necessary to provide additional protection to steel. This can be done in various ways as follows:

- The use of zinc or zinc/alloy coating systems (including Zn/Al, Zn/Fe, Zn/Ni, Zn/Co, Zn/Cr).
- The use of a conversion coating.
- The use of an organic coating applied by painting of liquid paint, or stoving of powder coatings. Polyester and epoxy powder coatings are commonly used.
- Cathodic protection systems.

### 2.7.4 Stainless Steel

**Hazards**
Stainless steel is used in buildings in a number of applications, including services, pipework, reinforcement bars for concrete and wall ties. There has been a general shift in recent years from copper pipes to stainless steel, as they can cope with a wider range of water qualities and conditions (Powell 1996). However, there is little knowledge of their performance in the long term and in aggressive environments. Box 19 provides more information on stainless steel.

**BOX 2.19: Stainless Steel Performance**
Stainless steel is an alloy of iron with chromium, nickel, zinc or molybdenum. There are various types of stainless steel that are described as Types 304, 304L, 316 and 316L. Type 304 is generally the most widely used, but type 316 that contains molybdenum is more resistant (Percival 1998). Stainless steel forms a durable layer of chromium oxide almost instantaneously on exposure to air and water. However, weaknesses in the film will be exposed by aggressive environments.

Atmospheric corrosion of stainless steel has been studied in roof and eaves situations (Tochihara 1996). It was found that chloride was the main factor that facilitated corrosion. In general the eaves were worse than the roof as they were not subject to washing from rainwater that removed salts.

**Risk Assessment**
Stainless steel can withstand pH of 6.5 to 8.5, but aggressivity of soil also depends on chloride content. At concentrations of chloride of less than 200 mg/l type 304 stainless steel can be used. However, for chloride concentrations of 200 to 1000 mg/l then type 316 should be used in preference to type 304 and above 1000 mg/l type 316 should always be used (Powell 1998).

**Remedial Measures**
Remediation of contaminated soil by removal, containment or treatment is not normally considered solely in order to protect stainless steel. Specific guidance is not available on the specification and protection of materials in contaminated land. However, the evidence presented above shows that 316 grades of stainless steel should be used in aggressive environments.

### 2.7.5 Galvanised steel

**Hazards**
Zinc galvanising of steel is in itself a way of protecting the steel from atmospheric corrosion and from aggressive environments. However, zinc galvanising can be corroded by salts and acids.

**Risk Assessment**
Galvanised steel is used in structural steelwork, cold rolled sections, decking, cladding, rebars, wall ties, fasteners and services. A study has been undertaken to assess the performance of galvanised steelwork in various aggressive environments in construction (Dennis 1997). Samples of steel with zinc and zinc alloys were immersed in various solutions. Zinc alloys generally performed better than pure zinc coatings. Chromate conversion coatings also enhanced the performance of all the coatings examined.

**Remedial Measures**
Remediation of contaminated soil by removal, containment or treatment is not normally considered solely in order to protect galvanised steel. However, there is currently no guidance on the use of galvanised steel in contaminated ground.

### 2.7.6 Copper

**Hazards**
Copper is commonly used in pipes for gas and water supplies. Copper is essentially immune to corrosion in most natural ground environments, but in contaminated ground could be subject to corrosion by acids, sulfates, chlorides and ground containing cinders. Copper

performance in aggressive soils is detailed in Box 20.

**BOX 2.20: Copper Performance**

Research by the British Non-Ferrous Metals Research Association (BNFMRA) between the early 1940s and the late 1950s found that copper could safely be used in a wide range of soils without corrosion (Davies 1996). Copper, when it does corrode, generally does so in a uniform manner. Pitting corrosion is less likely to be found and only under limited and rare conditions (Wagner 1997, Anon 1998).

Corrosion of copper pipe has been found in the following instances:

- Corrosion has been found in copper pipes installed in ground containing cinders (pH 7.1) and in highly aggressive soils, including wet acid peat (pH 4.6) and moist acid clay (pH 4.2).
- Copper has been found to be rapidly attacked by oxidising acids such as nitric acid and concentrated sulfuric acid, acid solutions containing oxidising agents such as ferric and stannic ions, and strongly oxidising alkaline solutions (Crathorne 1987, Davies 1996).
- Salts of sulfate and chloride have been strongly linked to copper corrosion, particularly when found in soils with poor drainage and high moisture retention capacity (Myers 1984). Cyanides can also attack copper pipes through the formation of complexes with copper (Davies 1996).
- In soils containing sulfate-reducing bacteria (srb), where anaerobic conditions develop, sulfides can be formed, and these are aggressive to copper. A European funded research project has recently been studying microbially induced corrosion of copper (Wagner D 1997). It was found that the basic corrosion process appears to follow the chloride model, but this can become overshadowed by the effects of additional anions such as sulfate and bicarbonate.
- Severe corrosion of copper pipe has also resulted from the formation of differential aeration cells (Anon 1998). A 6 m copper pipe, of which 4 m was in sand and 2 m in clay, corroded through in less than six months.
- Corrosion of copper pipes was caused by cinders, acid peaty soil, sulfate reducing bacteria, and the presence of deleterious chemicals in the soil. There is, however, no direct relationship between any single feature of soil composition or constitution and the rate of corrosion.

**Risk Assessment**

The resistance of copper to corrosion is due to the formation of a protective oxide film, $Cu_2O$, that covers the entire surface of the metal. In atmospheric corrosion the green patina which provides protection is initially $CuSO_4.Cu(OH)_2$ and changes in time to $CaSO_4.3Cu(OH)_2$. If this film is destroyed and cannot be replaced, then copper will corrode. In most soil conditions the film remains intact or is readily repaired, and so corrosion is limited (Myers 1984).

**Remedial Measures**

Remediation of contaminated soil by removal, containment or treatment is not normally considered solely in order to protect copper pipes. There is no guidance on specific issues of the durability and protection of copper in contaminated land. However, copper is resistant in natural soils and to a number of contaminants that are likely to be found in the ground. Protection of copper pipes could be achieved through the following:

- Laying the pipe in a trench with clean backfill.
- Routing the pipe away from the contaminated ground.
- Providing a sleeve or coating to the pipe surface.
- Laying the pipe in a clean soil cover system.

### 2.7.7 Lead

**Hazards**
Lead has been used in construction in various applications such as pipes, flashings, damp proof courses, tanking and roof sheets. Lead pipes are no longer used, although many may still be found in buildings. Lead has been found to be subject to corrosion from acids in construction, especially in lead roofs (LSA 1990).

**Risk Assessment**
Lead is a durable material that is resistant to corrosion in most environments. There are no particular concerns over lead sheets used in urban, rural or coastal environments and even thin sheets will last the lifetime of a building. However, other factors such a thermal movement can lead to breakdown of the material. Slow corrosion of lead has been noted by the release of dilute acids from lichen and mould growth.

Lead sheets are protected by a patina which forms on contact with air which are composed of cerrusite ($PbCO_3$) or hydrocerrusite ($Pb_2(CO_3)_2(OH_2)$) (Edwards 1997). In some cases this patination is undesirable as it is aesthetically unacceptable. A coat of patination oil should be used to protect the lead if it is exposed to air and water. The formation of lead sulfate on the surface of lead prevents further corrosion as it is insoluble. For this reason sulfuric acid is manufactured in a lead retort.

Organic acids from timber in the roof can leach out and caused deterioration of the lead sheets. Lead damp proof courses can be subject to attack from free lime released by Portland cement based mortar and concrete. In the presence of moisture a slow corrosive attack is initiated on the lead sheet. It is recommended that a thick coat of bitumen coating should be used to protect the lead damp proof course.

**Remedial Measures**
Remediation of contaminated soil by removal, containment or treatment is not normally considered solely in order to protect lead components. There is no guidance that is currently available on lead in contaminated soils. However, the literature has shown that acids and alkalis (lime) could be aggressive towards lead and clearly protection would be required where these conditions exist.

## 2.8 Organic Materials

### 2.8.1 Plastics

The range of plastics used in construction is wide and increasing. The principal uses of plastics below ground are shown in Table 13. The deterioration of plastics varies with the individual material (chemical and morphological structure, and the type and content of any additive) and with the environment in which it is exposed. In general, plastics deteriorate through degradation of their polymeric constituent. However, loss of plasticiser and other additives can render plastics ultimately unserviceable.

The main mechanisms of polymer degradation are fully described in BRE Report BR 255 and

are summarised as follows (BRE 1994):

- Polymer degradation - This is a collective term given to the various processes that change the physical properties and characteristics of polymeric materials (Crarthorne 1987, Schnabel 1981, Kelen 1983).
- Solvation (swelling and dissolution) - Diffusion of solvent molecules into a polymer results in swelling of the plastic (Matrecon Inc. 1988).
- Environmental stress cracking (ESC) – This is craze or crack growth, brought about by the simultaneous action of surface-active substances (for example alcohol, soap, wetting agent) and mechanical stress (Crathorne 1987).
- Microbial degradation (biodegradation) - This is essentially a chemical process, involving extracellular enzymes produced by bacteria (Huang 1990). Fungi can also cause cracking and crazing of some plastics (Seal 1988).

Sunlight, heat, moisture and certain chemical agents are the main environmental factors that affect the durability of plastics (BRE 1977). The susceptibility of polymers used in geosynthetics to aggressive soils is shown in Table 14.

Permeation is the transport of compounds through plastic without necessarily causing the plastic to fail mechanically (BRE 1994). The driving force for permeation is the difference in concentration of a contaminant on the upstream and downstream sides of the plastic. Permeation through plastics proceeds in three phases (Matercon Inc 1988):

- Organic chemicals accumulate in the soil/plastic interface, either by going into solution or by adsorption of the permeant at the surface of the plastic,
- The organic chemicals diffuse through the plastic,
- There is partition between the organic chemicals in the plastic and in the water contained by the plastic, i.e. evaporation or desorption of the permeant occurs at the downstream side of the plastic.

However, the precise mechanism by which an organic chemical permeates a plastic differs with the type and form of polymer (Vonk 1985).

### 2.8.2 Plastic Membranes and Geotextiles

Plastic membranes and textiles are used in construction as damp proof courses, gas resistant membranes for buildings, cover systems and liners. They are required to restrict the movement of water or gas from the ground into the building, building materials or components. The common materials used for membranes are polyethylene and poly vinyl chloride.

**Hazards**

Membranes of polyethylene and PVC are attacked by a variety of acids and solvents. Boxes 21 and 22 provide details of the performance of polyethylene and PVC in aggressive environments.

**BOX 2.21: Polyethylene Membrane Performance**

The chemical resistance of high-density polyethylene (HDPE) has been investigated by Bellen, Corry and Thomas (Bellen 1987). The HDPE membrane was immersed at $23^0$C and $50^0$C in twenty different chemical solutions and liquids for up to 2 years. The chemical resistance was then assessed by measuring changes in appearance, weight, dimensions and tensile properties. The results are shown in Table 15 where generally the properties were little affected, except by one type of lubricating oil.

Further studies of the effect of waste liquids and acids on HDPE membrane have concluded that there was little change in properties after long immersion times (Matrecon Inc. 1988, Billing 1990).

High molecular weight polyethylene is resistant to microbial degradation (Kelen 1983, Seal 1988). A number of soil burial tests have shown that the maximum weight loss that can be expected for a high molecular weight polyethylene due to microbial degradation is 1 to 3% (Seal 1988).

Polyethylene membranes and geotextiles have also been shown to be resistant to installation damage (Greenwood 1992, Watts 1990). Damage trials with crushed limestone fill found that even under the most severe compaction regime employed in the tests the polyethylene geogrid suffered only a 13% decrease in tensile strength.

Compounds of high polarity have extremely low permeability coefficients and polyethylene is essentially impermeable to them. However, a number of compounds have been shown to permeate polyethylene in laboratory experiments. Table 16 gives an indication of the permeation behaviour of a variety of chemicals. Polyethylene is readily permeated by low molecular weight compounds such as benzene, toluene and tetrachloroethane (Vonk 1985). More polar compounds such as phenols, aliphatic alcohols and ketones, permeate polyethylene to a lesser extent.

**Risk Assessment**

Polyethylene has poor corrosion resistance to oxidising acids (nitric and sulfuric) at high concentrations. Hydrochloric acid (HCl) does not chemically attack polyethylene but can have a detrimental effect on the mechanical properties of the polymer. HCl can easily diffuse into the polymer, where it disrupts the intermolecular forces between the polymer chains (Bellen 1987). Alkalis, basic salts, ammonia solutions and bleaching chemicals such as chlorine, will all cause deterioration in polyethylene due to environmental stress cracking (ESC). Polyethylene is resistant to non-oxidising salt solutions. However, the presence of oxidising salts may result in surface degradation as the ions in the salt solution have a low rate of diffusion in polyethylene. Organic compounds, though they do not react with polyethylene, may cause swelling or ESC to occur.

Polyvinyl chloride (PVC) is degraded by the action of oxidising acids. Nitric acid is particularly aggressive towards PVC, causing the surface to become brittle (Bergman 1985). PVC does not deteriorate under the action of neutral and alkaline solutions. The presence of oxidising salts may cause deterioration, but in most cases this is not a problem, as the rate of deterioration is slow.

**Remedial Measures**

There is no guidance in the literature that is based on quantitative assessment of the risk to polyethylene and PVC. There is a lot of general advice on how contaminants will react with these plastics. However, there is no indication of how the ground conditions will alter the susceptibility to certain types of chemicals.

In general, the more concentrated the contamination then the greater is the risk to plastic membranes. The nature of the soil must be taken into account in assessing the risk, for example, soils have been shown to sorb organic chemicals, decreasing their mobility and activity (Holsen 1991). The amount of organic chemical sorbed by a water-saturated soil depends on the organic carbon content of the soil, the mass of the soil, the mass of water, and the mass and type of the organic compound.

**BOX 2.22: PVC Membrane Performance**

The chemical resistance of plasticised PVC geomembrane exposed to various chemical solutions is shown in Table 17. Bellen (1987) found that the dimensional and tensile properties of PVC were largely unaffected by water, sodium chloride and potassium dichromate solutions. However, some oils, acids and organic substances caused large changes in weight and tensile strength.

The chemical compatibility of three PVC geomembranes with various waste liquids has been investigated in a series of exposure tests (Matrecon Inc. 1988). The three PVC membranes differed considerably in their response to the different wastes. All three PVCs lost weight in 'slop water' (an alkaline waste), brine waste and 'oil pond waste'.

The resistance of PVC towards hydrocarbons is generally as good as, or better than, that of polyethylene. Organic compounds such as chlorinated hydrocarbons, anilines, ketones and nitrobenzenes cause PVC to swell and eventually to dissolve (Vonk 1985). Chemicals that do not cause PVC to soften do not permeate PVC. Thus, no significant permeation occurs for alcohols, organic acids or aliphatic hydrocarbons. The chemical resistance of plasticised PVC is greatly influenced by the chemical resistance of the plasticiser, which can constitute up to 40% of the plastic. Acids, alkalis and hydrocarbons can cause the plasticiser to deteriorate, and this in turn makes the PVC brittle.

The permeation of polyvinyl chloride (PVC) depends on the ability of the permeant to swell the polymer, and on its activity. The greater the ability of the permeant to swell the polymer, the lower the activity required to initiate permeation. Compounds that do not soften PVC do not permeate it to any significant degree (Vonk 1987). Thus, PVC is essentially impermeable to alcohols, aliphatic hydrocarbons and organic acids.

Plasticised PVC is highly susceptible to microbial degradation. The extent to which it is degraded depends on the type and quantity of any additives (Kelen 1983). Bright (1992) mentions De Coste's soil burial tests on PVC plasticised with phthalate-based plasticisers, which found that after 4 years the samples had suffered a 4 to 8% weight loss in plasticiser. This loss made the samples more brittle, with higher tensile strengths and net lower elongations.

### 2.8.3 Plastic pipes

**Hazards**

Plastic pipes are predominantly manufactured from PVC and PE, but other materials can be used. In general they perform well, but it is known that chemical attack and permeation of contaminants through the pipes can result from use in contaminated land, Box 23 provides further detail on pipe performance.

**BOX 2.23: Plastic Pipe Performance**

A review of plastic pipes and their properties for pipeline use has covered five types of material that could be used (Raman 1994). The description and various properties of the plastics can be summarised as follows:

- Polyethylene (PE) – This is an ultra high molecular weight material, it is highly impermeable and has good resistance to solvents, alkalis and acids. It retains good properties over a wide temperature range and has good abrasion resistance.
- Polyvinyl chloride (PVC) – The most common type of thermoplastic material used in pipeline construction. It is of relatively low cost, but has good physical properties and resistance to corrosion and chemical attack. PVC tends to be attacked by solvents such as ketones, chlorinated hydrocarbons and aromatics. It is generally used at ambient temperature.
- Polypropylene (PP) – This is this lightest of the industrial grade plastics. It has excellent strength to weight ratio and is used at high temperatures. It is chemically resistant to acids, alkalis and organic solvents. However, it is not recommended for use with strong oxidising acids, chlorinated hydrocarbons or aromatics.
- Polyvinylidene fluoride (PVDF) – PVDF is a strong, tough and abrasion resistant material. It can be used over a wide range of temperatures from –40°C to 300°C. PVDF is inert to most solvents, acids and alkalis as well as chlorine, bromine and other halogens. It is reported as having good ageing and leaching performance and can withstand bacteria.
- Polytetrafluorethylene (PTFE) – This material, otherwise known as Teflon, is one of the most inert of the thermoplastics available. PTFE retains good mechanical properties to high temperatures. It has good chemical resistance to solvents, acids and alkalis. However, it has poorer tensile strength and creep resistance.

The chemical resistance of these various pipe materials has been tested in the laboratory over a range of temperatures; the results are given in table 19. The resistance generally reduces as the temperature increases. PTFE is seen to be the most resistant material, but high costs prevent its widespread use.

A review of the potential for damage to plastic drainage pipes from petroleum fuel spills has been undertaken at BRE (1997). Whilst the potential for permeation of the pipes was recognised, it was considered that structural damage to polyethylene and polypropylene pipes was unlikely to occur.

A survey by the Water Research Centre in the UK on the effect of contaminated land on the distribution system in the UK found that of the reported incidents of permeation (more than 25) only two involved PVC (Crathorne 1987). Both these reported incidents involved gross contamination, arising from the spillage of aviation fuel in one case and a leak of sump fuel in the other.

A review of permeation of plastic pipes used for the distribution of potable water in the United States (Holsen 1990, Holsen 1991) found that the majority of permeation incidents (89%) were caused by petroleum products. Most of the incidents were associated with gross contamination resulting from spills or leaks, i.e. free product and not aqueous solutions. In 95% of the permeation incidents the soil contamination occurred after pipe installation. A survey by the Water Research Centre on the effect of contaminated land on the distribution system found a similar situation in the UK (Crathorne 1987). The large majority of incidents involved contamination resulting from the spillage of petrol or other petroleum products such as heating oil.

## Risk Assessment and Remedial Measures

Plastic pipe performance in contaminated land has been the subject of a report from the WRc (Stephens 1994). This report describes three types of site from high to low risk, A = High risk site, B = Suspect site, C = Low risk site. A flow chart was developed to assess the correct

choice of pipeline material and any necessary protection, see Figure 2. It can be seen that the choice of pipe material is made on the basis of the type of contamination present which is either organic, inorganic or mixed contamination. The basis of this report is that organic chemicals are more likely to attack plastic pipes and therefore metal pipes are preferred in these conditions. Conversely, inorganic contaminants are more likely to attack metal or cement based pipes. However, no single pipeline material is immune from all contaminants. In cases where no measures are taken to remove or treat contamination then there is the need for special precautions such as ensuring pipeline material is resistant and good pipe laying practice is followed. Table 20 describes examples of each type of site used in the ranking procedure.

The WRc report has extracted data from the ICRCL lists in order to provide an assessment of where there could be a risk to the use of plastic pipes in contaminated ground (DoE 1987). However, the report recognised that this data had been developed for the purposes of human health risk assessment and therefore, its use in assessing whether there is a risk to plastic drinking water pipes is limited.

This report indicated that permeation of plastic pipes by organic solvents and substances was a major problem. Data has been produced where there could be a risk to permeation of pipes that carry drinking water. The data as presented in the report is reproduced in Table 21, and had been adapted from a report by Wilson and Norris (Wilson 1992). It is unclear how this data has been derived and thus its usefulness is in some doubt. However, given the lack of quantitative data that is available even an empirical guide based on best estimates or educated guesses is a valuable assistance to the specifier.

Additional protection can be given to the pipeline by the following (Stephens 1994):

- Divert the pipeline route to avoid the contaminated area.
- Remove contaminated soil from the site.
- Protect the pipeline in the trench – e.g. isolate the pipeline in the trench, line the trench, use impermeable and inert backfill material, use protective sleeves, use trench drains or install non-return valves.
- Install the pipe above the contaminated ground in a clean cover system of sufficient depth.

In cases where water supply pipelines are laid directly into contaminated soil then it is necessary to check that the water flowing through the pipe has not become contaminated. Such checks should be carried out by sampling and analysing water from the pipe at various intervals. As described above plastics are potentially subject to permeation by various contaminants. The rate of permeation through a pipe wall depends (non-linearly) on its thickness. Small diameter pipes with thinner walls will be more affected than larger diameter pipes for a given pressure rating.

### 2.8.4 Electrical Cables

**Hazards**

Electrical cables are generally protected by plastic sleeves. These sleeves are potentially subject to chemical attack and permeation in similar modes as plastic pipes (RAPRA 1971, Billing 1998)). Medium and low voltage cables are often laid directly into the ground and are thus at risk of attack by contaminants. High voltage cables tend to be protected directly from the ground as they are buried in clean backfill. The following hazards were thus identified as

important to the use of electrical cables in contaminated land:

- Degradation of the cable sheathing leading to deformation or permeation.
- Swelling of plastic sheathing leading to deformation or permeation.
- Ignition of combustible materials in the soil due to temperature rises in the soil induced by cable heating.
- Mechanical damage caused by large, sharp or heavy objects in the soil.
- Ageing or softening of cable insulation due to high temperatures in the soil.
- Transport of contaminants, in particular landfill gas, along the cable routes.

**Remedial Measures**
The selection of appropriate cable sheathing material is obviously important to the proper functioning of the cable over time. However, other factors such as the possibility of underground fires could affect the function of the cable. A number of precautions have been proposed for the installation of electrical cables, as follows:

- Route the cable through a clean area, although this may not always be possible and there is the potential for contaminant migration to the clean area.
- Enclose the cable in a clean fill material, possibly enclosing the backfill itself in a geomembrane.
- Treat or contain the contaminated soil in order to remove the hazard or prevent movement of the contamination to the cables.
- Provide over-sheaths to the cable, these could either be metallic such as lead or polymeric materials.
- Lay the cables in a clean cover system above the contaminated ground.

The performance of various polymeric cable sheathing materials subjected to acids, organics and oils is given in Table 22.

### 2.8.5 Rubbers

Rubbers are crosslinked polymeric materials containing a number of additives such as carbon black, fillers, antioxidant and vulcanising agents. The corrosion resistance of rubber is determined by its polymeric constituent (Heap 1968). They are used in membranes and damp proof courses.

**Hazards**
The mechanism by which rubbers deteriorate when placed in aggressive chemical environments are similar to those described for plastics. Box 24 contains further details on the performance of rubbers in contaminated soils.

**Risk Assessment**
Oxidation is the principal form of degradation, leading to hardening and cracking of rubber. Thus, while rubbers are resistant to strong acids and alkalis, they are rapidly attacked by oxidising acids such as nitric acid and oxidising salts of metals such as copper, manganese and iron (RAPRA 1971).

Rubber is susceptible to attack by certain hydrocarbons and oils. The absorption of these organic liquids causes the rubber to swell. As rubber contains an appreciable amount of

crosslinking, the mechanism of swelling is similar to that of polyethylene. Swelling causes deterioration of tensile properties as well as softening (Bergman 1985). The resistance to swelling of a number of rubbers in different liquids is shown in Table 24.

**BOX 2.24: Rubber Performance**

The susceptibility of natural rubber to microbial degradation has been known for more than 90 years. In 1950 a series of papers reported that underground cables made from rubber had deteriorated as a result of microbial attack. This attack was described as visible pitting and micro-porosity. Seal (1988) describes more recent soil burial tests by Williams, which have confirmed that natural rubber (crepe and smoked latex sheet) can support microbial growth and can be oxidised in the presence of micro-organisms. Vulcanisation improves the resistance of natural rubber to microbial attack. However, the incorporation of sulphur into the rubber during this process makes it vulnerable to attack by sulphur-oxidising bacteria. Heap and Morrell (1968) discuss a 1945 report by Thaysen in which attack on the sulphur in vulcanised rubber was said to be responsible for the deterioration of fire hoses that had not been dried thoroughly before storage.

Synthetic rubbers are more resistant to microbial attack than natural rubbers. Of the types of rubber most commonly used in water pipelines in the UK, styrene-butadiene rubber (SBR), ethylene-propylenediene (EPDM) and acrylonitrile-butadiene (NBR), SBR is the most susceptible to microbial attack. The biodegradation of SBR is thought to be due to preferential attack on the compounding ingredients rather than degradation of the styrene-butadiene copolymer. The presence of low molecular weight residues and oxidation products of SBR in the formulation probably increases the rate of deterioration.

The mechanism of permeation of rubber is similar to that described for polyethylene, and so rubber is permeable to the same range of chemicals which permeate polyethylene (see Table 16). Laboratory experiments (Cassady *et al,* 1983, cited in Crathorne *et al*) have shown that rubber is highly permeable and is more permeable than plastic pipe material such as polyethylene and polyvinyl chloride. Vonk (1985) found that in general SBR was more permeable than EPDM. For example, the partition coefficient for chlorinated alkanes and alkenes is 10 times greater in SBR than in EPDM, and for aromatic hydrocarbons it is two to four times greater. Although rubber has been shown to be highly permeable, in a survey carried out by the Water Research Council on the effects of contaminated land on the distribution system, no incidents were reported involving the failure or permeation of rubber gaskets (Crathorne 1987). One explanation of this is that gaskets have a relatively small surface in contact with the drinking water, so for any effect on drinking water quality to be noticed the permeation rate would have to be high.

## Remedial Measures

General guidance on the use of rubber in pipelines is given in British Standard BS 2494:1990 'Specification for elastomeric seals for joints in pipework and pipelines'. The Standard does not contain any information on the use of rubber in aggressive environments. However, it does make reference to the need to carry out immersion tests to determine the effect of chemicals and micro-organisms on the performance of rubber seals.

Information on the effect of a range of chemicals on the physical properties of various rubbers has been produced by the Rubber and Plastic Research Association (1971). The information was obtained from laboratory immersion tests using undiluted chemicals, but has some limitations such as no information on the following:

- the effects of combination of chemicals,
- the effect of dilution,

- the effect of the soil environment.

## 2.9 Problem Investigation and Remedial Action

It is not a normal requirement for most buildings to monitor foundations, piles or services over their whole life. In cases where contaminated sites have been built upon there are no recorded cases where monitoring of the materials has been undertaken. It would normally be expected that the materials and services should be resistant to chemical attack.

In above ground structures it is possible to monitor the building for signs of distress by visual assessment. Cracking, spalling and crumbling indicate that problems have occurred. Common forms of chemical attack above ground are chloride attack on concrete reinforcement and acid attack in industrial plants. In these cases the deterioration of the materials is obvious.

In below ground situations it is likely that the problems will remain hidden for a period of time. A good example is the thaumasite form of sulfate attack on piled foundations on M5 motorway bridges (DETR 1999). No signs of distress to the structure were noted prior to excavation work taking place around the piles. However, in other cases chemical attack on concrete or masonry has resulted in cracking in the above ground structure. In extreme cases structural collapse of the building could result from attack by contaminants.

Investigation of the condition of materials in underground structures and services may be initiated as a result of the following:

- Signs of deterioration of the above ground structure.
- Evidence that contamination exists on the site, but was not taken into account during construction works or at any other time in the lifetime of the building.
- Problems with contaminated water supplies or leakage from service pipes.
- Problems or signs of leakage through membranes and damp proof courses.

There is further a need to investigate both the ground conditions and the building materials or services. This may include the normal steps in hazard identification, hazard estimation, risk assessment and risk management. If problems are already known to have occurred then management of the problem becomes the issue.

In general, it would be unlikely that an entire building would need to be replaced as a result of contaminant attack. However, repairs and remediation would be required. For foundations and piles it may be necessary to excavate around the area of material that has been affected and then carry out repairs or replacement. The remediation may also include the removal of contaminated soil or treatment to destroy the contamination. Protective barriers or coatings could also be applied to the surface of the affected materials. Any replacement materials would need to be of a suitable type and quality that would be resistant to the contamination on the site.

For building services the amount of remedial works will depend on the extent to which the services have been affected. If contaminant attack or permeation is limited to a small area then remedial works may be straightforward. However, there may be other cases where remedial works are required to long lengths or the entire service pipe. The process of repairing and remediating service pipes could include the following:

- Undertake ground investigation and service investigation to determine the type and nature of the contamination and its effect on the services.
- Remediate the soil by removal or treatment in order to remove the hazard.
- Excavate and replace affected sections of service pipe.
- Ensure that further risks are prevented by ensuring isolation of the pipe in clean backfilled trenches or by other means. If service pipe has been chemically degraded then ensure the replacement pipe is resistant to any remaining ground contaminants.

## 2.10 Implementation of Risk Management Action

In the context of building materials and services the implementation of risk management is concerned with ensuring that the materials that have been specified in the evaluation and selection process are properly manufactured and installed in the structure. Monitoring of condition and performance may also be required in some cases where the site conditions, or other reasons, indicate that this is necessary.

The risk management procedure will depend on the type of material, the form of construction or services, the hazards on the site and the requirements for design life. In general, the specification of building materials and materials for services is covered within the requirements of British and International standards. These standards set minimum requirements for the necessary properties of materials such as strength, dimensional stability and durability. The conformity to British Standards will often be approved by either third party certification schemes or via manufacturer's declaration of conformity. This provides some assurance with regard to the quality of the materials that are provided to construction project. For materials such as concrete that have a number of constituents, including aggregates, cement, admixtures and water, it is necessary that the constituent materials are all similarly specified to British or International Standards.

In carrying out construction works there are a number of important requirements to ensure that the building materials are used in appropriate ways. The following will need to be included in any construction project:

- Testing – Materials should be tested to ensure that they comply with specification requirements. For example concrete should be routinely sampled and tested for strength during a construction project. The same applies to mortar. Whilst it is normal to test strength on all construction projects in contaminated land work it may be necessary to test to ensure that the correct cements and aggregates are being used. This will provide assurance that the correct cement type (for example blastfurnace slag or pulverised fuel ash cement) is used and at the correct cement content. For proprietary materials, such as plastics, rubbers, bricks and precast concrete the materials can also be tested to ensure compliance with the specification. However, where sufficient control is exercised over the manufacturing process and the products are quality assured then it may not be necessary to test samples of these materials from the site. Where tests determine that materials do not meet their performance requirements then it may be necessary to rebuild parts of the building or structure.
- Operatives – All operatives should be properly trained and be competent in the installation or construction of materials and services.

- Site Supervision – This is important to ensuring that all works are carried out to an appropriate level of quality. The supervision should ensure that all parts of the building are suitably constructed.
- Quality control – This includes all aspects of testing and site work, good QC procedures will ensure that all test results are recorded and that inventories are maintained of all work carried out. These records should be kept for future reference should problems or failures occur, or the building or site changes ownership.

After the completion of the construction phase of the work there may be a period of monitoring to ensure that the building continues to perform as required. However, in most building projects no provision is made for the monitoring of foundations or other parts of the ground that will come into contact with contamination. The building materials should be resistant to the effects of contamination so that their performance will not significantly reduce over time. The presence of contamination may result in such requirements being put into place.

There are inevitably difficulties in trying to monitor the performance of materials and services below ground. However, methods of protection have been developed for reinforced concrete, such as cathodic protection, and this could be applied where there are concerns over potential corrosion of the reinforcement.

Building services that carrying drinking water may not be accessible for monitoring readily. However, samples of water from the pipe could be sampled at suitable intervals to ensure that contamination of the water is not occurring. Where, however, the risks of such contamination occurring is considerable then measures should be taken to reduce the risk to acceptable levels.

## 2.11 Conclusions

This review has shown that there are few cases where there is good data to link real ground conditions and contaminant concentrations to the performance of a material. Most guidance on the aggressive nature of chemicals towards materials remains qualitative. This means that professional judgement is needed to appraise the risk presented by an aggressive environment and to select a suitable quality assured material. Quantitative data exist only in a few cases. The best known example of such data is BRE Digest 363 (Sulfate and acid resistance of concrete in the ground). There are however a number of combinations of building materials and contaminants for which there is information in the available literature. The current situation with respect to the knowledge and guidance that is available for building materials in various ground conditions is summarised in Table 24. This table provides an indication of the potential to provide guidance in the form of secondary model procedures for materials in contaminated land.

Attempts are being made through research to expand the range of contaminants for which quantitative data on chemical aggression exist. This includes research that has been undertaken by BRE for a number of years on dense concrete, concrete blocks and steel.

In general, guidance based on the recognition of potentially deleterious reactions could be developed. The guidance should be based on advice on materials that are durable in certain ground conditions and methods of protection. The latter could include the need to use

protective coatings or to surround the material with clean backfill. There are also a number of issues such as the form of the construction that are more difficult to include in the guidance. For example, it is recognised that concrete that is thicker in section and entirely surrounded by soil is less likely to be attacked than a slender section, for example a ground floor slab, where moisture can evaporate from the upper side. In this latter case the contaminants in the ground are encouraged to enter the concrete by capillary suction on contaminated ground water. However, the form of construction can be a secondary issue if the materials are chemically resistant and of good quality.

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**Table 1: Chemical attack of concrete by waters and soils containing aggressive agents: assessment of the degree of attack (after draft recommendations for inclusion in the European Pre-Standard ENV 206)**

| **Degree of attack** | Weak | Moderate | Strong |
|---|---|---|---|
| Water | | | |
| pH | 6.5 to 5.5 | 5.5 to 4.5 | 45 to 4.0 |
| Aggressive ($CO_2$ mg $CO_2$/l) | 15 to 40 | 40 to 100 | >100 |
| Ammonium (mg $NH_4^+$/l) | 15 to 30 | 30 to 60 | 60 to 100 |
| Magnesium (mg $Mg^{2+}$/l) | 300 to 1000 | 1000 to 3000 | >3000 |
| Sulfate (mg $SO_4^{2-}$/l) | 200 to 600 | 600 to 3000 | 3000 to 6000 |
| Soil | | | |
| Degree of acidity | | 200 ml/kg (20°C Baumann-Gully) | |
| Sulfate (mg $SO_4^{2-}$/l) air dry soil | 2000 to 6000 | 6000 to 12 000 | 12 000 to 24 000 |

**Notes**

- The table deals with static (non-flowing) conditions at 20 ± 5°C.
- Flowing conditions, especially high-velocity waters, require additional protection.
- Industrial effluents/pollution are not considered and must be assessed by a specialist. Similarly, sewage and sulfide-oxidation effects are not included.
- The age of the concrete before the first contact with aggressive agents should be taken into account.
- Design aspects (shape) are important for concrete performance.
- Simultaneous influences, where the aggressive classification is close to the class limits, should be dealt with by moving to the next higher class.
- Problems involving nitrates and other unusual agencies (organic acid, fats, oils, etc) must be referred to experts.
- Gases, in the absence of water, are not considered aggressive.
- For buried concretes, the permeability of the soil should he considered in relation to the renewal of water/solution in contact with the concrete. Soil permeability greater than $10^{-5}$m/s may require an upgraded classification.
- Baumann-Gully determination is carried out by titration with tenth normal sodium acetate solution and is a measure of volume of tenth normal acid in soil.

**Table 2:Classification of chloride conditions in groundwater (after Bartholomew)**

| **Chloride limit (ppm)** | | |
|---|---|---|
| **Degree of attack** | **Temperate climate** | **Tropical climate** |
| Negligible | 0 to 2000 | Not applicable |
| Moderate | 2000 to 10 000 | 0 to 2000 |
| High | >10 000 | 2000 to 20 000 |
| Very high | Not applicable | >>20 000 |

**Table 3: Acids commonly encountered in building practice (after Biczok)**

| **Inorganic acids** | **Organic acids** |
|---|---|
| Carbonic acid | Acetic acid |
| Chromic acid | Fermenting material |
| Hydrochloric acid | Formic acid |
| Hydrofluoric acid | Humic acid |
| Hydrogen sulfide | Lactic acid |
| Nitric acid | Oxalic acid |
| Phosphoric acid | Sugar solutions |
| Sulfuric acid | Tannic acid |
| Sulfurous acid | Wine acid |

**Table 4: Details of concrete mixes used in BRE test programme**

| Mix no. | Cement composition | Cement ratio | w/c ratio (max) | Cement content ($kg/m^3$) | Fine agg. ($kg/m^3$) | Coarse agg. ($kg/m^3$) | 28 day CS ($N/mm^2$) |
|---|---|---|---|---|---|---|---|
| 1 | PC | 100 | 0.55 | 220 | 1200 | 910 | 34 |
| 2 | PC | 100 | 0.55 | 300 | 772 | 1192 | 59 |
| 3 | PC | 100 | 0.6 | 300 | 772 | 1192 | 42 |
| 4 | PC/ggbs | 30:70 | 0.57 | 320 | 769 | 1075 | 36.5 |
| 5 | PC/ggbs | 30:70 | 0.45 | 380 | 729 | 1055 | 52 |
| 6 | PC/pfa | 70:30 | 0.58 | 320 | 829 | 1025 | 38.5 |
| 7 | PC/pfa | 70:30 | 0.45 | 380 | 799 | 995 | 30 |
| 8 | SRPC | 100 | 0.45 | 360 | 710 | 1175 | 73 |
| 9 | HAC/ggbs (BRECEM) | 50:50 | 0.55 | 320 | 700 | 1175 | 21 |

***Notes:*** *PC - Portland cement; ggbs - ground granulated blastfurnace slag; pfa - pulverised fuel ash; SRPC - sulfate resisting Portland cement; HAC - high alumina cement. Mix 1 had a superplasticiser added to achieve adequate workability*

**Table 5: Solutions of contaminants used in BRE concrete immersion tests**

| Contaminant | **Soln A** | **Soln B** | **Soln C** | **Soln D** | **Soln E** | **Soln F** |
|---|---|---|---|---|---|---|
| PH | 7.8 | 2.5 | 8 | 7.8 | 7 | 2.5 |
| Sulfate | 4200 | 4200 | 4200 | 4200 | 4200 | 4200 |
| Sulfide | 34 | 34 | - | - | | |
| Chloride | - | - | 218 | 24 | | |
| Arsenic | 5 | 5 | 65 | 1 | | |
| Cadmium | - | - | - | 0.8 | | |
| Chromium | 23 | 23 | 39 | 41 | | |
| Cobalt | - | - | - | 11 | | |
| Copper | 26.5 | 26.5 | 180 | 103 | | |
| Lead | 91 | 91 | 530 | 130 | | |
| Manganese | 355 | 355 | - | 730 | | |
| Mercury | - | - | 2 | 0.1 | | |
| Nickel | 23.5 | 23.5 | 28 | 43 | | |
| Vanadium | - | - | - | 47 | | |
| Zinc | 65 | 65 | 351 | 175 | | |
| Phenol | 1 | 1 | 3.5 | - | | |
| Toluene | 100 | 100 | 100 | 100 | | |

***Note****: All concentrations in mg/l (except pH), water control solution termed soln G*

**Table 6: Compressive strength of concrete cubes as a percentage of control samples**

| | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 | Mix 6 | Mix 7 | Mix 8 | Mix 9 |
|---|---|---|---|---|---|---|---|---|---|
| Sol A | | | | | | | | | |
| 1 year | 85.7 | 72.1 | 49.4 | 102.8 | 97.7 | 99.0 | 96.9 | 94.9 | 120.3 |
| 2 year | NT | 21.5 | 15.0 | 74.7 | NT | NT | NT | NT | NT |
| 3 year | 63.3 | STD | STD | 50.0 | 77.1 | 94.4 | 86.1 | 82.4 | 97.7 |
| Sol B | | | | | | | | | |
| 1 year | 70.0 | 72.1 | 54.3 | 76.4 | 84.1 | 90.0 | 69.4 | 100.6 | 110.9 |
| 2 year | NT | 27.4 | 22.2 | 52.9 | NT | NT | NT | NT | NT |
| 3 year | 51.9 | 21.5 | 17.0 | STD | 66.7 | 43.9 | 33.7 | 68.2 | 70.1 |
| Sol C | | | | | | | | | |
| 1 year | 88.6 | 96.4 | 72.8 | 83.0 | 100.0 | 101.0 | 94.9 | 103.8 | 103.1 |
| 2 year | NT | 51.4 | 15.4 | 74.7 | NT | NT | NT | NT | NT |
| 3 year | 63.3 | STD | STD | 86.4 | 84.0 | 94.4 | 103.0 | 89.2 | 98.9 |
| Sol D | | | | | | | | | |
| 1 year | 95.7 | 76.6 | 50.6 | 99.1 | 97.7 | 100.0 | 98.0 | 104.5 | 95.3 |
| 2 year | NT | 40.9 | 16.9 | 66.5 | NT | NT | NT | NT | NT |
| 3 year | 63.3 | STD | STD | 64.4 | 86.1 | 100.0 | 99.0 | 91.5 | 101.1 |
| Sol E | | | | | | | | | |
| 1 year | 95.7 | 88.3 | 75.3 | 98.1 | 100.0 | 113.0 | 87.8 | 108.3 | 115.6 |
| 2 year | NT | 41.2 | 38.7 | 67.1 | NT | NT | NT | NT | NT |
| 3 year | 60.8 | 21.5 | 21.6 | 63.6 | 88.9 | 94.4 | 98.0 | 85.2 | 94.3 |
| Sol F | | | | | | | | | |
| 1 year | 90.0 | 91.9 | 79.0 | 84.0 | 86.4 | 95.0 | 67.4 | 99.4 | 112.5 |
| 2 year | NT | 61.9 | 39.5 | 59.1 | NT | NT | NT | NT | NT |
| 3 year | 59.5 | 38.0 | 35.2 | 50.0 | 63.2 | 59.8 | 56.4 | 71.6 | 71.3 |

***Notes***
*NT = Samples not due to be tested after two years*
*STD = Samples too badly deteriorated to be tested*
*Control samples have been cured in tap water for 3 years*

**Table 7: Compressive strength of concrete cubes as a percentage of 28- day value**

| | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 | Mix 6 | Mix 7 | Mix 8 | Mix 9 |
|---|---|---|---|---|---|---|---|---|---|
| Sol A | | | | | | | | | |
| 1 year | 88.2 | 67.8 | 47.4 | 148.7 | 125.7 | 128.6 | 160.2 | 101.6 | 184.8 |
| 2 year | NT | 24.6 | 15.8 | 115.5 | NT | NT | NT | NT | NT |
| 3 year | 73.5 | STD | STD | 80.5 | 108.1 | 131.2 | 146.7 | 98.9 | 204.0 |
| Sol B | | | | | | | | | |
| 1 year | 72.0 | 67.8 | 52.2 | 110.5 | 108.1 | 116.9 | 114.6 | 107.8 | 170.4 |
| 2 year | NT | 27.4 | 23.3 | 81.8 | NT | NT | NT | NT | NT |
| 3 year | 60.3 | 22.0 | 17.8 | STD | 93.5 | 61.0 | 57.3 | 81.9 | 146.4 |
| Sol C | | | | | | | | | |
| 1 year | 91.2 | 90.7 | 69.9 | 120.0 | 128.6 | 131.2 | 156.8 | 111.2 | 158.4 |
| 2 year | NT | 51.4 | 16.2 | 115.5 | NT | NT | NT | NT | NT |
| 3 year | 73.5 | STD | STD | 139.1 | 128.6 | 131.2 | 175.3 | 107.1 | 206.4 |
| Sol D | | | | | | | | | |
| 1 year | 98.5 | 72.0 | 48.6 | 143.2 | 125.7 | 129.9 | 161.8 | 111.9 | 146.4 |
| 2 year | NT | 40.9 | 17.8 | 102.7 | NT | NT | NT | NT | NT |
| 3 year | 73.5 | STD | STD | 103.7 | 120.8 | 139.0 | 168.6 | 109.8 | 211.2 |
| Sol E | | | | | | | | | |
| 1 year | 98.5 | 83.1 | 72.3 | 141.8 | 128.6 | 146.8 | 145.0 | 116.0 | 177.6 |
| 2 year | NT | 41.2 | 40.7 | 103.6 | NT | NT | NT | NT | NT |
| 3 year | 70.6 | 22.0 | 22.5 | 102.3 | 124.7 | 131.2 | 166.9 | 102.3 | 196.8 |
| Sol F | | | | | | | | | |
| 1 year | 92.7 | 86.4 | 75.9 | 121.4 | 111.1 | 123.4 | 111.3 | 106.4 | 172.8 |
| 2 year | NT | 61.5 | 41.5 | 91.4 | NT | NT | NT | NT | NT |
| 3 year | 69.1 | 39.0 | 36.8 | 80.5 | 88.6 | 83.1 | 96.1 | 85.9 | 148.8 |
| Sol G | | | | | | | | | |
| 1 year | 102.9 | 94.1 | 96.1 | 144.6 | 128.6 | 129.9 | 165.2 | 107.1 | 153.6 |
| 2 year | NT | 100.0 | 105.0 | 154.6 | NT | NT | NT | NT | NT |
| 3 year | 116.2 | 102.5 | 104.4 | 160.9 | 140.3 | 139.0 | 170.3 | 120.1 | 208.8 |

***Notes***

*NT = Samples not due to be tested after two years*

*STD = Samples too badly deteriorated to be tested*

*Sol G = Water control*

**Table 8: Limits of chloride content of concrete (after British Standard BS 811: Part 1)**

| Type of use of concrete | Maximum total chloride content expressed as a percentage of chloride ion by mass of cement (including pfa and ggbs) |
|---|---|
| Prestressed concrete; heat-cured concrete containing embedded metal | 0.1 |
| Concrete made with cement complying with BS 4207[52] or BS 4248[53] | 0.2 |
| Concrete Containing embedded metal and made with cement complying with BS 12[54] BS 146[55], BS 1370[56], BS 4246[57] or combinations with ggbs or pfa | 0.4 |

**Table 9: Soil galvanic series**

| Metal | Suggested potential (V)* | |
|---|---|---|
| Carbon, coke, graphite | + 0.1 | Noble end (cathodic) |
| High silicon cast iron | + 0.1 | |
| Copper, brass and bronze | + 0.1 | |
| Mild steel (in concrete) | + 0.1 | |
| Lead | -0.2 | |
| Cast iron | -0.2 | |
| Rusted mild steel | + 0.1 to - 0.2 | |
| Clean mild steel | + 0.5 to - 0.2 | |
| Aluminium | -0.5 | |
| Zinc | -0.8 | Active end (anodic) |
| Magnesium | - 1.3 | |

* Approximate potentials only

**Table 10: Aggressiveness of soils (after King)**

| Aggressiveness | Resistivity (ohm cm) | Redox potential (mV) (corrected to pH7) |
|---|---|---|
| Mildly or non-corrosive | >5000 | >400 (>430 if clay soil) |
| Moderately corrosive | 5000 to 2000 | 400 to 200 |
| Corrosive | 2000 to 700 | 200 to 100 |
| Very corrosive | <700 | <100 |

**Table 11: Soil characteristics of burial sites**

| Location | Soil type | Resistivity (ohm/cm) | pH | Chloride (g/kg soil) | Sulfate (g/kg soil) |
|---|---|---|---|---|---|
| Varel | Anaerobic peaty clay, about 70% water | 900 | 7.5 to 8.5 | 1.6 | 2.7 |
| Colchester | Heavy clay | 500 to 900 | 7.0 | 0.3 | 1.0 |
| Mont St Michel | Littoral sandy clay, liable to submersion by high tides | 110 | 8.0 to 9.0 | 5 to 9 | 5 to 10 |

**Table 12: Intrinsic corrosivity of sulfide films on ferrous metals (Tiller)**

| Sulfide film | Rate of corrosion (mm/year) |
|---|---|
| Hydrogen sulfide, $H_2S$ | 12.8 |
| Machinawite, $FeS_{1-x}$ | 5.3 |
| Gregigite, $Fe_2S_4$ | 119.6 |
| Elemental sulphur | 1110.0 |

**Table 13: Principal uses of plastics below ground, and polymer types used (after Barry and Hassan *et al*)**

| |
|---|
| **Pipework for underground utilities**<br>• Polyethylene (low-, medium- and high-density: LDPE, MDPE and HDPE)<br>• Unplasticised polyvinyl chloride (PVC-U)<br>• Polypropylene<br>• Polybutylene (PB)<br>• Acrylonitrile-butadiene-styrene (ABS)<br>• Cellulose acetate-butyrate (CAB)<br>• Glass-reinforced plastic, incorporating epoxy or polyester resins |
| **Cable sheathing for electrical and telecommunication use**<br>• Polyethylene<br>• Polyvinyl chloride (electrical only) |
| **Damp-proof courses, membrane and fabrics**<br>• Polyethylene<br>• Polyethylene with bituminous adhesive |
| **Geomembranes**<br>• Polyethylene (LDPE, HDPE)<br>• Polyvinyl chloride<br>• Chlorinated polyethylene<br>• Chlorosulphonated polyethylene (CPSE)<br>• Ethylene propylene rubber (EPDM) |
| **Geotextiles (fabrics and meshes)**<br>• Polyethylene<br>• Polypropylene<br>• Polyvinyl chloride<br>• Nylon |
| **Miscellaneous**<br>• Polystyrene boards (thermal insulation for foundations)<br>• Polyurethane foams (void filling and thermal insulation) |

**Table 14: Guide to the resistance of polyethylene and polyvinyl chloride to soil environments (after Elias)**

| Soil environment | Polymers used in geosynthetics | | | | |
|---|---|---|---|---|---|
| | **PETP** | **PA** | **PE** | **PP** | **PVC** |
| Acid sulfate soil, characterised by low pH and high $Cl^-$ and $S0_4^{2-}$ ion concentrations (e.g. pyritic soils) | QU | NR | NE | QU | QU |
| Organic soils, characterised by high organic content and susceptibility to microbial attack (e.g. dredged fills) | NE | QU | NE | NE | NR |
| Salt-affected soils: area saturated by sea-water or dry alkaline area | QU | NE | NE | NE | NE |
| Ferruginous: area containing $Fe_2SO_3$ | NE | QU | NE | NR | NR |
| Calcareous: dolomitic area | NR | QU | NE | NE | QU |
| Modified soils: soil subjected to de-icing salts, cement-stabilised or lime-stabilised | NR | QU | NE | NE | QU |

**Notes:**
PETP = polyester
PVC = plasticised polyvinyl chloride
PA = polyamide
NE = no effect
PE = polyethylene
QU = questionable use
PP = polypropylene
NR = not recommended

**Table 15: Chemical resistance of 0.76 mm HDPE membrane exposed to various test liquids (after Bellen *et al*)**

| Chemical | Conc. (%) | Temp. (°C) | Chemically resistant* | Type of interaction |
|---|---|---|---|---|
| HCl | 10 | 50<br>23 | Y<br>Y | — |
| NaOH | 10 | 50<br>23 | Y<br>Y | — |
| 1,2-Dichloroethane | 0.8<br><br>0.5<br><br>0.1 | 50<br>23<br>50<br>23<br>50<br>23 | N<br>Y<br>M<br>M<br>M<br>M | Weight gain with decrease in strength and elongation |
| Furfural | 8<br><br>4<br><br>1 | 50<br>23<br>50<br>23<br>50<br>23 | M<br>M<br>M<br>M<br>M<br>M | Weight gain with decrease in strength and elongation |
| Methyl ethyl ketone | 26<br><br>13<br><br>3 | 50<br>23<br>50<br>23<br>50<br>23 | M<br>M<br>M<br>Y<br>M<br>Y | Weight gain with decrease in strength and elongation |
| ASTM #2 oil | Saturated solution<br>100 | 50<br>23<br>50<br>23 | N<br>N<br>N<br>N | Weight gain with softening |
| Phenol | 8<br><br>4<br><br>1 | 50<br>23<br>50<br>23<br>50<br>23 | M<br>M<br>N<br>M<br>M<br>M | Weight gain with decrease in strength and elongation |
| NaCl | 35<br><br>10 | 50<br>23<br>50<br>23 | Y<br>Y<br>Y<br>Y | — |
| Potassium dichromate | 10 | 50<br>23 | M<br>Y | — |
| Water | | 50<br>23 | Y<br>Y | — |

* Chemically resistant: Y = yes, N = no, M = marginal

**Table 16: Organic compounds that permeate polyethylene (after Crathorne *et al*)**

| Compounds that readily permeate PE | Compounds that permeate PE but relatively slowly | Compounds that do not permeate PE |
|---|---|---|
| Benzene | Hexane | Atrazine |
| Toluene | Octane | Malathion |
| Xylene | 2,2,4-Trimethvlpentane | Paraquat |
| Ethylbenzene | Pentachlorobenzene | |
| Trimethylbenzene | Di-isopropylether | |
| Propylbenzene | Methyl ethyl ketone | |
| Chlorobenzene | Ethanol | |
| Di-, tri-chlorobenzene | Methanol | |
| Chlorotoluene | Hexanol | |
| Dichloromethane | Nitrobenzene | |
| Tetrachloromethane | Chloroanilines | |
| Trichloroethylene | Aniline | |
| Tetrachloroethylene | Nitroaniline | |
| Dichloroethane | Phenol | |
| Trichloroethane | Chlorophenols | |
| Tetrachloroethane | Di-, tri-chlorophenols | |
| Dichloropropane | Pentachlorophenol | |
| Methyl bromide | Pentane | |
| | Cyclohexane | |

**Table 17: Chemical resistance of 0.76 mm PVC membrane exposed to various test liquids (after Bellen *et al*)**

| Chemical | Conc. (%) | Temp. (°C) | Chemically resistant* | Type of interaction |
|---|---|---|---|---|
| Water | | 50<br>23 | Y<br>Y | |
| HCl | 10 | 50<br>23 | N<br>N | Swelling at 50°C |
| NaOH | 10 | 50<br>23 | N<br>Y | Shrinking and stiffening |
| 1,2-Dichloroethane | 0.8<br><br>0.5<br><br>0.1 | 50<br>23<br>50<br>23<br>50<br>23 | N<br>N<br>N<br>N<br>Y<br>Y | Swelling and softening |
| Furfural | 8<br><br>4<br><br>1 | 50<br>23<br>50<br>23<br>50<br>23 | N<br>N<br>N<br>N<br>N<br>Y | Swelling and softening, later shrinking and stiffening |
| Methyl ethyl ketone | 26<br><br>13<br><br>3 | 50<br>23<br>50<br>23<br>50<br>23 | M<br>M<br>M<br>Y<br>M<br>Y | Swelling and softening at low concentrations, shrinking and stiffening at high concentrations |
| ASTM #2 oil | Saturated solution<br>100 | 50<br>23<br>50<br>23 | N<br>N<br>N<br>N | Shrinking and stiffening |
| Phenol | 8<br><br>4<br><br>1 | 50<br>23<br>50<br>23<br>50<br>23 | M<br>M<br>N<br>M<br>M<br>M | Swelling and softening at low concentrations, shrinking and stiffening at high concentrations |
| NaCl | 35<br><br>10 | 50<br>23<br>50<br>23 | Y<br>Y<br>Y<br>Y | - |
| Potassium Dichromate | 10 | 50<br>23 | M<br>Y | - |

* Chemically resistant: Y = yes, N = no, M = marginal

**Table 18: Compounds that cause PVC-U to swell (after Crathorne *et al*)**

| Compounds causing excessive swelling | Compounds causing swelling but to a lesser extent | Compounds which have no or little effect |
|---|---|---|
| Chlorinated hydrocarbons* | Benzene | Alcohols |
| Ketones (particularly low molecular weight compounds such as acetone, methyl ethyl ketone, etc.) | Toluene | Aliphatic and alicyclic hydrocarbons |
| Nitrobenzene | Alkyl benzenes | *Solid* halogenated benzenes |
| Aniline | | |
| Esters (for example methyl, ethyl acetate) | | |

**Note**

* PVC appears to be more resistant to perchlorinated compounds such as tetrachloroethylene and carbon tetrachloride, and also to compounds containing a trisubstituted carbon atom, for example 1,1,1-trichloroethane.

**Table 19: Corrosion resistance of plastic pipe material at various temperatures (after Raman)**

| | **PVC** | | | **PP** | | | **PE** | | | **PVDF** | | | **PTFE** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temp/$^{o}$C** | 27 | 65 | 85 | 27 | 65 | 85 | 27 | 65 | 85 | 27 | 65 | 85 | 27 | 65 | 85 |
| **Medium** | | | | | | | | | | | | | | | |
| $H_2SO_4$ (99%) | + | + | - | + | + | - | + | + | - | + | + | 0 | + | + | + |
| HF (40%) | + | + | - | + | - | - | + | - | - | + | + | - | + | + | + |
| KOH (45%) | + | + | - | + | + | - | + | - | + | - | - | - | + | + | + |
| NaOH (45%) | + | + | - | + | + | + | + | + | - | + | + | - | + | + | + |
| Benzene | + | + | - | + | + | + | + | + | - | + | + | | + | + | + |
| Toluene | + | + | - | + | + | + | + | + | + | + | + | + | + | + | + |
| Chloroform | + | + | - | + | | | + | | | + | | | + | + | + |
| Aniline | + | + | 0 | - | | | - | | | - | | | - | | |
| Tea | + | + | - | + | | | - | | | - | | | - | | |

**Notes**

+ = polymer is resistant

0 = use under these conditions is doubtful

- = polymer is not resistant

blank = no result

**Table 20: Examples of categories of sites for contaminated land, use of plastic pipes (WRc)**

| |
|---|
| **Type A = High Risk** |
| Asbestos works, chemical works, gasworks, hazardous waste treatment, wood preservative use/manufacture, landfill sites, metal mines, smelters, foundries, steel works, munitions production/testing sites, oil and fuel production/storage/use, paper and printing works, pesticide manufacture, pharmaceutical manufacture, scrap yards, sewage works, tanneries. |
| **Type B = Suspect Sites** |
| Dry cleaners, electric/electrical equipment manufacture, fertiliser storage, garage/filling stations, mechanical engineering works, metal finishing installations, paint and ink manufacture, railway land, textile production, research laboratories, road haulage yards. |
| **Type C = Low Risk** |
| Agriculture, brewing and distilleries, food preparation and storage. |

**Table 21: Threshold (trigger) values for volatile organic (Group 1) receptor compounds that could affect water quality in plastic pipes (WRc)**

| | **Maximum acceptable concentrations in drinking water (µg/l)** | **Trigger values** | | |
|---|---|---|---|---|
| | | **Soil gas (µg/l)** | **Pore water (µg/l)** | **Soil (µg/l)** |
| **Group 1 (a) Compounds:** | | | | |
| Carbon tetrachloride | 3(1) | 3 | 15 | 0.15 |
| Trichloroethane | 10(1) | 30 | 150 | 1.5 |
| Tetrachloroethane | 10(1) | 20 | 100 | 0.5 |
| Benzene | 10(2,3) | 10 | 50 | 0.5 |
| Toluene | 10(2) | 10 | 50 | 0.5 |
| Xylenes | 10(2) | 10 | 50 | 0.5 |
| Chlorobenzene | 20(4) | 10 | 40 | 0.4 |
| **Group 1(b) Compounds:** | | | | |
| Dichloromethane | 20(3) | 20 | 100 | 1 |
| 1,2-dichloroethane | 4(3) | 4 | 20 | 0.2 |
| 1,1,1-trichloroethane | 160(4) | 160 | 800 | 8 |
| 1,2-dichloropropane | 2(4) | 2 | 10 | 0.1 |
| vinyl chloride | 2.5(3) | 3 | 10 | 0.1 |
| methyl bromide | 400(5) | 400 | 2000 | 20 |
| dichlorobenzenes | 0.3(4) | 0.3* | 1 | 0.01 |
| trichlorobenzenes | 5(4) | 10 | 50 | 0.5 |
| ethylbenzene | 10(2) | 10 | 50 | 0.5 |

*It may be difficult to analytically satisfy this requirement. Concentration techniques would be needed.

1. Water supply regulations 1989
2. Water supply regulations 1989 – hydrocarbon parameter
3. Acceptable concentrations calculated at WRc based on recent toxicity data
4. Concentrations based on taste and odour threshold values (lower value of range reported)
5. DOE/Welsh Office water policy letter WP10/1986, pesticides in water supplies

**Table 22: Chemical resistance of various sheathing materials (ERA)**

| Chemical | Rating | | | |
|---|---|---|---|---|
| | **PE** | **Chlorinated PE** | **PVC** | **Chloro-sulfonated PE** |
| 30% sulfuric acid | E | E | G | E |
| 10% nitric acid | G | E | G | E |
| 10% HCl | E | E | E | G |
| 10% NaOH | E | E | E | G |
| 5% acetic acid | E | E | E | E |
| 10% $NH_4OH$ | G-E | E | E | G |
| ASTM #1 oil | - | E | E | E |
| ASTM #2 oil | - | E | E | E |
| ASTM #3 oil | - | E | E | E |
| #2 diesel oil | - | E | E | E |
| Gasoline | D-P | E | P | P |
| Kerosene | D-P | E | E | G |
| Acetone | G-E | E | D | G |
| Benzene | D-P | G | P | D |
| Transformer oil | - | E | G | E |

**Notes:** E = excellent, G = good, P = poor, D = not recommended

Range of rating values for PE indicates rating for increasing density

**Table 23: Resistance of rubbers to various liquids* (after Southern)**

| Rubber | Hydrocarbons† | | | | Alcohols | Animal and vegetable oils | Water |
|---|---|---|---|---|---|---|---|
| | **Aliphatic (a)** | **Aromatic (a)** | **Halogenated (b)** | **Oxygenated (c)** | | | |
| Natural | P | P | P | G | G | P-G | E |
| Cis-polyisoprene | P | P | P | G | G | P-G | E |
| Styrene-butadiene rubber (SBR) | P | P | P | G | F | P-G | G-E |
| Butyl | P | P | P | G-E | E | E | G-E |
| Cis-polybutadiene | P | P | P | G | P-G | P-G | E |
| Ethylene-propylene-diene (EPDM) | P | P-F | P | G | P | P | E |
| Nitrile | E | F | P | P | E | E | F-G |
| Polyurethane | E | F | F | P-F | G | G | G |
| Polysulfide | E | E | G | G | G | E | F |
| Silicone | P-G | P-F | F | F-G | G | F | F |
| Fluorubber | E | E | G | P | E | E | E |
| Chlorosulphonated polyethylene | F | F | P | P | G | G | G |
| Acrylic | E | F | P | P | P | E | E |

* E = excellent, G = good, F = fair, P = poor

† Common examples are: (a) mineral oils, (b) degreasing solvents, and (c) ketones

**Table 24: Summary of literature and guidance available on interactions between contaminants and materials**

| Material | Specified Cont | Literature available | Guidance | Qual. Data | Quan. Data | Model Procedure Potential | Other Information Available* |
|---|---|---|---|---|---|---|---|
| Concrete | Sulfate | Yes | Yes | Yes | Yes | Yes | Yes |
| | Chloride | Yes | Yes | Yes | Yes | Yes | No |
| | Acids | Yes | Yes | Yes | Yes | Yes | Yes |
| | Chromat | Yes | No | Yes | No | No | No |
| | Magnem | Yes | Yes | Yes | Yes | Yes | No |
| | Ammonia | Yes | No | Yes | Yes | Yes | No |
| | Organics | Some | Yes | Yes | Some | Yes | No |
| | **General** | Yes | No | Yes | Some | Possible | Yes |
| Rein. Concrete | Chloride | Yes | Yes | Yes | Yes | Yes | Yes |
| | **General** | No | No | No | No | No | No |
| Brick | Acid | Yes | Yes | Yes | No | Yes | Yes |
| | **General** | Yes | No | Yes | No | Possible | Yes |
| Concrete Blocks | Sulfate | Yes | Yes | Yes | Yes | Yes | Yes |
| | Acid | No | No | No | No | Yes | Yes |
| | **General** | No | No | No | No | Yes | Yes |
| Mortar | Sulfate | Yes | Yes | Yes | Yes | Yes | Yes |
| | Chloride | Yes | No | Yes | No | Yes | Yes |
| | Acid | Yes | No | Yes | No | Yes | Yes |
| | **General** | No | No | No | No | Yes | Yes |
| Cast Iron | **General** | Yes | Yes | Yes | No | Yes | Yes |
| Steel | **General** | Yes | Yes | Yes | No | Yes | Yes |
| Stainless Steel | **General** | Yes | No | Yes | No | Possible | Yes |
| Copper | **General** | Yes | No | Yes | No | Possible | Yes |
| Lead | **General** | Yes | No | Yes | No | Possible | Yes |
| Galvan. Steel | **General** | Yes | No | Yes | No | Possible | Yes |
| PE | In. Acids | Yes | Yes | Yes | No | Yes | Yes |
| | Og Acids | Yes | Yes | Yes | No | Yes | Yes |
| | Hydrocar | Yes | Yes | Yes | No | Yes | Yes |
| | Oils | Yes | Yes | Yes | No | Yes | Yes |
| | In Salts | Yes | Yes | Yes | No | Yes | Yes |
| PVC-U | In. Acids | Yes | Yes | Yes | No | Yes | Yes |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Og Acids | Yes | Yes | Yes | No | Yes | Yes |
| | Hydrocar | Yes | Yes | Yes | No | Yes | Yes |
| | Oils | Yes | Yes | Yes | No | Yes | Yes |
| | In Salts | Yes | Yes | Yes | No | Yes | Yes |
| PP | Acids | Yes | Yes | Yes | No | Yes | Yes |
| | Organics | Yes | Yes | Yes | No | Yes | Yes |
| PTFE | Acids | Yes | Yes | Yes | No | Yes | Yes |
| | Organics | Yes | Yes | Yes | No | Yes | Yes |
| PVDF | Acids | Yes | Yes | Yes | No | Yes | Yes |
| | Organics | Yes | Yes | Yes | No | Yes | Yes |

* includes knowledge of effect of physical ground conditions and protection of materials by coatings or clean fill

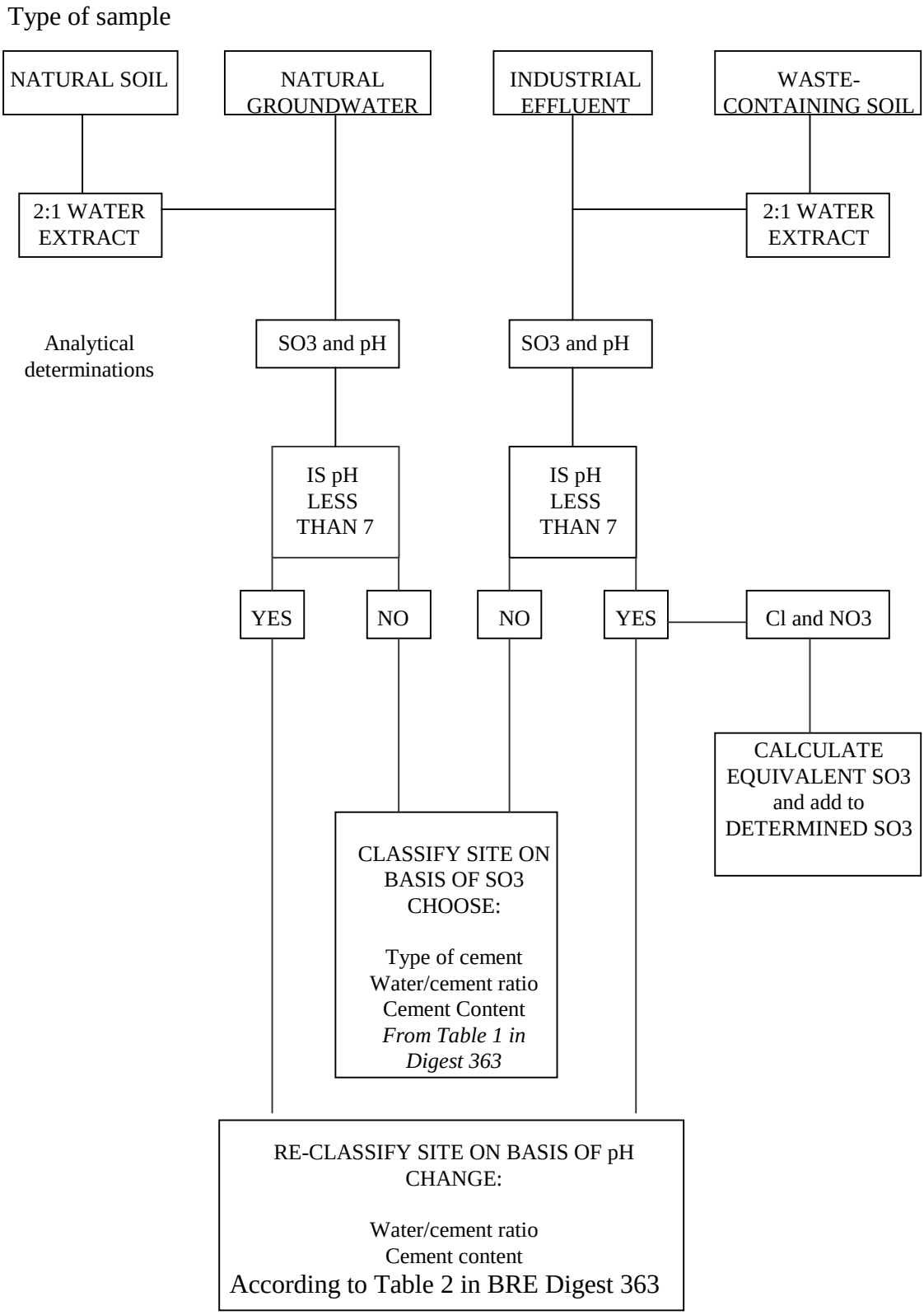


**Figure 1. Procedure for classification of site according to its sulfate level (BRE 1996)**

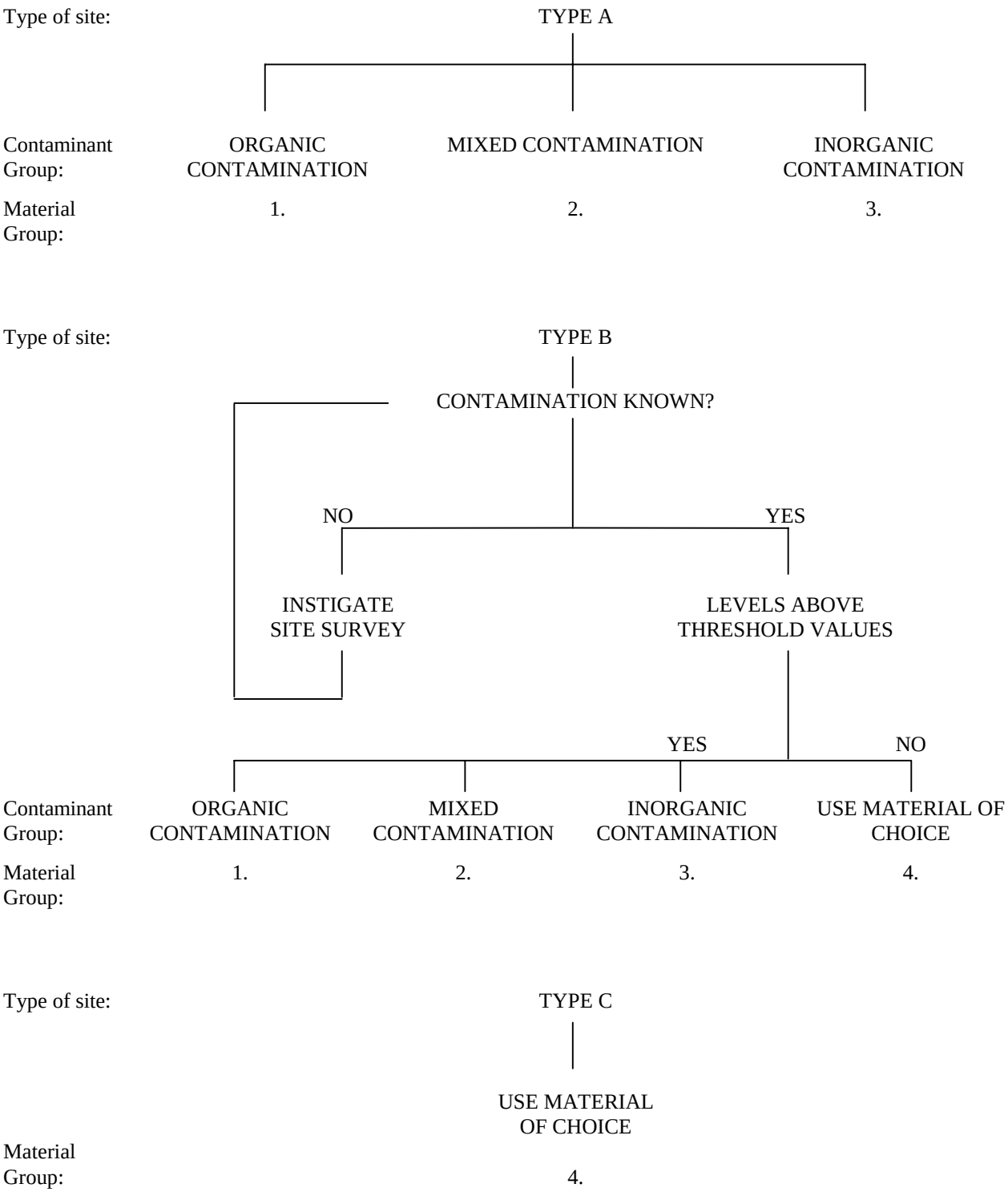


**Figure 2. Pipe material for three site classifications (WRc)**

**Key to Pipe Material Groups**

Group 1. Organic contamination

- PE sleeved ductile iron.
- Tape wrapped or coated steel.
- Sheathed copper.
- Wrapped metal fittings.
- Protection for joints and seals.
- Clean suitable backfill.
- Seek specialist advice on use of PVC-U or GRP pipes.

Group 2. Mixed contamination

- Plastic-coated or wrapped metal pipes.
- Cathodic protection (coated metal and prestressed concrete pipes only).
- Protection for joints and seals.
- Clean suitable backfill.

Group 3. Inorganic contamination

- Plastic pipes.
- Plastic-coated metal pipes.
- Cathodic protection (coated metal and prestressed concrete pipes only).
- Clean suitable backfill.
- Seek specialist advice on use of GRP pipes.

Group 4. Material of choice

NOTE 1. For all material groups, good pipelaying practice must be followed.
NOTE 2. For sites where the threshold values are greatly exceeded use all measures and/or seek specialist advice.

# 3. SUBTERRANEAN FIRES

## 3.1 Background

There is little published information on the hazards arising from subterranean fires in contaminated land sites, and none could be found that specifically relates to the effects of such fires on building materials and services. The majority of published information deals with on-site prevention and protective methods rather than the direct effects and consequences of a fire on the services and building materials of any buildings that may be present. However, there are a few papers that briefly mention some of the potential problems that may be encountered, along with a case study.

## 3.2 Surveys

Two surveys were undertaken in the 1980s to estimate the incidence of subterranean fires in the UK (BRE 1989, CES 1990). These reports also identified the types of waste involved, which is useful when undertaking a risk assessment of a site. The majority of fires occurred in sites containing domestic refuse and coal/colliery waste.

## 3.3 Hazards

Hazards posed by subterranean fires to buildings that have been identified include (Crowhurst & Beever 1987, Hope):

- *Settlement to the buildings and services*

  A smouldering fire occurring in the combustible materials under a building will consume these materials producing cavities. This may compromise the stability of the building causing subsidence and may result in service pipes cracking.

- *Heat damage to underground structures such as foundations and service pipes*

  The passage of a fire beneath a building may expose the construction materials and services to high temperatures. It is reported (Smith 1988, Beever 1986) that temperatures of up to 1000°C can occur, which could cause concrete to spall and melt plastic service pipes.

- *Acid gases causing a degradation of building materials and pipework*

  Depending on the nature of the combustible materials, a smouldering combustion can produce such acidic gases as carbon dioxide, carbon monoxide, hydrogen sulphide, and hydrogen chloride. If these are produced and attack the building materials over a long time period (some subterranean fires are known to have been burning for more than twenty years) they could lead to deterioration in the integrity of the materials.

Hope briefly describes a fire occurring beneath a small estate of bungalows, causing subsidence and structural collapse.

## 3.4 Site Investigation and Risk Assessment

Site inspections may be undertaken that could reveal tell-tale signs of fires, these include visible signs such as smoke plumes and settlement, or ground temperature surveys (Smith 1988, Bedford & Smith 1988).

Once a site has been identified as containing waste that may be potentially combustible, then assessment tests (Beever 1982, ICRCL 1986, Crowhurst & Manchester 1994, Cairney, Baker) are available that can be undertaken on samples of ground materials. However, these tests are limited in their use and the results difficult to relate directly to site conditions. Some guidance is given in ICRCL 61/84.

The seat of the fire may not even occur directly under the buildings. A fire could start at a location distant from the building but could still pose a threat due to lateral migration through the combustible material of the site if there are no barriers to halt the passage of the flame front.

## 3.5 Evaluation and selection of remedial measures

If a potential problem has been shown to exist then there are various preventative measures that can be implemented to ensure a fire will not start. These include (Crowhurst & Manchester 1994):

- remove combustible materials,
- mix inert substances with the combustible materials,
- compact the site to remove air voids, and,
- protect the site against possible ignition sources.

There are a number of techniques that have been reported to try and control and extinguish subterranean fires. These include (Prince *et al* 1988, Crowhurst & Manchester 1994, Ayres):

- Isolation barriers
- Compaction
- Smothering
- Flooding
- Injection of inert materials
- Excavation
- Controlled burn-out

Crowhurst & Manchester (1994) undertook a critical review of these techniques.

## 3.6 Conclusions

There is a small body of literature on the subject of subterranean fires and, indeed, there is guidance on assessing ground combustibility. However, the guidance is dated, and the tests for assessing combustibility do not provide an adequate indicator of actual site conditions, i.e. how susceptible ground material is to ignite from either self-heating or external ignition sources such as a fire on the surface. This is an area where further research is needed.

The literature on managing the risks of subterranean fires (i.e. their prevention and control) is better, although there is still no up to date published guidance.

Despite these limitations with the available literature it is felt that it should be possible to produce a secondary Model Procedure.

## 3.7 References (Section 3)


Ayres,D.J. 'Treatment of Shallow Underground Fires'. Symp. on failures in earthworks, TN23. Institution of Civil Engineers, London.

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Bedford,F. & Smith,A.J. 'Underground Heating Beneath Oakthorpe', Leicestershire. Municipal Engineer, Vol.5, pp.167-181, August 1988.

Beever,P.F. BRE Information Paper IP 6/82, May 1982.

Beever,P.F. 'Assessment of the Fire Hazard in Contaminated Land'. Meeting on combustible materials in geology and engineering. Engineering group of the Geological Society, 1986.
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Cairney,T. 'Evaluating the Potential for Subterranean Smouldering'. W A Fairhurst & Partners, Newcastle-upon-Tyne.

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Crowhurst,D & Manchester,S.J. 'Subterranean Fires: Assessment and Control'. BRE Client Report CR5/94, June 1994.

ICRCL Note 61/84, 2nd Edition.' Notes on the Fire Hazards of Contaminated Land', 1986.

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Prince,D.J. Cozzi,T.J. & Antebi,J. 'Remediation of a Burning Landfill'. HWHM'88 Proc. 5th Int. Conf. on Hazardous Wastes and Hazardous Materials. Las Vegas, USA, pp.278-281,1988.

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# 4. BUILDING ON FILL

## 4.1 Background

As well as the risks to building materials there are various geotechnical risks that need to be considered. They can affect both the load carrying characteristics of the ground, the aggressiveness of the contaminants in the ground and their effect on foundations. A significant proportion of contaminated land may be classified as non-engineered fill and the problems associated with building on non-engineered fill need to be taken into account. The significance of ground water level and flow on the mobility and availability of contaminants to cause deterioration of foundations and services must be addressed in any risk assessment.

## 4.2 Hazards

Fill is material that has arisen as the by-product of human activities generally associated with the disposal of waste or contaminated materials. The occurrence of problems and failures on filled ground emphasise the importance of developing an adequate understanding of the behaviour of fills and of identifying potential hazards so that appropriate types of building development can be successfully undertaken. The poor load carrying characteristics of many non-engineered fills have been associated with the heterogeneity and the loose condition of those fills.

The load carrying characteristics of fill and the causes of ground movement are summarised in BRE Digest 427, Part 1. Damaging settlement is generally caused by effects other than the weight of the building. Fill materials that have been inadequately compacted, or placed excessively dry usually undergo a reduction in volume when their moisture is increased. This phenomenon, known as collapse compression can occur without any increase in stress. Collapse compression can occur on inundation arising from a rising ground water level or from downward infiltration of surface water. Mechanisms that can cause collapse compression include the following:

- weakening of interparticle bond
- softening of aggregations of particles in fine grained fills, and,
- weakening of particle of coarse-grained fills.

The mere passage of time does not diminish the potential of a fill to collapse on inundation. Differential settlement arising from variable depth and type of fill are likely to cause the greater distress to buildings and services. Vertical compression of up to 7% has been measured on some non-engineered fill.

## 4.3 Risk Assessment

BRE Digest 427 Part 1 provides guidance to make a qualitative classification of fills and their potential for settlement. Volume changes, usually expansion, may occur due to chemical reactions with fill. Fills that should be treated with particular caution include sulphate bearing

wastes materials, steel slags, pyritic shales and alkali wastes. BRE Digest 276 gives some guidance on these hazards. It is important to emphasise that such contaminated fills can cause deterioration of the foundations and services through ground movements and chemical attack, see Parts 2 and 5 of this review.

## 4.4 Ground Water Level and Flow

Ground water level and flow play a crucial role in the availability of aggressive contaminants and the likelihood of deterioration of the foundations and services. Where contamination is left in place, the present and likely future ground water regime needs to be assessed. Soluble sulphate concentrations can be high in some ash surface sites and are of little concern if the ground is dry. The same ashes become acidic and aggressive to concrete foundations if they become wet. Ground water levels and flows can change dramatically if an in-ground containment barrier is constructed around a contaminated site, and rainfall run-off is not managed either by an effective cap or ground water drainage control.

## 4.5 Evaluation and selection of remedial measures

Part 2 of BRE Digest 427 provides guidance on ground improvement techniques and foundation design. The interaction between the selected foundation type, such as piles, to avoid potential settlements needs to take into account foundation deterioration due to contamination.

Control of contaminated ground water flow across a site may be achieved by various barriers systems. Guidance on the use and performance of containment systems is given in the bibliography under the subtitle of containment. A specification for the construction of slurry trench cut-off walls, the most commonly used in-ground barrier to control ground water migration, has been produced by the Institution of Civil Engineers (ICE, 1999).

## 4.6 Conclusions

The geotechnical properties and load carrying characteristics of contaminated ground consisting of non-engineered fill need to be addressed as part of the overall risk assessment of the effects of contaminated land on buildings. General guidance to deal with this assessment particularly in relation to collapse compression is covered in a series of BRE publications and other publications in the bibliography.

## 4.7 References (Section 4)

Charles J A, Skinner H D and Watts K S (1998). ‘The Specification of Fills to Support Buildings on Shallow Foundations: The "95% Fixation"’. Ground Engineering, vol. 31, no 1, January, pp 29-33.

Skinner H D and Charles J A (1999). ‘Problems Associated with Building on a Variable Depth of Fill’. Accepted for publication in Ground Engineering.

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Watts K S and Charles J A (1999). ‘Settlement Characteristics of Landfilled Wastes’. Accepted for publication in Geotechnical Engineering.

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Charles J A and Watts K S (1997). ‘Building on Fill: Collapse Compression on Inundation’. BRE Information Paper IP 5/97. Construction Research Communications, London.

BRE Digest 276 Hardcore (1992)

BRE Digest 318 Site investigation for low rise buildings: desk instructions (1987)

BRE Digest 322 Site investigation for low rise buildings: procurement (1987)

BRE Digest 348 Site investigation for low rise buildings: walk-over survey (1989)

BRE Digest 381 Site investigation for low rise buildings: trial pits (1993)

BRE Digest 383 Site investigation for low rise buildings: soil description (1993)

BRE Digest 427 Low rise buildings on fill (1997): Part 1 Classification and load carrying capacity; Part 2 Site investigation, ground movement and foundation design; Part 3 Engineered fill

# 5. EXPANSIVE SLAGS

## 5.1 Hazard

The principal hazard from the presence of old blastfurnace or steel slags is that they will expand, possibly decades after deposition, causing damage to buildings, roads or other structures. Slags may be present as a result of disposal as waste or use as fill or hardcore. The background to the problem including the nature of the expansive reactions is set out below. There are potentially a number of other hazards associated with slags (see Box 1) but these are not dealt with in detail here.

**BOX 5.1: Other hazards associated with slags**

**Presence of Potentially Harmful Substances**
Although the concentrations of certain toxic elements may be elevated in some blastfurnace and steel slags this is not usually a problem because they are not easily soluble. However, some of the wastes that may be found in association with them (e.g. flue dusts) can contain high concentrations of toxic substances.

Other problems known to be associated with slags are the production of water soluble complex sulfides that can give rise to severe water pollution (Smith, 1987) and the leaching of calcium hydroxide that then deposits in surface drains alongside roads as carbonate (tufa) (Gupta & Kneller, 1989). The latter has affected the drains along an UK motorway that also suffered severe distress due to expansion of the slag-containing sub-base material.

**Mixing with Other Materials**
Great care should be taken, for example, during reclamation of industrial complexes to avoid inadvertent mixing of blastfurnace or steel slag with other wastes such as colliery spoil or domestic refuse. Experience has shown that this can cause both expansive reactions and the generation of highly polluting leachates. Sulfur compounds are a particular problem.

**Reworking Old Deposits**
The specialist slag companies sometimes rework old slag deposits to recover good quality material meeting the appropriate British Standards. This is an exercise that should only be undertaken by specialists.

**Non-ferrous Slags**
Slags are an unavoidable by-product of the production of all kinds of metals. They all present some potential difficulties, e.g. stability, toxicity, radioactivity or potential to cause environmental damage. All, therefore, require careful identification and assessment.

## Background

### 5.2.1 Nature of Slags and the Hazard

Two main types of slag are produced during the manufacture of iron and steel (see Box 2). The first, blastfurnace slag, arises when iron ore is smelted to produce pig iron. The second, steel slag, arises when pig iron is converted into steel. Slags are also produced during the production of special steels and alloys such as ferromanganese but the quantities produced are small.

Large deposits of mixed slags and other wastes will usually be found around, and sometimes under, iron and steel making plants and on sites in the same general locality. Where these plants have been operating until comparatively recently it should be easy to recognise and locate the main slag deposits. However, many industries including, for example, some car manufacturers, operated their own foundries in the past. Slags may therefore be found on sites not directly related to the iron and steel industry,

The expansive properties of steel slags, including those that have been stockpiled for many years, are well known. There have been numerous failures of structures built on such slags, both in the UK (Anon 1984a, Anon 1984b and Smith 1987) and overseas. However, as these failures have often led to legal actions, little information about the circumstances of most of these occurrences is in the public domain. Warnings about the potential problems were first published by BRE in 1981 (Digest 222 which was replaced by Digest 276 in 1983).

Some older blastfurnace slags may also sometimes be expansive although there is less direct evidence that this has led directly to structural failures except in a few cases. For example, Crammond & Dunster (1997) describe a case in which the expansion of 70-year old blastfurnace slag caused disruptive heave beneath the concrete floors of a number of houses. Although modern blastfurnace slags are almost invariably volume stable, work by Crammond & Dunster (1997) suggests that there may be exceptions to the rule and that the chemical criteria used to assess stability may not always be fully reliable when the slag is to be used as fill.

In practice, there is often a co-mingling on old steelworks of blastfurnace and steelmaking slags, old refractories (some of which may also be expansive) and other wastes such as flue dusts. It is conceivable that these various wastes may interact chemically to enhance the expansive reactions.

In some cases disruption has resulted simply from reactions within the slag. In others, sulfates arising from the slag have attacked adjacent concrete. The presence of moisture is an essential requirement. Changes in the groundwater regime have been implicated in cases where the expansive reactions have occurred only several years after placement of slag as hardcore.

**BOX 5.2: Production and characteristics of iron and steel slags**

**Blastfurnace slag**

Historically two principal types of slag have been produced during the production of iron: basic and hematite iron slags. All current UK production of blastfurnace slag is "basic". Hematite iron slags are largely only of historic interest although large unused deposits remain in Cumbria. The main characteristic differences between currently produced basic blastfurnace slags and hematite iron slags is that the latter have higher lime and sulfur contents. The higher lime content favours the formation of dicalcium silicate ($2CaO.SiO_2$). Fresh blastfurnace slag comprises predominately the mineral melilite, a solid solution of which the two end members are gehlenite ($2CaO.Al_2O_3.SiO_2$) and akermanite ($2CaO.MgO.2SiO_2$).

For many years most, if not all, of the slag produced during the manufacture of pig iron has been processed for use as aggregate, ballast or roadstone, or in the production of blastfurnace cement in compliance with the appropriate British Standards. These standards have been in existence for several decades so in general blastfurnace slags reaching stockpiles will have been those failing the chemical criteria for stability in the appropriate standard specifications. However, not all blastfurnace slag could be used in the past, in part because the quantity produced was much larger and, in part, because a proportion of it was less chemically stable. The quantity of blastfurnace slag produced has fallen, not only as a result of reduction in the amount of iron manufactured, but also because the use of richer ores and improvements in operating efficiencies have reduced the amount of slag produced for each tonne of iron. In recent years it has been possible, through employment of a comprehensive testing regime to utilise about 1M tonnes of stockpiled hematite slags from Cumbria.

**Steel slag**

Pig iron is refined by melting under oxidising conditions with a flux of limestone or dolomite. The elements in excess in the pig iron such as carbon, silicon, and sulfur are either oxidised to gases or pass into the slag. The composition of steel slags is fundamentally different from blastfurnace slags and they are chemically and mineralogically very variable. Steel slags are of two principal types: acid and basic. Acid steel making slags are so called because they are low in lime and high in silica. Little if any steel is made at present using an "acid" process and only small quantities of acid slag tend to be encountered on closed works sites. All current production and almost all the steel slags encountered on sites are basic slags. Chemical analyses vary between processes and within works to a much greater extent than blastfurnace slags.

Most basic steel slags consist mainly of four phases: dicalcium silicate, "free" uncombined lime, a divalent metal oxide solid solution ("wustite" based on FeO and CaO) and a calcium aluminoferrite solid solution. Some contain tricalcium silicate ($3CaO.SiO_2$) or "alite" and uncombined magnesia (MgO). Metallic iron may also be present. The free lime, which is mainly undissolved fluxing material (see Box 5), is reactive and will in the presence of moisture hydrate or react with other chemical species (e.g. sulfates) causing disruption. Current production of steel slag is often processed to remove residual iron/steel. After removal of the iron and a period of controlled weathering to hydrate free lime, it is sometimes sold as roadstone, fill or for specialist applications.

**Old banked slag**

Blastfurnace and steel slags were frequently deposited in mountainous quantities around iron and steel works, often in close association with one another and often with a mixture of other, sometimes highly toxic wastes, such as those arising from associated coking plants, steel fabrication and manufacture of specialist steels. Old, possibly unstable refractories may also be present. Thus, any deposit of slag requires careful surveying to identify the materials present.

Procedures for assessing the stability of slags have been in existence for many years. For air-cooled blastfurnace slags, for use as aggregates, these are set out in BS 1047 (1983). For steelmaking slags a variety of tests have been employed to detect the potential for expansion (see below) and to determine its likely magnitude, although there is no British or European Standard (CEN) method at present.

The procedures employed for on-site sampling and laboratory preparation and sub-sampling are critical factors in obtaining reliable and representative assessments of slag stability. Whilst it is usually possible to identify a potential to expand it is questionable whether it is possible to predict the likely magnitude of expansion in the field from results obtained in the laboratory.

## 5.3 Slag Stability

Blastfurnace and steel slags have markedly different compositions (information on typical compositions of modern slags have been provided by Barry (1985)). "Typical" compositions have also tended to change as parent metallurgical processes have been modernised. Because of their chemical or mineralogical composition, some slags may undergo expansive reactions in the presence of water, or be otherwise unstable. Steel slags pose the greatest problem but there is some evidence that some old blastfurnace slags, which differ in composition from modern slags, may also be expansive. Typically mixtures of slag types will be encountered on sites, often in association with other wastes, such as flue dusts and spent refractories. Some of the latter may also be reactive/expansive.

There are six commonly recognised chemical reactions leading to volume instability in blastfurnace or steel slags (see also Boxes 3 and 4):

- free lime hydration - typical of steel slags but may occur in very old blastfurnace slags
- periclase hydration - typical of steel slags, occasionally occurs in blastfurnace slags
- sulfoaluminate formation - primary reaction of some blastfurnace slags but secondary product in steel slags
- iron unsoundness - affects blastfurnace slags
- rusting of metal inclusions - characteristic of steel slags
- "lime unsoundness" - characteristic of blastfurnace slags.

There have also been recent suggestions that thaumasite ($CaCO_3.CaSO_4.CaSiO_3.15H_2O$) formation might lead to instability in some old blastfurnace slags (Crammond & Dunster, 1997).

Volume instability due to sulfoaluminate (ettringite - $3CaO.Al_2O_3.3CaSO_4.32H_2O$) formation is the commonest form of volumetric instability in air-cooled blastfurnace slags (Thomas, 1999). However, it only occurs in "mature" slags, i.e. slags that are old enough, and have been exposed to the atmosphere long enough, for a significant proportion of the sulfur originally present as sulfide to have oxidised to sulfate. This sulfate, initially present as gypsum ($CaSO_4.2H_2O$), can, under certain conditions react to form of a sulfoaluminate hydrate phase, apparently similar to that formed during sulfate attack on concrete. The result is similar: volumetric expansion and disruption of the mass.

Iron unsoundness is rare in modern blastfurnace slags. Given that the process is rapid and once started continues to completion, it is unlikely that an iron unsound slag can remain on an open site under moist conditions for many years and remain intact. Thus, the prospect of

encountering still potentially iron unsound slag in mature well weathered material would be appear to be remote (Thomas, 1999).

Lime unsoundness is the misleading term applied to the transformation of beta dicalcium silicate to the gamma form. This process is "athermal" rather than "isothermal". Thus the reaction is "temperature dependent" rather than time dependant". The range of transformation temperatures for the reaction are well above ambient so it is unlikely that beta dicalcium silicate present in the old weathered blastfurnace slag will "invert" to the gamma form many years after it has fully cooled (Thomas, 1999).

The hydration of free CaO and free MgO are by far the commonest source of serious expansion in fills containing steel slags (Harris *et al*, 1995). The extent of expansion can be very extensive and the associated pressure exerted massive. Almost all basic steel slags contain residual free lime. There are three principal types (see Box 5): undigested lime, free lime form the break down of tricalcium silicate (alite) and reprecipitated lime. Some basic slags may also contain free MgO (magnesia or periclase).

Free CaO and MgO will, in the presence of water, ultimately hydrate to portlandite ($Ca(OH)_2$) and brucite ($Mg(OH)_2$) respectively. The formation of the hydrates is associated with massive expansion. In slags which have been weathering in-situ for long intervals, more easily hydratable free CaO, and to a more limited extent MgO will have hydrated. What remains are the more slowly hydratable oxides. Generally free MgO is much slower to hydrate than free CaO.

A common and significant component of steel slags is a wustite type solid solution of FeO, MnO, MgO and CaO. These solid solutions can vary considerably in composition but are either CaO and/or MgO rich or alternatively FeO and/or MnO rich. The FeO and/or MnO rich compositions are essentially stable whilst the solid solution with high CaO and/or MgO contents ultimately will be hydrated. In assessing basic steel slags for stability, care must be exercised so as not to miss free CaO and free MgO "masked" as a wustite solid solution (Thomas, 1999).

Long term exposure to the elements is no guarantee that steel slags do not retain a potential to expand. Slag that has spent even several decades in stockpiles may expand in later years if disturbed. Possible enhancing factors include: the ingress of moisture to previously dry materials (there is sometimes a cemented layer inhibiting water ingress), ingress of air permitting the oxidation of sulfide to sulfate, and the bringing into juxtaposition slags of different composition or stages of degradation that chemically interact with one another. For example, water-soluble sulfate produced by oxidation of sulfide in blastfurnace slag (or water-soluble sulfide derived from slag) might react with lime or calcium hydroxide in steel slags etc.

**BOX 5.3: Main reactions leading to instability of steel making slags (Thomas 1999 and Harris *et al* 1995)**

**Free lime hydration**
Calcium oxide (free lime) found in steel making slags arises from the limestone (calcium carbonate) added during the steel making process. It hydrates to form calcium hydroxide, and subsequently carbonates, with a large (100%) volume increase. It may also react with any sulfate present to form calcium sulfate (gypsum) which can then further react to form calcium sulfoaluminate.

**Periclase hydration**
Magnesium oxide (periclase), arising from magnesian limestone or dolomite, may hydrate to form brucite with a large volume increase (130%). However the reaction is generally very slow.

**Rusting**
Rusting of the free metal frequently present in steelmaking slags is due to one of a range of hydrolysis reactions covered by the blanket term of "iron unsoundness".

**BOX 5.4: Main reactions leading to instability of blastfurnace slags (Thomas 1999 and Harris *et al* 1995)**

**Periclase hydration**
Magnesium oxide (periclase), occasionally present in blastfurnace slags, may hydrate to form brucite, also with a large volume increase (130%). Equations and tests included in BS 1047 are intended to exclude blastfurnace slags which might contain periclase from use as aggregate.

**Iron unsoundness**
This is properly the term used to describe a specific hydrolysis reaction involving an iron sulfide likely to occur in blastfurnace slag. However, it is conveniently used to describe hydrolysis of any iron sulfide, metal or low oxidation state oxide. Such hydrolysis reactions commonly require acid conditions. Slag pieces, in the process of disintegration, frequently become rounded by repeated "onion skin" peeling. The process is difficult to stop once started, particularly in the presence of water. It will continue with catastrophic effect on the slag reducing lumps to fine powder.

**Sulfoaluminate formation**
Blastfurnace slag glass can react with sulfate under alkaline conditions to form sulfoaluminates. The volume expansion is about 130% relative to the glass.

**"Lime unsoundness"**
This is the misleading term given to the expansion (leading to a 10% volume increase) resulting from the change (inversion) of higher temperature isomorphs of dicalcium silicate to the gamma form stable at normal temperatures. The reaction, which typically occurs during cooling of the slag, is capable of reducing hard crystalline blastfurnace slag to a fine powder (a process known as "falling" or "dusting"). Equations and microscopic tests included in BS 1047 are intended to exclude slags that might contain this compound from use as aggregate.

**BOX 5.5: Occurrence of Free Lime in Steel Slags**

**Undigested lime**
This is the main source of residual free CaO. It is lime that failed to dissolve into the molten slag during the steel making process. In fully cooled slag, nodules of residual lime may be partially or fully enclosed in a layer of beta dicalcium silicate, formed at the interface of the lime nodule and the slag melt. The free lime present may have suffered varying degrees of heat treatment resulting in increasing density. This in turn can influence the rate at which hydration takes place in the presence of water. "Free lime" may also be present as a lime-rich wustite type solid solution. This again may reduce the ease with which the free lime can hydrate.

**Free CaO from the breakdown of "alite"**
Alite, i.e. tricalcium silicate, is sometimes found in freshly cooled basic steel slags. When present the phase commonly breaks down to yield beta dicalcium silicate and free CaO. This source of free lime is considered less common (Thomas, 1999) - and less troublesome as a source of potential expansion (Thomas, 1999).

**Re-precipitated free lime**
As indicated by the description, free CaO may come out of solution during cooling. This possible source is controversial. It is unlikely to be the main source of volumetric instability in basic steel slag.

## 5.4 Risk assessment

### 5.4.1 Current Production Slags

Blastfurnace slags have been used for many years as construction aggregates (e.g. roadstone, road base, railway ballast, in asphalt, concrete aggregate), and in the production of cement. As a result, a range of tests (e.g. BS 1047) have been developed in the UK and other countries to confirm the suitability of blastfurnace slag for the intended use, including avoiding the dangers of volume instability. Tests to BS 1047 are only appropriate when the slag is to be used as aggregate and when the slag falls within the composition range covered by the standard - hematite slags are excluded. If the major oxide composition falls within the range of typical blastfurnace slags, a calculation can be made (according to BS 1047) to identify a potential for the slag to contain periclase (MgO) or dicalcium silicate ($2CaO.SiO_2$).

Steel slags, although used as aggregate in limited applications (e.g. roadstone for surface dressing), have not been the subject of such standardisation in the UK, although standardised test methods have been developed in a number of countries including the USA (ASTM D4792), Germany, Japan and Belgium for assessing potential volume instability.

British Standard methods developed for assessing the suitability of blastfurnace slag for use as aggregate are not generally applicable to the assessment of steelmaking slags; the chemical composition and hence possible mechanisms of reaction are too different.

### 5.4.2 Field Sampling and Selection of Material for Testing

When tests are required to determine the volume stability of blastfurnace and steel slags it is customary to take samples of about 20 to 50 kg. These are then inspected in the laboratory to select suitable sub-samples for testing. The guidance of the laboratory carrying out the testing should be obtained, and it will often be appropriate for someone experienced in the assessment of slags to supervise the sampling.

The large field samples must be sub-sampled and reduced in size to obtain a representative sample for testing. Different tests will be performed on material of different gradings. If X-ray analysis is to be performed then a few grammes reduced to less than about 50 µm will be required; chemical analysis usually requires material less than about 150 µm, and optical microscopy material less than about 5 or 10 mm. In contrast, the expansion test might be performed on material less than about 40 mm. Clearly, there is great scope for the results to be biased if inappropriate procedures are followed. Laboratories should describe the sub-sampling and sample preparation procedures employed when reporting results.

It is important to prevent the breakdown of hydrated reaction products already formed from earlier expansive reactions. Clearly if processing causes dehydration of such products, testing could exaggerate the potential for further expansion. To avoid this problem, low temperatures are necessary during sample preparation.

### 5.4.3 Identification of Slag Type

Because different mechanisms are involved when steel making and blastfurnace slags exhibit instability it is essential to identify the type of slag under investigation so that appropriate test procedures can be employed. It is not possible to identify slag type by simple visual inspection of a hand specimen. In addition, materials are often mis-identified as "slag" in field descriptions of materials. There have also been failures to identify "slag" as present even when the site history suggests that it is likely to be present.

Slag type can be determined by a variety of means. Major oxide analysis (i.e. for CaO, $Al_2O_3$, $SiO_2$, MgO, iron oxides) can provide a strong indication but positive identification requires determination of the mineralogy by optical microscopy and/or X-ray diffraction analysis. This mineralogical analysis is used to determine which minerals are present, thus confirming the type and condition (e.g. crystalline or glassy/vitrified) of the slag. It may also identify known reactive (CaO, MgO) or unstable (dicalcium silicate) compounds, or the products of reaction (e.g. calcium carbonate, calcium hydroxide, calcium sulfoaluminates). Other techniques, such as differential thermal analysis (DTA) and thermal gravimetric analysis (TGA) can also be employed to characterise and quantify reaction products (see below).

### 5.4.4 Approach to Assessment

The test sequence required once the main constituents of the sample have been established following appropriate sub-sampling and size reduction procedures is to determine:

- if there is a potential to expand, and,
- the magnitude of expansion under defined laboratory conditions.

The results of the latter (possibly following additional physico-chemical testing) may then be used to attempt to:

- estimate the full potential expansion
- predict performance in the field.

A test to determine a potential to expand will not necessarily indicate the likely magnitude of expansion. For example, a potential to expand might be considered to be established if uncombined lime or magnesia is detected by microscopy or X-ray analysis.

The chemical criteria for the presence of beta dicalcium silicate are difficult to apply to old mixed slags, due to the mixing and contamination that inevitably takes place. In any case these provisions, when applied to slag in fill, are ineffective and do not "fail safe" by identifying all blastfurnace slags containing beta dicalcium silicate (Crammond & Dunster 1997 and Thomas 1999).

When assessing slags for potential to expand it is important to bear in mind that:

- the degree of potential expansivity may vary widely within the slag, and,
- the distribution of unstable material may vary widely over the site.

It is impossible to predict when expansion will take place. Some instability may occur within weeks whilst the potential may persist elsewhere for decades. Exceptionally, very persistent forms of MgO can still present problems after 100 years of weathering. This variable time factor is of paramount importance because the time scale can vary widely within one deposit. Thus, industrial fill containing variable quantities of slag of variable potential expansivity can, in some instances, represent a series of time bombs with unpredictable fuses (Thomas 1999).

### 5.4.5 Chemical and Related Tests

A variety of tests may be employed in order to identify constituents associated with past expansion (if any) and to assess whether there is a potential for (further) expansion. According to Thomas appropriate determinants and test methods are:

- for blastfurnace slags - water soluble sulfate, acid soluble sulfate, total sulfur, thermal analyses (DTA and TGA)
- for basic steelmaking slag - free CaO, free MgO, thermal analyses (DTA and TGA)

If both types of slag are present, the full range of tests is required. Determination of sulfide and sulfate in all slag samples is relevant to assessment of stability, pollution potential and the suitability of the slag as fill material into which concrete is to be placed.

### 5.4.6 Tests for Expansion

Potential instability due to free lime, free periclase and sulfoaluminate reactions is usually determined in a test in which compacted and confined samples of slag are heated in water to elevated temperatures for a period of time (from several days to several weeks). As noted above, the test requires a significant amount of judgement in the selection of the test samples from the large volumes brought from sites.

The most commonly used method is often termed the "BRE test" ("Penndot" in the USA) although it was first developed by Dr John Emery (Emery 1974 and Emery 1980) (now of John Emery Geotechnical Engineering Limited - JEGEL). As it is a non-standardised test in the UK there is no certainty that all laboratories claiming to carry out the test are following the same procedure. What appear to be small changes, or poor design of the apparatus, may result in different laboratories obtaining different results. The temperature at which the tests are carried out is critical (see Box 6). Key features of the test as employed in one laboratory with extensive experience of the test over a number of years are as follows:

- temperature (80$^{o}$C),
- grading of the material to be tested (20-40 mm),
- addition of water before any measurements are made,
- measurements being started after 24 hours to ensure that the slag and apparatus are both at 80$^{o}$C.

**BOX 5.6: The effect of temperature on expansion**

Emery's original work (Emery, 1974) showed clearly the importance of temperature. The expansion at 60$^{o}$C after 7 days was only about one third of that at 82$^{o}$C (the temperature used in the original tests). He concluded that for the steel slags under investigation, a test period of seven days was sufficient to detect the potential to expand but not necessarily the full extent of expansion that could occur. After 475 days at 20$^{o}$C the expansion was about half that after 7 days at 82$^{o}$C.

A standardised variant of the test is the ASTM D4792 aggregate expansion test. This is done at 71$^{o}$C ± 3$^{o}$C at standard moisture content determined to ensure optimum compaction of the test specimen. Experience suggests that 7 days is sufficient to give an acceptably reliable indication of whether a steel slag aggregate has a potential to expand (Emery, private communication 1993). Measurements start one hour after immersion of the specimen.

A further variant of the Emery test was employed in a study by the British Steel Corporation for the Commission of the European Communities (Best, 1987). In this study, concerned with the use of current production of LD slag in road construction, the test was carried out at 80$^{o}$C at a nominal 98% relative humidity in a climatic cabinet.

Thomas Research Services employs a test procedure which it is claimed can detect instability due to the sulfoaluminate reaction in blastfurnace slag as well as instability due to the presence of free lime and/or free magnesia (periclase). A full description of the test procedure is not available. It is of propriety nature, however, it is understood to be based on a thermal cycling under high humidity conditions. The specimens, which are similar in form to those employed in the BRE-style test, are stored in a climatic cabinet.

The use of high humidity (in contrast to immersion) and high temperatures is a principal of a number of test procedures concerned with the detection of volume instability due to the presence of reactive species. It forms the basis of the German test for current production steel slags and the ASTM autoclave test for the stability of high magnesia cements[1].

[1] If the raw materials used to make cement contain too much magnesium, the fired clinker may contain uncombined "free" magnesia/periclase (MgO). Hydration of this periclase resulting in destruction of hardened concrete may only occur after many years despite the cement having been ground very finely.

A new test has recently been developed in Canada as a simple and rapid means of detecting the potential to expand (the test takes about one hour). This autoclave test was developed for use as a quality assurance test for current production of steelmaking slag coming directly from the furnace and intended for use a roadstone. It does not yield a magnitude for the expansion although it may give an indication of the proportion of expansive material present. The test method has not been published but the test has been employed in comparison with the BRE-style test during an investigation of materials from a distressed part of a motorway (Smith – private communication). Some individual particles were broken down although the bulk sample from which they were taken did not expand in the BRE-style test. This type of autoclave test may have potential as a fail-safe test for old steel slags offering the opportunity for testing a much greater number of samples then is currently practicable but would require thorough evaluation before being used in this way.

A test was also developed to check for deleterious expansion in bituminous mixtures containing steel slag aggregates. Compacted specimens of the mixture are submerged in a water bath at 71$^{o}$C for 72 hours and checked for expansion, ‘pop-outs’, cracking and staining.

"Iron unsoundness" in freshly made blastfurnace slags may be determined using the method specified in BS 1047 and it can be adapted to test for similar reactions in steel making slags. However, the application of this test to old stockpiled material or, more particularly, to fill containing weathered slags, can give rise to misleading results (Thomas 1999).

## 5.5 Evaluation and selection of remedial measures

The assessment of slags for instability is a specialist area of work requiring input from a specialist consultant who should preferably be involved in all aspects of the investigation. Simply obtaining results from a test house is not sufficient. Specialist interpretation is required. It is important that the "slag specialist" should engage in a dialogue with the ultimate client and his engineering advisors. In particular a geotechnical engineer should be involved.

There are no easy solutions for dealing with in-situ unstable slag. There are no means of stabilising unstable slags that are technically and commercially feasible. No two sites present the same problem. Depending on the scale of the problem and the type of development intended the following solutions may be possible:

- Engineer a way around the problem - only rarely possible
- Excavate for disposal or relocate the fill around the site in places where it can do no harm replacing with stable fill if necessary.
- Go elsewhere to build and convert the site into a golf course with naturally changing topography.

There are few examples of successful construction on known expansive slags. They appear to be restricted to steel works in Canada. It is to be assumed that in these cases removal of the slag was judged to be impracticable, but the project to be of sufficient importance to justify the development of an appropriate engineering solution, taking into account the potential risks. It should be noted that some of the major failures have occurred on steelworks and the clients should have been well aware of the potential risks. In the one well documented case in the UK (Eakin & Crowther, 1986) where an attempt was made to "engineer" a construction platform by compacting slag it was still rising after three years and was eventually removed.

Steel slags were used extensively in Ontario as an aggregate for hot-mix asphalt from the early 1970s until 1991 (Farrand & Emery, 1995). About 0.5 Mtonnes were used in this way in 1990. However, the Ontario Ministry of Transportation (MTO) began in about 1985 to express concern about pavements where steel slag aggregate had been used after about 1980. The initial concerns were random map cracking, grey veining about cracks, "flushing" of asphalt cement to the surface, and the general lack of performance compared to natural aggregates. Continued problems led to a moratorium on further use of all steel and blastfurnace slags in 1991.

A task force was set up to investigate the reason for the reduced performance compared to earlier periods. An important factor controlling stability was found to be the precise nature of the steelmaking process that could vary from shop to shop within a single works. In addition, there was a change in fluxing practice with more dolomite being used and a coarser feed – typically 25mm particles that do not readily or fully dissolve. This experience is important, not only because it is a well documented case of problems arising from the use of steel slag (even after it had been used successfully for many years), but also because when materials are derived from a complex site with a long history, one can expect a range of slag types of different ages and origins. Consequently, great care must be exercised in predicting stability on the basis of what must be a limited sampling and testing programme.

When disruptive expansion does occur there is little that can be done other than to excavate the slag and repair the damage. However, because of the unpredictable nature of the reactions, remediation on one part of the site may shortly be followed by problems developing elsewhere so that a rolling, but non-predictable, pattern of excavation and repair ensues over many years.

Avoidance of future problems requires that when steel works are demolished, premature spreading of unidentified stockpiles of slag around the site is avoided.

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