Field studies of the effectiveness of concrete repairs

Phase 1 Report: Desk study and literature review

Prepared by **Mott MacDonald Ltd** for
the Health and Safety Executive 2003

RESEARCH REPORT 175

Field studies of the effectiveness of concrete repairs

Phase 1 Report: Desk study and literature review

N J R Baldwin
BSc MSc FGS MIM CEng
Mott MacDonald Ltd
St Anne House
Wellesley Road
Croydon CR9 2UL

E S King
BSc DiplEng MPhil MICE CEng
Mott MacDonald Ltd
Capital House
Andover Road
Winchester SO23 7BH

This report presents the findings of the project Field Studies of the Effectiveness of Concrete Repairs. The projects was undertaken in four phases and is presented in five reports.

HSE has published the following four reports:

Phase 1: Desk study and literature review.

Phase 3: Inspection of sites, sampling and testing , at selected repair sites.

Phase 3a: An investigation of the performance of repairs and cathodic protection (CP) systems at the Dartford West Tunnel, (DWT).

Phase 4: Analysis of the effectiveness of concrete repairs and project findings.

Phase 2 of the project details the selection of study locations and the procedures for investigating and recording the repair sites. This phase is summarised in the Mott MacDonald report R1093 'Phase 2 Report Site Planning'.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE BOOKS

© Crown copyright 2003

First published 2003

ISBN 0 7176 2783 7

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photocopying, recording or otherwise) without the prior written permission of the copyright owner.

Applications for reproduction should be made in writing to:
Licensing Division, Her Majesty's Stationery Office,
St Clements House, 2-16 Colegate, Norwich NR3 1BQ
or by e-mail to hmsolicensing@cabinet-office.x.gsi.gov.uk

ACKNOWLEDGEMENTS

The authors acknowledge the following for their co-operation and contributions without whose support the project could not be executed:

Health and Safety Executive

Highways Agency

Industry Management Committee

Institution of Civil Engineers Research and Development Enabling Fund

MM Group Research and Development Fund

Concrete Repairs Ltd

Llewellyn Stonecare Ltd

Geomaterials Research Services Ltd

Building Research Establishment

Weber-Broutin SBD

BNFL Magnox Generation

TRL Limited

Sprayed Concrete Association

Concrete Repair Association

British Energy Generation UK Ltd

CONTENTS

SUMMARY vii

Chapters and Appendices

1 INTRODUCTION 1

1.1 Background 1

1.2 Objectives 1

1.3 Scope of Phase 1 – Literature search and expert meetings 2

1.4 Aims of the Literature Search 2

2 CORRESPONDING EXPERT GROUP 4

3 LITERATURE REVIEW 5

3.1 Repair of concrete structures 5

3.2 The repair process 6

3.3 Existing Standards and Specification 10

3.4 Repair options 11

3.5 Repair application and methodology 14

3.6 Electrochemical Repair Techniques 16

3.7 Effectiveness 19

3.8 Methods of testing effectiveness 24

3.9 Examples of studies into repairs 25

4 FINDINGS 30

5 PROGRESS AND FUTURE WORK 31

5.1 Phase 2 31

5.2 Phase 2a – Dartford site planning 31

APPENDIX A	FORTHCOMING EUROPEAN STANDARD EN 1504	32
APPENDIX B	BIBLIOGRAPHY	37

Tables

Table 1	Corresponding expert group members	4
Table 2	Composition of concrete repair systems	13
Table 3	Categories of systems for concrete patch repair (from Emberson and Mays[40])	13
Table 4	Application methods and properties of concrete repair materials	14
Table 5	Steps in the conventional repair of reinforced concrete	14
Table 6	Corrosion inhibitors and electrochemical techniques	16
Table 7	Components of EN 1504	32
Table 8	Main technical contents of ENV 1504-9	33
Table 9	Practical examples for application of terms used in the European Standard on concrete repair principles	34
Table 10	Examples of principles and methods for dealing with reinforcement corrosion defects (from DD ENV 1504:1997)[7]	35

Figures

Figure 1	Stages in the investigation and repair of a structure	8
Figure 2	Re-alkalisation of reinforced concrete affected by carbonation	18
Figure 3	Chloride extraction for chloride infected reinforced concrete	18
Figure 4	Factors affecting compatibility of repair systems	20
Figure 5	Processes involved in repair	23
Figure 6	Logic of European Standard Env 1504	34

SUMMARY

This report presents the findings of Phase 1 of the project Field Studies of the Effectiveness of Concrete Repairs. An expert group from industry and academia has been set up to consult on key issues and has been involved in the issue of this document.

A full literature search has been conducted, with the aid of experts in the field, to identify the state of the art with regard to repair materials, methods for selecting and specifying repairs and measurement of effectiveness of repairs. International studies of repair performance have been included in the search.

Phase 2 of the project, detailing the selection of study locations and the procedures for investigating and recording the repair sites, is summarised in Mott MacDonald report R1093 'Phase 2 Report Site Planning'.

1 INTRODUCTION

1.1 BACKGROUND

Mott MacDonald Ltd (MM) was commissioned by the Health and Safety Executive (HSE) in June 2000 to carry out a research study entitled 'Field Studies of Effectiveness of Concrete Repairs'. The project follows on from the project "Concrete repair materials and protective coating systems", 1995, completed under nuclear repair contract BL/G/31221/S by Sheffield University (Reference[1]).

The scope and objectives have been developed between the HSE, MM and other organisations whose interests are represented in an Expert Group associated with the project. Funding has also been received from the Highways Agency (HA) and the Institution of Civil Engineers (ICE) Research and Development Enabling Fund. The project receives substantial additional support from collaborating organisation and individuals, as well as the co-operation of owners of repaired structures.

The project is divided into four main phases with two additional sub-phases relating to work carried out at Dartford River Crossing. The first stage involves desk study and literature review (Phase 1). Repair sites will be selected by the project team and reviewed by the project's corresponding Expert Group (Phase 2 and 2a). Inspection of sites, sampling and destructive and non-destructive testing, at selected repair sites, will then be carried out (Phases 3 and 3a). The final stage involves analysis of data relating to the effectiveness of concrete repairs, and dissemination of the project findings (Phase 4).

This report presents the findings of Phase 1, the scope of which is shown in Section 1.2. This report presents the literature review undertaken to date. The review of literature and correspondence with other researchers is ongoing and all findings will be presented in the Phase 4 report. Because of the huge range of repair types we are initially focusing on concrete patch repairs, with inclusion of other types of repairs if present at sites we propose to visit.

1.2 OBJECTIVES

The aim of this project is to evaluate the effectiveness of the range of concrete repair systems as applied in practice, in order to improve practices for maintaining and improving the integrity of operational structures and so achieve higher standards of structural safety and reliability and better whole-life structural management. It is not necessarily intended to directly compare the performance of similar materials or products, but to assess the whole process whereby repair is carried out, and in particular what parts of the process lead to success or failure.

This project therefore seeks to identify, measure, assess and quantify the effectiveness of different repair procedures. It also investigates the effects of ageing of a representative sample of repairs. Degradation mechanisms will also be identified and durability models will be put forward for use in maintenance planning, where appropriate. The most effective means of providing enhanced durability will be identified.

The project output will include the production of guidelines covering the decision making process of concrete repair. These guidelines will be disseminated to industry through a new guidance note and inclusion in industry documents such as Nuclear Industry Guide R77 and

Highways Agency BD 27/86 ‘Materials for the repair of concrete highway structures’, and through a proposed ICE publication.

1.3 SCOPE OF PHASE 1 – LITERATURE SEARCH AND EXPERT MEETINGS

Phase 1 has involved industry-wide consultation and literature review to identify how to use existing information and new research work to the greatest effect. Phase 1 has resulted in a detailed scope for assessment of selected repair materials. It involved the following:

- Consultation with the client in order to ensure full understanding of the aims of the project and to discuss past experiences and potential sites.

- Full literature search, assisted by experts in the field, to identify the state of the art with regard to repair materials, methods for selecting and specifying repairs, measurement of effectiveness of repairs with the particular aim of identifying international studies of repair performance.

- Consultation with experts from academia and industry and explore and formation of co-operative and collaborative relationships with organisations such as the Highways Agency, Transport Research Laboratory, Building Research Establishment and other bodies.

- Establishing a small review panel, or Expert Group, to act as a steering group and corresponding advisors to the project team. The Expert Group help provide focus for critical issues, provide industry-wide expertise and ensure deliverables have the required industrial relevance. The Expert Group includes representatives form the nuclear industry, the Highways Agency, the Concrete Repair Association and from academia.

- Use of existing systems to identify and classify repair materials, to explore techniques for measuring effectiveness and to select repair types to focus on in subsequent Phases.

1.4 AIMS OF THE LITERATURE SEARCH

A summary of the literature search is contained within this report. The aim of the literature search was to identify the state of the art with regard to repair materials, methods for selecting and specifying repairs and measurement of effectiveness of repairs. International studies of repair performance were included in the search.

Previous research[1] found that there is little independent data on the long-term in-situ performance of most concrete repair systems. Existing information is often specific to a particular structure under a particular set of environmental and operating conditions.

The search has addressed the following key items:

- previous studies and publications relating to the performance of concrete repairs

- existing information relating to the process of specifying concrete repairs

- the possible definitions for ‘performance’ and ‘effectiveness’ of concrete repairs

- use of existing research to support new, original research

- description and classification of repair types and the implications for inclusion of different types in the project.

2 CORRESPONDING EXPERT GROUP

An Expert Group has been formed to advise, guide and review the research into the effectiveness of concrete repairs. The Expert Group also represents the interests of the industry. The group comprises 10 individuals from industrial and academic backgrounds, supported by additional corresponding ‘invitees’ with specialist knowledge in certain aspects of repair. Table 1 below lists the group members and their individual interests.

Table 1 Corresponding expert group members

Name	*Company/Organisation*	*Area(s) of interest*
1. Neil Loudon	Highways Agency	Collaborator
2. Brian Neale	HSE	H&S, client
3. John Drewett	CRL	Practical aspects
4. Dr George Sergi	BRE	Repair and corrosion
5. John Shaw	Weber Broutin SBD	Repairs and repair materials, European standards
6. Mike Eden	Geomaterials Research Services Ltd.	Repair/concrete interface
7. Dr Paul Lambert	Mott MacDonald	Corrosion and cathodic protection
8. Phillip Pearson	BNFL Magnox Electric	Repairs/maintenance in nuclear facilities
9. Robert Walker	TRL Limited	Corrosion specialist
10. Pat Quarton	Sprayed Concrete Association/Concrete Repair Association	Repairs, sprayed concrete
11. Dr Tony McNulty	HSE	Client
12. Brian Gardiner	Llewellyn	Practical aspects
13. Roger Crouch	Sheffield University	Concrete
14. Dr Michael Johnston	British Energy Generation (UK) Ltd	Repairs, nuclear facilities

3 LITERATURE REVIEW

3.1 REPAIR OF CONCRETE STRUCTURES

3.1.1 Engineering significance

Reinforced concrete has become a universal dominant construction material in the past 50 years. There is a vast stock of major structures and infrastructure constructed with reinforced concrete in the UK. These structures are subject to a range of degradation mechanisms, which results in the generation of defects. The nature of the deterioration mechanisms and the form of the structures is often such that repair is necessary at a stage considerably before serious structural implications arise. This has, and will continue to, generate a legacy of demand for repair of structures that are still serviceable but suffer defects in durability, cosmetic or safety function. Indeed Tuutti[2] states there is exponential growth in demand for concrete repair, and Davies[3] provides an estimate of a £1bn European market in the repair of premature deterioration in reinforced concrete structures. Van Gemert[4] quotes that repair, rehabilitation and protection of buildings and infrastructure account for 40% of construction workload.

It should be noted that the majority of reinforced concrete structures meet or exceed their intended service life (Walker[5]). However, many will have undergone some maintenance and repair.

3.1.2 Definitions of repair

Repair of reinforced concrete involves treatment, after defects have occurred, to restore the structure to an acceptable condition. Defects cause some compromise in condition or function relative to the original, and this generally means that a process or processes have resulted in movement, loss of material, and/or loss in materials properties. Repairs are therefore mostly reactive, and initiated when evidence of deterioration becomes apparent.

Etebar[6] defines the objective of repair as being to restore or enhance one property such as durability, structural strength, function or appearance.

Walker[5] indicates that rehabilitation refers to bringing degradation under control to enable a structure to continue to serve its intended purpose. This can be either repairing to bring concrete back to a state similar to the original, or using methods to arrest deterioration processes to enable ongoing service. The literature appears to make little or no differentiation between ‘repair’ and ‘rehabilitation’.

ENV 1504-9[7] presents the following definitions:

- Defect: an unacceptable condition which may be in-built or may be the result of deterioration or damage.
- Protection: a measure which prevents or reduces the development of defects.
- Repair: a measure which corrects defects.

3.1.3 Deterioration mechanisms

The reasons for deterioration of structures are manifold and involve complex interactions between natural processes, service environment, materials properties, and quality in design, detailing and construction. There are a number of major deterioration mechanisms. These are described in numerous existing text books[8,9,10] and technical publications, for example by The Concrete Society[11], BRE[12], and CIRIA. The following forms of deterioration and other processes result in defects in reinforced concrete, and may result in demand for repair:

- Chloride-induced corrosion of steel (see references[13],[14])
- Carbonation-induced corrosion of steel (see references as above)
- Chemical attack (sulphate attack, acid attack see reference[15], and for thaumasite attack see reference[16])
- Alkali-aggregate reaction (see references[17],[18])
- Fire damage (see reference[19])
- Freeze-thaw attack
- abrasion, impact, erosion, cavitation
- Structural damage

It is well established that corrosion of embedded reinforcement is the single most widespread cause of deterioration in reinforced concrete construction[1]. Repair of reinforcement corrosion damage is described in various references[1, 11, 20]. Pomeroy[21] states that most damage to structural concrete results from the corrosion of steel. Somerville[22] states that corrosion, arising from various causes, is the dominant deterioration mechanism, and of greatest significance to the occurrence of corrosion is the external environment, matched by a combination of low cover, poor quality concrete, poor design detailing, and poor workmanship. It follows that repair is most commonly related to defects arising from reinforcement corrosion.

Rostam and Faber[23] conclude that for repair, only four main mechanisms of deterioration need be considered; freeze/thaw, alkali-aggregate reaction, other chemical attack to the surface, and reinforcement corrosion caused by carbonation or chloride ingress. These mechanisms are controlled primarily by three transport mechanisms; diffusion, permeation (by pressure head) and capillary suction. It is the susceptibility of the substrate to these mechanisms, and the severity of the environment, that controls the rate of deterioration and demand for repair.

3.2 THE REPAIR PROCESS

3.2.1 Introduction

There is a considerable volume of literature relating to best approach to repair, which is summarised in earlier work[1], but basically the greater the level of information that is available concerning the structure, the better the potential for planning an effective remedial strategy.

There is broad agreement that condition of the structure must be known, including the extent and severity of defects. This is normally achieved by a planned regime of inspection and testing of the structure by suitably experienced and qualified engineers. In particular, it is important to understand the cause or causes of deterioration so that the subsequent repair strategy is appropriate for both rectifying the existing defects and resisting future deterioration.

The appropriate management strategy for a particular structure is a function of client requirements and resources, structure condition, suitable repair methods and application techniques and compliance with standards and relevant specifications. The strategy does not necessarily result in repair of a deteriorated building; controlled deterioration, dereliction and demolition are other possible options.

3.2.2 Planning of repair

The variables involved in repair make it a complex subject. It has been suggested[2] that repair is more complex than design of new structures, and that management of rehabilitation is more complex than of new construction[4].

Mays[24] provides a useful summary of the stages involved in the design of an appropriate repair or protection scheme. This involves seven stages, as follows:

(a) Assessment of the condition of the structure

(b) Identification of the causes of deterioration

(c) Deciding the Objectives of protection and repair

(d) Selection of the appropriate principles for protection and repair

(e) Selection of methods

(f) Definition of properties of products and systems to be used in works

(g) Specification of maintenance requirements following protection and repair.

Items 1 and 2 involve gathering sufficient information that the problems are understood, as described in Section 3.2.3. Items 3 and 4 involve relating the current condition of the structure to the intended use and life in order to select the required outcome of the future maintenance strategy. This required outcome leads to the identification and selection of appropriate methods and materials for repair in Items 5 and 6, described in Section 3.2.4.

3.2.3 Understanding the problem

There are numerous references describing methods for investigating the condition of a structure[13,19, 25]. These include methods presented by the Concrete Society and in British Standards. BA23/86[26] also describes an approach to investigation and testing for use on highway structures in the UK.

The investigation process may involve a preliminary visual survey, followed by more detailed inspection and testing to determine the cause and general extent of deterioration. Depending on these findings, further investigation and testing may be required, perhaps to identify specific boundaries of deterioration or potential deterioration.

Kamijoh[27] presents a detailed procedure for the investigation and repair of a deteriorated bridge structure. This involved inspection and testing to quantify the problem followed by repair. A modified form of the procedure is summarised as follows:

The information gathered during the investigations is used to provide an understanding of the mechanisms that cause deterioration, the severity and extent of defects, and the implications for repair or other rehabilitation strategy.

Regular inspection identifies presence of damage

↓

Primary survey of damaged locations, based on visual inspection

↓

Initial repair design, selection of materials, method and budgeting

↓

Detailed survey to quantify damage, including testing for carbonation depth, schmidt hammer strength testing, chloride content survey, examination of reinforcement condition, measurement of cover depth

↓

Detailed repair design, confirmation/modification of materials, method, quantities and costs

↓

Execution of repair

Figure 1 Stages in the investigation and repair of a structure

3.2.4 Selection of strategy

Before a strategy for effective management of a structure can be determined, the required structure life span, future use and maintenance regimes should be considered, and the practical aspects of how repair work could be carried out assessed. Walker[5] asserts that prior to rehabilitation, there is a need to determine the standard of future performance that is required, which directly affects the level of repair to be carried out. It is also important to review the implications of the nature and cause of deterioration on the treatment strategy.

Various classifications have been presented to describe the various strategies available for treating deteriorated buildings. These can be based on what action is required, the outcome of the action, or the principle behind the action. Johnstone[28] quotes unpublished work by Thomson, based on the outcome of the action, identifying three strategies for concrete repair;

- to restore as built,
- to conserve as found, and,
- to slow continuing deterioration.

The first option requires major work to remove the accumulated effects of deterioration since construction. The second option is most commonly adopted[28], and often the aim is to remove loose concrete and stop corrosion, probably involving limited use of repair or protection systems. The last option is specific to defects arising from reinforcement corrosion and involves treatment to reduce corrosion rates. There is currently limited information on the effectiveness of these treatments.

The most common maintenance strategies, based on action, as identified in Reference 1, include:

- Do nothing (i.e. make the structure safe and allow controlled deterioration to an identified end-point)
- Carry out holding repairs (and accept future maintenance and repair episodes may be required)
- Carry out a once and for all major refurbishment
- Demolish and rebuild.

These strategies are similar to the six options presented in EN 1504 Part 9[7] (see section A.3) and further described in BRE Digest 444[29]. This project is concerned principally with the options involving some form of repair. Rostam and Faber[23] provide a further division of such repair options, as follows:

A Structural repair
- replace material
- replace or strengthen elements.

B Materials repair
- surface protection (coatings, impregnations)
- change the environment
- electro-chemical repairs (cathodic protection, chloride extraction, re-alkalisation).

This project includes the study of elements of these options. However, no fully satisfactory classification has been found for choice of strategy. This is in part due to the complexity and number of possible approaches and actions. It is because of this that the selection of the strategy must involve interaction between suitably qualified and experienced technical staff and the client.

3.2.5 Costs, cost modelling, whole-life costing

There are considerable benefits in modelling the costs and implications of different repair strategies in order to provide a future maintenance strategy and budget. It is particularly important in instances where the extent of repair works exceeds available funding, and hence there is a need to optimise spending. C Henriksen and C Michaux[30] suggest there are no well established service life models available that there is a need for reliable service life prediction to optimise repair budgets.

Rowe et al[31] developed a process to optimise repair strategies which can be used in a management methodology for the structural maintenance of structures. The process used a costing tool, including pilot software, which allowed the comparison of whole-life costs for different repair options to a highway structure.

Guidance is now available for planning[32] and prediction[33] of service life for structures, though it is not specifically include repair application and effectiveness.

3.3 EXISTING STANDARDS AND SPECIFICATION

A British Standard[34] concerning the cleaning and surface repair of buildings was published in 1985. This provided recommendations for the cleaning and surface repair of concrete and precast concrete masonry. The standard was withdrawn in March 2000 and superseded by BS8221 Parts 1 and 2[35] in 2000. The cleaning of natural stones, brick, terracotta and concrete surfaces is covered in BS8221 Part1. The scope of Part 2 includes surface repair of natural stones, brick and terracotta, but excludes repair of concrete.

There are several other existing options for specification and guidance in executing repairs in the UK. This includes information supplied by the Highways Agency[26] and the Concrete Society[14]. In addition, both the manufactures of proprietary products and repair applicators may generate specific specifications and methods of working. It is important to be aware of these as they dictate the way in which repairs are selected and executed and therefore have a strong influence on the future performance. Of particular future significance will be the forthcoming European Standard for concrete repair, discussed further in Appendix A.

Mott MacDonald Ltd carried out research into waterproofing and repair of underground service reservoirs in 1995. This resulted in CIRIA Report 138[36] aimed to assist Water Undertakers to carry out effective investigations, repairs and waterproofing to underground service reservoirs with improved quality and cost effectiveness. Within this report, quality management in repairs is discussed. Flowcharts are used to illustrate the stages of repair in relation to a quality system. Selection of a method of repair within the report is defined as a function of:

- Technical assessment
- Durability
- Maintenance
- Cost

Concrete repair is classed by method of application, namely hand-placed, sprayed and flowable concrete. The only material considered for concrete repair in CIRIA Report 138 is polymer modified cementitious.

It is apparent that attempts over the past twenty years in preparing repair specifications have not been entirely successful. At the end of the 1980's a Concrete Society working party[37] on the patch repair of concrete was set up. This brought together the many specifications for concrete repairs and began to set standards for the methods employed. A standard specification and method of measurement resulted from the study.

3.4 REPAIR OPTIONS

3.4.1 Selection of repair system

Once it has been agreed that repairs are needed to meet the remaining life required of a structure, the types of repair that may be appropriate can be selected. However, there is a large range of options dependant on what the repair is meant to do, and how long it is to last. The purpose of a concrete repair system can be one of, or combinations of, the following:

- To restore structural integrity
- To arrest deterioration
- To prevent future deterioration
- To restore original profile
- To restore integrity of sealed system e.g. waterproofing
- Aesthetic appearance

It is generally accepted that repair materials should be selected to provide the best compromise of the properties required, and may be further influenced by the funding available, availability of materials, and technical or other constraints such as application techniques and environment of working.

Tuutti[2] states that when selecting a repair, the behaviour and properties of different materials, and how different parameters affect service life, must be understood. Failure to appreciate these factors can cause detrimental effects to a structure by the repair process, such as an increase in corrosion activity caused the formation of incipient by anodes. Areas of intense corrosion, found in structures prior to repair, have an incidental protective effect on the surrounding steel even if the concrete is chloride contaminated, and therefore incipient anodes can develop into new corrosion sites after the intense corrosion site is repaired[38].

3.4.2 Conventional repair materials and systems

There are many variables in past and present repair materials and systems. These include the technique or form of repairs, material composition, method of application, fresh properties and set properties. This project deals mainly with patch repair materials for concrete substrates. For the purposes of this project, patch repairs are defined as those applied to substrate concrete and contained within an element, and are typically less than 1m^2 in area and less than 100mm in depth. However, where patch repair systems include additional components such as bonding and finishing coats, these are also considered. Hewlett and Oliver[39] describe the components of a full repair system as including:

- Coating for reinforcing steel
- Bonding agent
- Repair mortar(s)
- Fairing coat (to level irregularities between the repair and the retained area of un-repaired concrete)
- Decorative/protective coating (to conceal the repair and create a uniform overall appearance)

The generic types of concrete repair materials available, as described in earlier work[1], are summarised in Table 2. Emberson and Mays[40] recognised the current range of generically different systems for patch repair as including resin mortars, polymer modified cementitious mortars and cementitious mortars, as shown in Table 3.

Common properties of the materials are shown in Table 4. These generic types of materials cover a multitude of proprietary materials; Johnstone[28] quotes a US study in the mid 1980's which identified more than 1600 concrete repair materials.

Patch repair materials with cementitious-only binders can provide acceptable protection to existing concrete structures. The set properties are strongly influenced by the cement content and water/binder ratio. The performance or application parameters are often enhanced with the addition of polymers. Kruger and Penhall[41] report that polymer concrete is commonly used as a repair material which has benefits including rapid set, reduced shrinkage, chemical resistance, abrasion resistance, high bond strength, and good workability. Materials with epoxy binders may also provide these advantages and rely on their very low intrinsic permeability to prevent ongoing deterioration. The properties of a repair material and the interaction is an important consideration in the selection of a repair system and in the design of a successful patch repair.

Detailed descriptions of the properties of the different types of binders and formulations can be found in several documents[1], (Williams and Parker[42]). These may affect the method of application, durability in certain environments, and therefore performance and effectiveness of a repair. It is unlikely that a representative sample of all of these materials can be studied. The present work will therefore attempt to include as wide a range of these materials as possible, noting the composition and properties of the particular repair materials in relation to the substrate and environment.

Table 2 Composition of concrete repair systems

Component or type of system	*Type of material*
Cement only systems	OPC, SRPC, RHPC, White Portland HAC Magnesium Phosphate Others (regulated set, alkali activated, gypsum-based cements) Supplementary cementing materials (pfa, ggbs, sf, mk)
Polymer-modified cementitious systems:	Synthetic rubbers, eg styrene butadiene rubber Acrylic and modified acrylic latexes Polyvinyl acetate latexes (homo-polymers, co-polymers, terpolymers) Epoxy emulsions
Resin repair materials	Epoxy resins Polyester resins Acrylic resins
Fibres	Glass Steel wire (mild, stainless, hooked, crimped etc.) Polypropylene (polypropylene or homopolymer resin). Monofilament, fibrillated Acrylic (monomers and monomer blends etc.)

Table 3 Categories of systems for concrete patch repair (from Emberson and Mays[40])

Resinous materials	*Polymer modified cementitious materials*	*Cementitious materials*
Epoxy mortar	S.B.R modified	OPC/sand mortar
Polyester mortar	Vinyl acetate modified	HAC mortar
Acrylic mortar	Magnesium phosphate modified	Flowing concrete

Table 4 Application methods and properties of concrete repair materials

Application method	*Properties*
Hand trowelled	Self-levelling
Hand packed	Self-compacting
Poured in shuttering	Thixotropic
Sprayed	High build
Injected	Lightweight
	Rapid set

3.5 REPAIR APPLICATION AND METHODOLOGY

The application method of a concrete repair is one way of classifying the repair method. The most common forms are manual (by hand or trowel), placing in formwork, and spraying. There is considerable overlap in the materials used in these methods; the material composition can be almost identical with only relatively small variations in the additives and aggregate gradings to provide the different properties required for different placement techniques. Application methods, and the materials used, are described in some detail in Reference 1. A summary is presented in the following sections.

3.5.1 Hand placement techniques

Hand placement techniques include the hand or trowel methods of concrete application typified by 'break out and repair'. Currie and Robery[43] proposed steps for this type of repair, simply illustrated in Table 5 below.

Table 5 Steps in the conventional repair of reinforced concrete

Step	*Description*
1	Inspection and diagnosis
2	Concrete breakout
3	Cleaning and supplementing existing reinforcing bar
4	Coatings for reinforcing bar
5	Bonding aid/chloride barrier
6	Formwork
7	Repair concrete and mortar
8	Curing
9	Concrete coating
10	Supervision and quality control

The inspection and diagnosis step allow the repair strategy to be planned and areas for repair to be marked or otherwise identified. The remaining stages are generally described in some detail in method statements supplied by the manufacturer of the proprietary material, or by the repair contractor carrying out the work.

Concrete can be broken out using a variety of methods. Good practice dictates that the perimeter of the repair is saw-cut to prevent feather-edges, and that break-out equipment and techniques cause minimal damage to the substrate. There is some debate over the procedures for treating reinforcement exposed in break-outs, generally relating to the condition (either due to deterioration of the steel or damage during break-out). Perkins[44] states that there is no need to cut concrete from behind the bars unless there is significant corrosion. It is generally accepted where there is corrosion, the bars should be fully exposed and that cleaning by abrasion or blasting techniques is required. Where bars are severely damaged, they are generally replaced with new overlapping lengths.

Reinforcement within a break out can then be coated to protect from ongoing corrosion. The coatings are generally designed to isolate the steel from the surrounding material and minimise exposure to water, oxygen and chloride ions. The surface of the break-out is generally prepared to minimise fracture and loose material. The surface is then cleaned to remove dust and other debris. It may be coated with a bonding primer to increase the adhesion with the main repair material. This latter is applied , worked and compacted to provide a dense, homogenous infill with continuous bond to the substrate, devoid of cracks, partings, cavities and voids. The surface is finished so as to be flush with the surrounding concrete, or a fairing coat may be used to achieve a smooth finished surface.

A curing process is applied to the material to minimise the detrimental effects of drying and exposure to the environment whilst the material is still immature. Overcoating of the repaired area may then be carried out. This may be for cosmetic reasons or for additional protection using a barrier designed to reduce the ingress of water, ions, oxygen and carbon dioxide.

Supervision and quality control procedures apply at each stage and strongly influence the quality of the repair achieved.

3.5.2 Flowable

Repairs using flowable materials involves preparation of the substrate in a similar way to that described above for hand placed techniques. However, after preparation, formwork is constructed in the area that will receive the material, and an access for delivery is created. A fluid repair material can then be poured into the shutter through a funnel and pipe. This provides benefits in the volume of repair that can be effected at a single time, and may be the best technique in the presence of congested reinforcement or a complex or inaccessible substrate. Curing processes may be applied to exposed surfaces of a flowable material after removal of the formwork. Some degree of additional curing protection is afforded by the presence of the formwork at least in the first days and weeks after casting.

3.5.3 Sprayed concrete

Sprayed concrete has become a common form of construction and repair largely over the last 15 years. This form of concrete is composed of a cementitious binder, aggregates, water and additives that are formulated to be projected, or sprayed, from a nozzle and to form a cohesive, durable material upon impact with the target substrate. Sprayed concrete repairs are particularly appropriate for larger repair volumes, such as large surface areas of repair or multiple repair sites situated close together.

Research into the structural effectiveness of sprayed concrete repairs was carried out by Mays and Barnes[45] in 1996 on purpose-built reinforced concrete frame structures. Comparisons were made between theoretical predictions and actual behaviour. It was concluded that:

"The research showed that for the spray applied material investigated, the repaired section behaved in a similar way structurally as if unrepaired, thus giving some confidence in the use of such materials in structural situations."

A project by Mangat and O'Flaherty[46] addressed long-term performance of sprayed concrete repair in highway structures. This project was funded by the LINK TIO Programme "Long term performance of concrete repair in highway structures". The dry spray process was used with different generic materials to repair deteriorating bridge structures. The preliminary findings of this study indicated that the elastic modulus – of both the repair material and its substrate – was the property which had the greatest effect on the performance of the repair. Eight different spray materials were used in this project on two deteriorating highways structures located in Nottinghamshire, UK and West Yorkshire, UK respectively. One of the key findings of this project is that spray-applied repair materials with a higher elastic modulus than the substrate attracted load from the parent concrete.

3.5.4 Flood grouting

Flood grouting is a relatively rare form of repair and is unlikely to be included within the present scope for study. The process involves poring a highly fluid grout through a pre-placed single sized aggregate. The fluid then sets and binds the aggregate to form a solid material.

3.6 ELECTROCHEMICAL REPAIR TECHNIQUES

Several techniques have been developed which can be applied to deteriorating reinforced concrete that fit into the category of electrochemical techniques. The methods are cathodic protection (CP), re-alkalisation and chloride removal. There are also 'corrosion inhibiting' systems that rely on the action of materials on the reinforcement to inhibit ongoing corrosion. The forms of corrosion inhibitor and electrochemical techniques are shown in Table 6.

Table 6 Corrosion inhibitors and electrochemical techniques

Corrosion inhibitors	*Electrochemical techniques*
Inorganic Anodic Inhibitors	Cathodic Protection (CP)
Organic Mixed Inhibitors	Re-alkalisation
Vapour Phase or Volatile Inhibitors	Electrochemical Chloride Extraction (ECE)

3.6.1 Re-alkalisation

Re-alkalisation is a method where temporary current is applied to an anode (fixed to the exterior of the concrete) and an internal cathode (the steel reinforcement). The positive ions in the electrolyte (an alkaline solution, commonly of sodium carbonate) move towards the reinforcement whilst hydroxyl ions are produced at the steel reinforcement due to the reduction of water. The method, as illustrated in Figure 2, is best applied to carbonated concrete where the material is still sound. The re-alkalisation treatment is typically applied for 3-5 days, and is intended to generate an environment of sufficient alkalinity at the reinforcement to prevent de-passivation and subsequent corrosion of the reinforcing steel.

3.6.2 Chloride extraction

Chloride extraction relies on similar mechanisms to the re-alkalisation process; it is another temporary process intended to provide long-term solutions to problems of chloride ingress in sound concrete. It has sometimes been referred to as desalination. Figure 3 illustrates the process. An electrical current is set up in the reinforced concrete, with an externally applied anode and the reinforcing steel once more playing the role of the cathode. Negatively charged chloride ions are attracted by the positive anode and repelled by the cathode (steel). The net result is that chloride is either removed from the concrete into the electrolyte, or at the minimum, taken further away from reinforcing steel where it would have accelerated the corrosion process. Hydroxyl ions are generated at the steel. Three to five weeks are required for this process to take place and electrolytes are commonly water or saturated calcium hydroxide. There are systems available that offer high-tech expert system management enabling remote anode monitoring and control using the latest computer software[47]. Such systems are also available for cathodic protection installations.

3.6.3 Cathodic protection

Cathodic protection is an electro-chemical technique that has traditionally been used as long-term form of protection to prevent the corrosion of steel. A detailed report on cathodic protection of reinforced concrete has been published by the Concrete Society[48]. The principle is similar to that for chloride extraction, with an electrical current set up in the reinforced concrete so that the steel is cathodic, but with a much smaller current. There are two main types; impressed current systems use a conductive anode overlay, typically over the external surface of the concrete, with an external power source, whilst sacrificial anode systems use discreet, independent anode units normally buried within the concrete.

There has been concern voiced over the long-term use of cathodic protection systems. These concerns involve the generation of hydrogen at the cathode which can potentially cause hydrogen embrittlement to the reinforcement, and possibly interfere with the bond between the reinforcement and the concrete. These effects may reduce the load-bearing and spreading capacity of elements. Although these concerns are theoretically sound, there is no definitive confirmation of the occurrence in practice. McKenzie[49] [50]reported tests on the effect of cathodic protection on steel-to-concrete bond strength – there was no indication that cathodic protection had significantly affected the ultimate bond stress, although scatter in the results was considerable.

Further potential side-effects involving the increase in the risk of alkali-silica reaction from hydroxyl-ion generation around the steel and paste softening in the same region from alkalisation electro-migration were found to be insignificant at the current densities normally associated with CP[51]. At the higher current densities associated with chloride extraction and re-alkalisation, however, alkali-silica reactivity was shown to increase under specific conditions[52].

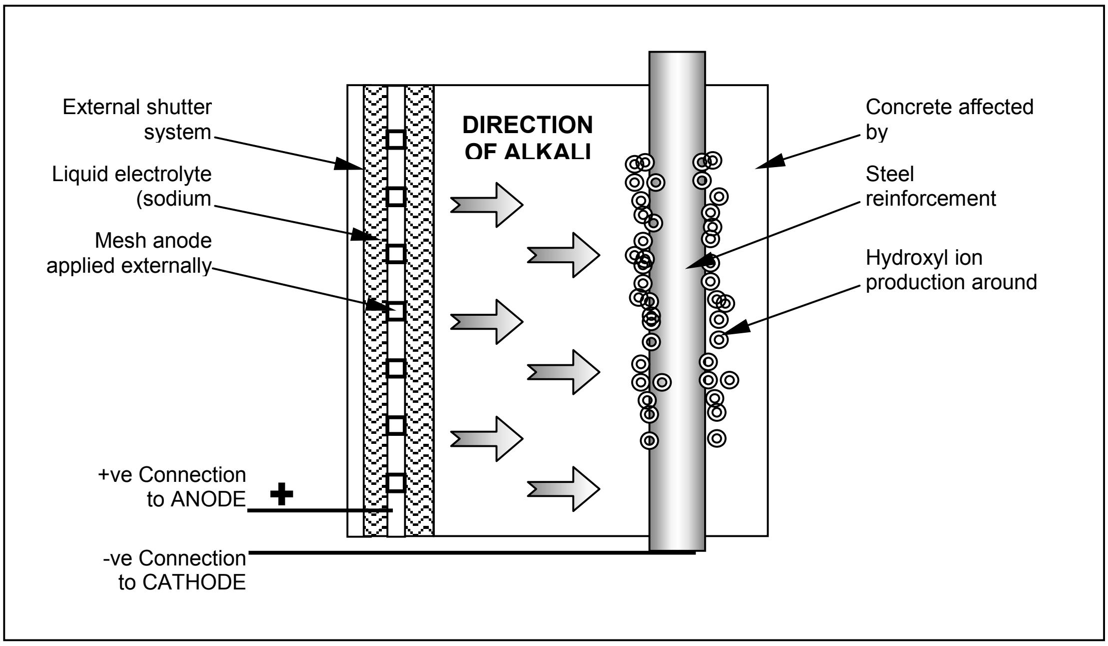

Figure 2 Re-alkalisation of reinforced concrete affected by carbonation

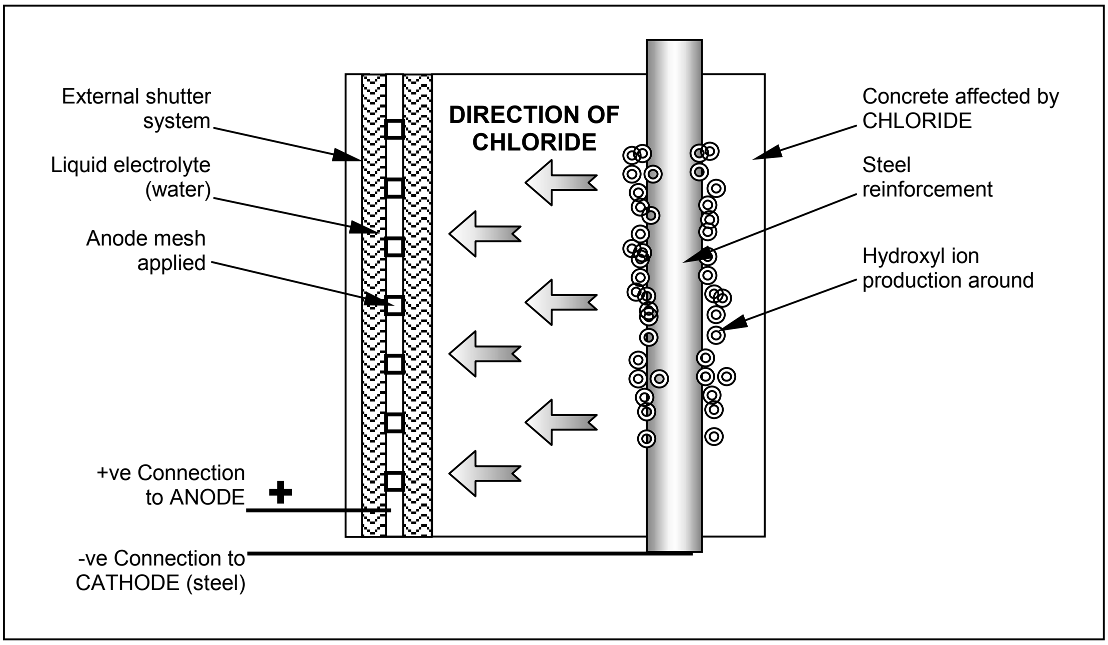

Figure 3 Chloride extraction for chloride infected reinforced concrete

3.7 EFFECTIVENESS

Reaching an effective repair can be achieved at two levels. At a 'technical' level, this involves the physical actions involved in execution of the repair, i.e. the site activities. At a 'process' level, effectiveness is about achieving quality in the planning and management of the repair, i.e. the approach is correct.

3.7.1 Technical factors influencing effectiveness

In order for a repair system to be effective, various criteria must be met. The 'SPALL' criteria, defined by King and Ecob[53] and listed below, are one way of assessing the repair.

Structural:	Possesses the required structural properties
Protection:	Provides protection for the reinforcement
Application:	Can be applied effectively within the given constraints
Longevity:	Once applied it remains in place
Looks:	Has an appropriate surface finish

Structural

The structural requirements for a repair are situation specific, and are important chiefly in structural repairs where the new repair material is intended to carry load along with the parent material. The properties relevant to a structural repair may include compressive, tensile shear and bond strength, and the dynamic and static moduli.

Most patch repairs are not intended to be load-bearing, and the new material is provided for other reasons such as restoring the surface profile and durability to the substrate. In this case, a structural requirement is often provided in the form of a minimum strength requirement as a crude approximation of durability.

Protection

The principle objective of many repairs is to provide protection to the substrate concrete and reinforcement to prevent or minimise further deterioration that may compromise the safe operational use of the structure. This is achieved by removing the conditions allowing deterioration and restoring an environment that is not susceptible to continuing deterioration. The nature of the protection afforded is specific to the environment and deterioration mechanisms that are operating, but for repair materials, the main principle used is provision of a dense and durable barrier to isolate the substrate from the forms or agents of attack. For example, to prevent reinforcement corrosion, a repair system may provide a barrier to oxygen, water and chloride ions.

The type of repair selected must be able to resist the deterioration processes to which it will be exposed; if it can do so, it has the potential to be effective. This does not mean it has an indefinite life. The future performance of the repaired structure is influenced by the environment of exposure and the materials properties of the repair, substrate and the interaction between them. Protection against deterioration must extend to the substrate, including re-spalling due to new corrosion, to failure of the bulk repair material inappropriately specified or applied, and to deterioration of the interface allowing ingress of aggressive species or delamination.

Application

The size, orientation, location and environment of the repair may influence the method of application and the selection of material properties. Difficult conditions, such as congested reinforcement or overhead repairs, may demand specific properties, for example the ability to flow and self-compact, and rapid set and high build properties. Application methods are further described in Section 3.5.

Longevity

Longevity is a function of the intrinsic durability of the repair materials, the long-term stability of the bond with the substrate, and the nature of future deterioration within the original substrate. Research into the repair for highway structures[54] suggests that the durability of repairs to reinforced concrete structures depends on both the compatibility and interaction of the applied systems; those being the existing concrete, the repair material and the interface between them. Emmons[55] defined the compatibility of a repair system as:

"The balance of physical, chemical and electrochemical properties and dimensions between repair materials and existing substrates that ensures that a repaired structure withstands all stresses induced by loads, volume changes and chemical and electrochemical effects without distress and deterioration in a specified environment over a designated period of time."

The stages involved in achieving compatibility between the different elements of a repair system are illustrated in Figure 4 below, proposed by Morgan[56].

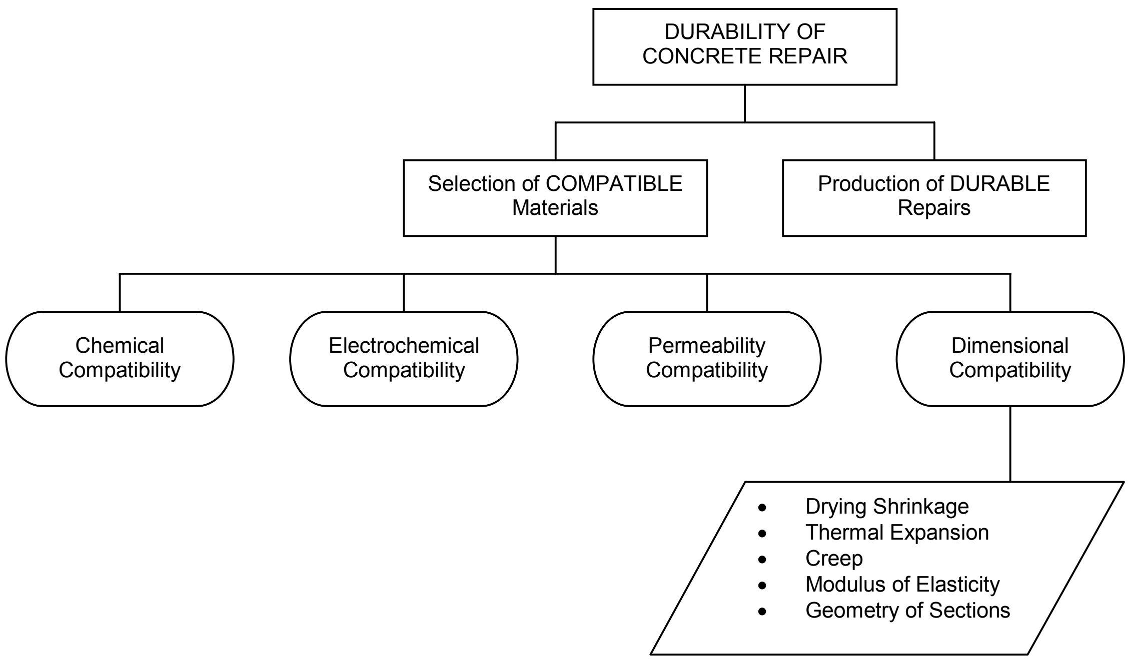

Figure 4 Factors Affecting Compatibility of Repair Systems[56]

Dimensional compatibility of repair materials is essential to the long-term performance of the repair. Pomery[21] reports that a significant difference in the elastic or thermal moduli between the repair and the original concrete can result in debonding between the layers, and therefore repair materials should have a larger strain capacity and the bond should be as strong as possible.

Looks

Aesthetic considerations of repair are not always a significant factor in industrial structures. However, appearance can be of importance in commercial and residential structures. Repairs are often required in 'public' structures, such as car parks, because structurally acceptable defects, such as cracks of 0.3mm width, are alarming to the general public.

Repairs can be finished so as to be flush with the surrounding concrete surface and, when overcoated, their presence may not be detectable. This presents some difficulty in locating and identifying repairs which may affect the selection of sites and method of working in Phases 2 and 3.

Emberson and Mays[40] state that patch repair materials are only successful if the cause of the original damage has been eliminated, appropriate materials are selected and these are applied in a suitable manner.

It is stated in BA23/86[26] that, for bridges, to achieve a lasting repair, it is necessary to correct any deficiencies in waterproofing or drainage that lead to deterioration, as well as treat the actual damage.

BD27/86[57] states that for concrete repairs to be effective, it is necessary to use materials and techniques that will give significantly added protection to highway structures. Failure to do this will result in a recurring maintenance problem.

The criteria used to define the repair boundaries can also be significant. Criteria for repairing concrete is often based on a combination of half-cell values (for example more negative than -350mV when using a wrt saturated CuSO4 electrode) in combination with the chloride content of the concrete (for example >0.3% by weight of cement).

3.7.2 Process factors influencing effectiveness

The processes involved in a repair project are shown in . This demonstrates that effectiveness is related to the quality of the repair process (i.e. the client brief, investigation, specification, site management, attitude of contractor, level of supervision etc) as well as the actual site activities of mixing and placing the materials. It is clear that if the specification is inappropriate, even well executed repairs may not be effective.

There is agreement within the literature that repairs are effective only if the cause of deterioration has been correctly diagnosed and understood. Sopko[58] states that the key to long-term durable repair is the evaluation to determine the cause of deterioration, through testing and analysis. If the cause can not be eliminated, the repair must include protection against it, which may result from improper design and/or detailing, construction methods, and poor quality.

Etebar[6] believes that thoroughness and correct diagnosis and understanding the process involved in repair technique are essential for the success of the integrity of the repair.

Somerville[22] argues that durability performance is best improved by understanding the aggressive action and improving the quality of construction. Both are equally applicable to new construction and repairs.

van Gemert[4] states that durability, synonymous with long-term performance, is a key aspect for repairs and rehabilitation projects and is obtained by careful execution of design.

The quality of workmanship and supervision are critical factors in future perfromance[1]. It is therefore often difficult to ascertain whether the material or applicator is at fault if the repair fails to perform satisfactorily.

3.7.3 Definition of effectiveness

This project will measure and compare the in situ performance and effectiveness of different concrete repairs. It is therefore important to define what “effectiveness” actually means and how it can be measured and quantified on site. In its simplest sense, a repair may be effective if it has achieved the performance that it was originally intended to. However, there may be several aspects to the original intention, such as cost, longevity and cosmetic issues. There may also have been requirements or restrictions for preparation and application of the repair, that form part of its effectiveness. It is therefore necessary to review the processes of selection and specification of repair at individual sites to ascertain the parameters whereby effectiveness can be measured. The parameters include the following:

The multiple requirements of a repair is illustrated by Emmons and Vaysburd[59], who state that the object of any repair project is to produce a durable repair, that is to *“produce a repair at the relatively low cost with a limited and predictable degree of change over time and without deterioration and/or distress throughout its intended life and purpose”*.

For the purposes of this project, we will use a detailed definition of effectiveness, adopting the principles of the SPALL criteria, and also considering the quality of the processes behind the repair. We will use site observations and testing to gather information on the effectiveness of technical aspects of the repair and contract information and records to evaluate the process effectiveness.

3.7.4 Costs

An effective concrete repair might be defined as one that satisfies the original client brief in terms of performance and cost. The most technically effective repair strategy may not be cost-effective. A full analysis of costs of concrete repairs is therefore necessary to ascertain their overall effectiveness.

The cost of concrete repairs is dependent on the time of the repair being carried out – as a technique becomes more widely accepted and commonplace its cost may drop. Contract terms have a major influence on the cost of repair work, as does legislation such as the Construction (Design and Management) Regulations 1994.

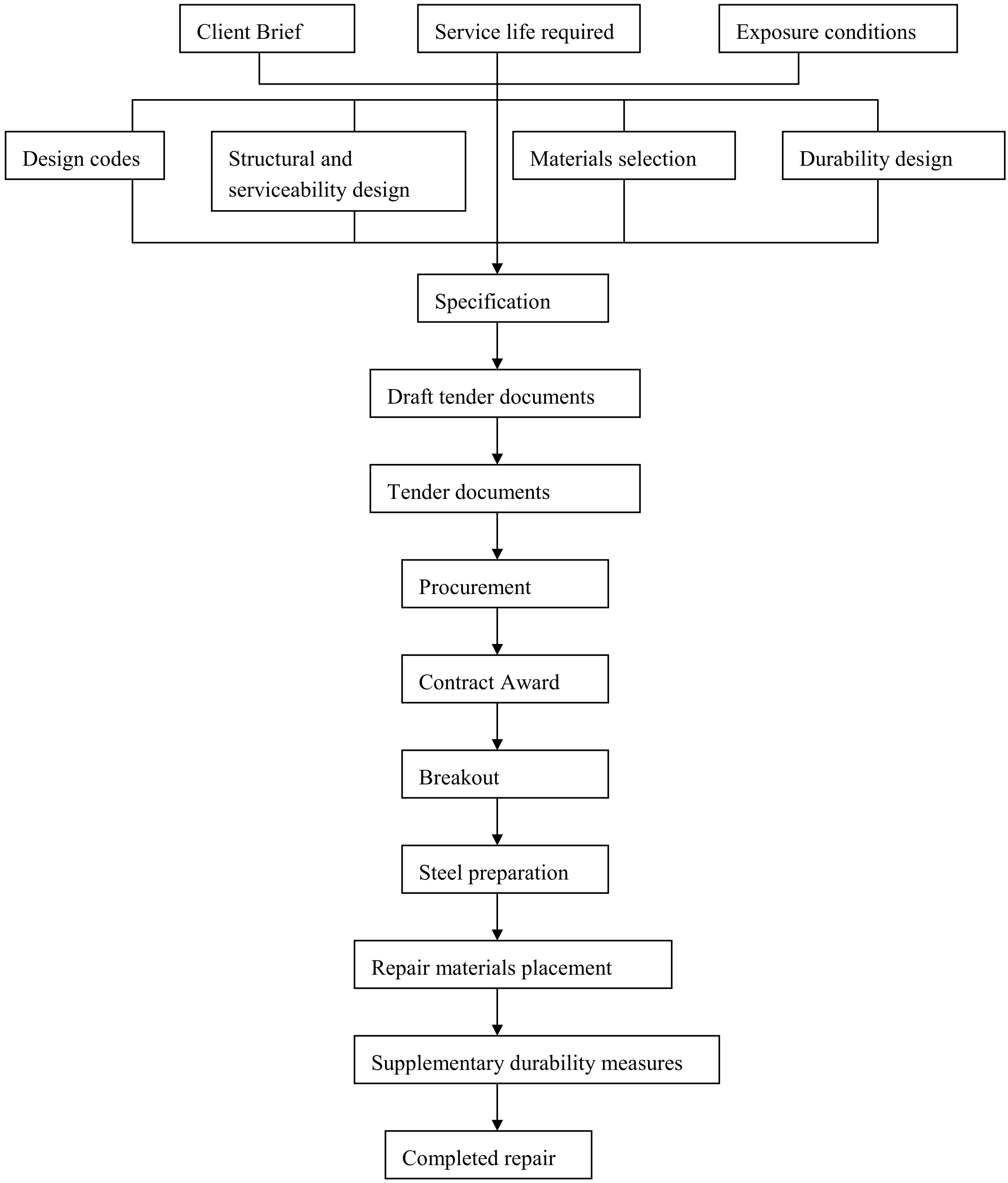

Figure 5 Processes involved in repair

3.8 METHODS OF TESTING EFFECTIVENESS

Performance of a concrete repair needs to be measured in physical terms and quantification of physical parameters for comparison is necessary. Other parameters such as environmental effects, safety and whole-life costs are not as easy to quantify and should be included as part of a broader model.

To examine properties of concrete repairs a series of destructive and non-destructive tests are available. These include:

- Visual inspection
- Half-cell survey
- Covermeter survey
- Carbonation depth
- Pull-off tests
- Petrographic analysis
- Microprobe analysis
- Metallurgical testing

These tests will be used to study the effectiveness of existing concrete repairs, as described in the draft Phase 2 report presented in December 2000.

Research work[60] carried out to assess electrochemical chloride extraction treatment on a 30-year-old motorway bridge in Northern Ireland utilised methods of testing suitable for this study. The University of Ulster carried out an independent assessment of the treatment, with a full testing programme including the following:

- Half-cell surveys – to highlight areas of ongoing corrosion, before, immediately after and sometime after electrochemical treatment.
- Acid soluble chloride profile analysis – To determine total chloride content at depths before and after treatment.
- Porewater analysis (1) – to determine the chloride ion (free chloride) and hydroxide ion concentrations before and after treatment.
- Porewater analysis (2) – to determine sodium and potassium ion concentrations in the vicinity of reinforcement to give an indication of the potential for development of the alkali-silica reaction (post-treatment).
- Petrographic analysis – to examine the structure and quality of the concrete and to examine for alkali-silica reaction (post treatment).

Pore water testing of the concrete was carried out on single concrete cores using a unique (patent pending) system developed by the University of Ulster. The method tested for chloride, hydroxide, sodium, potassium and calcium ion content. Conclusions reported that the method of chloride extraction was successful, but emphasised the need for concrete repairs before the application of such techniques to be of the 'highest quality'. The application of coatings or systems to prevent further chloride ingress is necessary. This introduces an ongoing maintenance cost with further risk of chloride ingress leading to repeated application of the technique.

Sopko[58] used extensive testing and visual inspection to identify damaged areas, including:

- Chain drag to locate delamination,
- Electric potential for future deterioration
- Chloride tests
- Core compression tests
- Petrographic analysis for quality

Independent laboratory research carried out by the University of Leeds in 1997[61] looked at performance related properties of four different repair materials. These properties were compressive strength, bond strength, porosity and permeability. The research was part of a large project on the evaluation of the performance and durability of repair materials being carried out at the University's Civil Engineering Materials Unit (CEMU). The aim of the project was to develop a range of tests to be used in the assessment of the potential performance of repair materials; particularly their ability to inhibit corrosion of repaired reinforced concrete elements.

3.9 EXAMPLES OF STUDIES INTO REPAIRS

A number of projects have looked at the performance of repair materials, not only in laboratory conditions but on purpose-built structures and on existing structures. A number of these studies are summarised in the following sections. However, there is a paucity of information on the long-term performance of repairs. It has been concluded[3] that there is a need for more reliable information on long-term performance of repair options under known service conditions. Without such information, it is difficult to predict the life of repairs with any confidence[28].

The performance of repairs may become increasingly relevant due to changes in standards adopted. Van Gemert[4] reports that it is expected that the liability of designers and contractor, under Eurocodes, for repair, will extend beyond the usual 10-year insurance period. Compared to this 10 year period, experience with repair materials and techniques is relatively short, partly due to the rapid evolution in repair technologies. Rostam and Faber[23] state that unproven methods, systems and products are one of the major uncertainties associated with rehabilitation of structures.

3.9.1 Case study 1

Research was carried out by Mangat and O'Flaherty[62] in both the laboratory and on in-situ reinforced concrete highway bridge structures. The research considered the long-term performance of concrete repairs. Properties investigated in the project were compressive strength, elastic modulus, stress-strain relationship, shrinkage and shrinkage cracking, repair/substrate structural interaction and flexural strength of repaired beams. The study concluded that repair materials stiffer than the substrate concrete were desirable. This was in order to prevent cracking during the shrinkage period and to provide efficient structural interaction – load transfer from the substrate - in the long term.

3.9.2 Case study 2

A field experiment[63] conducted in Quebec studied purpose made concrete repairs to a one-year old exposed highway structure subject to heavy traffic loading. Five different repair materials were used for the repairs in combination with four different surface preparation techniques, as listed below:

Repair material:	**Surface preparation:**
OPC concrete	Cement slurry (0.3 w/c ratio)
OPC concrete with reduced cement content	Brushing surface with water prior to placement
SF concrete	Brushing surface with water and SF prior to placement
Steel-fibre reinforced OPC concrete	None
Steel-fibre reinforced OPC SF concrete	

All of the mixes contained a water-reducing admixture and air-entraining agent, and all with the exception of the OPC concrete contained a super-plasticiser.

In the study, compressive strength, air-void characteristics and drying shrinkage were measured parameters from specimens prepared on-site. The evolution of bond strength was measured annually by carrying out pull-off tests. The authors suggest that durability of thin concrete repairs is generally related to the durability of bond between the parent and repair concrete, and not the durability of the repair material itself. Relatively little information was available during the research on parameters that influence bond strength. Previous laboratory studies[64] into the effects of accelerated ageing on mechanical resistance of concrete led to the selection of types of surface preparation as variables.

The findings of the study indicated that durable concrete repairs are possible, irrespective of the type of repair concrete and of surface preparation type. However, the repairs were carried out superfluously on a 'new' structure. This somewhat limits the usefulness of the research findings in terms of a field experiment. Bond strength increased between 28 days and 1 year, but did not vary significantly after this time in the majority of cases. However, the pull-off testing indicated that after 3 years, fractures were more readily occurring in the interface between repair and parent concrete as opposed to within the repair material itself. The repair comprising OPC with cement slurry surface preparation was an exception to this and fractures occurred in the parent material itself indicating a strong bond between parent concrete and repair material.

3.9.3 Case study 3

Vassie[38] investigated the performance of repairs carried out to a UK corroded reinforced concrete bridge deck, including the effectiveness of the waterproof membrane, the integrity of the concrete repairs and the incidence of reinforcement corrosion within the repair areas and in the original concrete surrounding the repair areas.

Criteria for deciding the extent of concrete areas needing repair were established after a thorough investigation of the deck. This involved a combination of the results of chloride content determination in the outer 25mm of concrete and measurement of the half-cell potential.

Repair work was then carried out by removing the chloride-contaminated concrete and corroded steel and backfilling with new concrete and waterproofing the deck. The repairs were instrumented to monitor corrosion activity. In 1990, the deck was tested to determine if the waterproofing had prevented chloride contamination, whether further corrosion had occurred in the repairs, and if the embedded probes had detected it, and whether corrosion of reinforcement in the original concrete had been stimulated by nearby repairs.

The repair material and process was as follows:

- Vertical edges at repair perimeter
- Clean substrate, saturated for 24 hours
- 1:1 cement/sand grout used as bonding agent
- Concrete repair mix of 1:1.8:2.5 with 10mm aggregate, w/c 0.48, and 28 day cube strength of $55N/mm^2$ was used and placed in depths of either 75mm or 25mm
- Careful curing for 7 days under polythene sheet; almost entirely preventing shrinkage cracking
- Test probes were incorporated, capable of measuring electrical resistance, polarisation resistance and concrete resistivity, to assess future corrosion and moisture movement
- Subsequent waterproofing was by mastic asphalt

In the 1990 investigation, 14 areas were examined by removing the mastic asphalt and drilling incremental chloride samples at 0-25 and 25-50mm depths into the deck. Half-cell testing was carried out on a 0.2m grid, and break-outs were made to locally expose the steel. Hammer tapping was used to detect areas of delamination, carbonation depth was measured by phenolpthalein indicator, and resistivity was measured using the Wenner four probe method.

No evidence for corrosion was found in the repairs of 75mm depth. For the 25mm depth repairs, 2 sites were found to be corroding. One was at the perimeter of the repair, where the repair concrete had delaminated. A second area of corrosion occurred in the centre of a repair, probably relating to insufficient cleaning of the original corrosion deposit. Vassie concluded

repairs should be sufficiently deep to fully expose the reinforcement for inspection and to allow for sufficient bond.
The probes appeared to be still operational and agreed with the data from visual examinations, half cell potentials and concrete resistivities.

3.9.4 Case study 4

Sopko[58] reported that repairs were carried out to corroded reinforced concrete slabs in a garage. The concrete was of low quality and high porosity, and there was no barrier to prevent de-icing salts being tracked in by vehicles. The repair process involved breaking out and replacing substantial areas of the deck with high strength air entrained concrete and epoxy coated reinforcement, with movement joints introduced to prevent previously observed mid-slab cracking. A waterproof polyurethane membrane and wearing course were added. After 12 years, the deck appeared to be performing satisfactorily.

No data is provided on the client requirements in terms of design life. The repair strategy implemented provides several forms of protection to prevent ongoing deterioration, and may be overspecified. This may not have been a cost-effective repair.

3.9.5 Case study 5

A second example reported by Sopko[58] involved survey and testing of a concrete façade suffering from cracking and spalling resulting from corrosion of embedded steel. Testing included excavating the concrete to expose bars, R-meter tests, delamination testing, core strengths and petrographic analysis. It was determined that the construction procedures were the cause of the deterioration, and the rusting was caused by inadequate concrete cover. In general, it was found that where the concrete was cracking, this resulted from reinforcement at cover less than 20mm, and where cover was >25mm, there was no rusting and cracking. The specified cover of 40mm had not been achieved.

All existing corroded bars were exposed, cleaned and repaired. In addition, all concrete with cover less than 25mm was removed and repaired. To provide an architecturally acceptable surface, and protection for the reinforcement, an acrylic waterproofing membrane system was used as a coating.

It is possible that the cause, carbonation-induced corrosion, could have been treated by an anti-carbonation coating after repair treatment of the cracked areas. The repairs to undamaged concrete with <25mm cover may not have been necessary and therefore financially ineffective.

3.9.6 Case study 6

Etebar[6] states that studies of the effectiveness of repaired and/or strengthened reinforced concrete elements, which fail primarily due to formation of major diagonal shear cracks, are limited. Etebar therefore carried out repeated loading on beams that were repaired in the laboratory. The results showed that if the quality of the repair is not as required then the repair becomes virtually ineffective. Some failures indicated that particular attention should be given to the bond between the parent concrete and the repair material. It was concluded that appropriate repair material (and properties) selection is essential for structural repairs.

3.9.7 Current work

Research is currently being carried out into concrete repairs by other organisations. We are continuing to pursue information exchange with researchers and funders of research from the BRE, TRL Limited, the Highways Agency and the County Surveyors Society.

4 FINDINGS

Literature describing concrete repair materials, properties and performance has been reviewed. There is little published information describing or comparing the long-term performance of different repair types. There are currently other research programmes that are being carried out into repair methods and techniques; these may provide additional benefit to the project and information exchange will be pursued.

The classification of repair materials and techniques has been reviewed. For concrete patch repair materials, the classification is based largely on the binder composition. There are many subdivisions of binder type and a great many more proprietary products with varying combinations of components. It is impossible to investigate a representative sample of all the possible materials, but we aim to include examples of cementitious, epoxy and polymer repair material.

There are various classifications available for repair types. We have included, in Phase 2, a selection of repair sites with traditional 'patch' repairs, applied by hand or trowel, by spraying, or using formwork for flowable materials. We have also selected sites with CP-systems to investigate the effectiveness of repairs in the protected zones and to assess the effects of CP on the substrate concrete. The sites currently identified include a range of locations, functions, service and exposure environments and age. We propose to select additional sites that are to be reviewed by the Expert Group.

The meaning of effectiveness has been explored in order to provide a framework for measuring the performance of a repair in situ. Effectiveness may involve several aspects including those relevant to preparation and application in addition to long-term performance. It is important to review the original specification and client requirements for each individual repair prior to formulating targets for effectiveness. In summary, an effective concrete repair is one that satisfies the original client brief in terms of performance and cost, and includes both technical and process elements.

The methods available for investigating repairs has been reviewed. We have selected a range of techniques we believe will provide maximum information within a limited budget and facilitate quantitative assessment of effectiveness. There are additional techniques available within the industry which may not have been selected due to cost or their relative lack of widespread acceptance.

Standards and guidance relevant to UK repairs have been reviewed. There is no current British Standard for concrete repair. However, the forthcoming Eurocode EN 1504 provides a framework for identifying the causes of deterioration in a structure and selecting appropriate methods of repair. The code will also standardise the measurement of properties of repair materials to provide some comparison of relative performance.

5 PROGRESS AND FUTURE WORK

5.1 PHASE 2

In accordance with the original proposal, a state of the art literature review has been undertaken. The Expert Group has been established, and input provided. Phases 2 and 2a have been planned and measures undertaken to allow access to the sites.

Phase 2 involves the identification of available, accessible repair sites and planning of the sampling and testing to be carried out. The first draft of the Phase 2 report has been issued. Completion of Phase 2 includes:

(a) Design of proforma/data sheet for use on site and a database for handling of information.

(b) Agreement on sites to be visited where access and sampling will be achievable within the anticipated duration of the project.

(c) Planning of desk study for each repair area. For each category of repair, a number of sites will be identified where such a system has been applied. The design and specification for each repair will be obtained (where possible) and reviewed in order to establish the intended performance and life of that repair. In selecting the sites, account will be taken of factors such as the environment and the function and loading of the structural element repaired, in order to provide a representative sample.

(d) Planning and costing of anticipated site work.

(e) Summary report for Phase 2 and review of progress and proposed Phase 3 work.

A draft report has been prepared for Phase 2 which includes the first batch of sites for Phase 3 work. Additional sites are being investigated and will be incorporated into later drafts.

5.2 PHASE 2A – DARTFORD SITE PLANNING

(a) Prepare a detailed scope of work and work plan with Kvaerner and HA.

(b) Summary report for Phase 2a and review of progress and proposed Phase 3a work.

(c) This phase has been substantially completed; samples that were taken in the site phase are now being tested in a phased programme with review of results and findings prior to commencing subsequent stages.

APPENDIX A FORTHCOMING EUROPEAN STANDARD EN 1504

A.1 STATUS

A new European standard is being developed to cover surface protection products, concrete repair materials, structural bonding agents, crack injection systems and products for anchoring reinforcement bars. The standard, EN 1504, is entitled ‘Products and systems for the protection and repair of concrete structures’, and is in 10 parts, as listed Table 7 below. The standard provides a general methodology of repair, from initial diagnosis, through selection of the most appropriate repair option for the particular circumstances and client needs to specification of the materials. EN 1504 also includes standard test methods for materials and systems.

Table 7 Components of EN 1504

Standard	*Activity*	*Status*
BS EN 1504 Part 1	General scope and definitions.	Published as a national standard in 1998[65]
pr EN 1504 Part 2	Surface protection.	Not available
pr EN 1504 Part 3	Structural and non-structural repair.	Not available
pr EN 1504 Part 4	Structural bonding.	Not available
pr EN 1504 Part 5	Concrete injection.	Not available
pr EN 1504 Part 6	Grouting to anchor reinforcement or to fill external voids.	Not available
pr EN 1504 Part 7	Reinforcement corrosion prevention.	Not available
pr EN 1504 Part 8	Quality control and evaluation of conformity.	Not available
DD EN 1504 Part 9	General principles for use of products and systems	Published as a pre-standard in 1997[7]
Draft BS EN 1504 Part 10	Site application of products and systems and quality control of the works.	Draft for comment published 1999[66]

According to Mays[24], European standardisation is well advanced within the CEN/TC104/SC8 technical committee and supported by BSI Committee B/517/8. However, acceptance of the standard is taking longer than expected. The minimum 3 year voluntary period for European standards is expected by Robery[67] to take a further 4-5 years.

The progress of the standard was discussed by Mays[24], who believes the development of a coherent set of specification and test method standards will benefit the industry by working from a common set of tests and therefore comparable data. This may also eventually reduce costs for certification of products.

A.2 STRUCTURE OF STANDARD

Davies[3] reports that pre-standard ENV1504 Part 9 (1997) recognises the following needs:

- To define a logical repair methodology
- To structure a technical standard to allow a client to exercise economic choices
- To provide a framework for specification of repairs
- To accommodate solutions covered by other standards

To meet these needs, Part 9 provides a framework for approaching the repair process and identifies the key stages in planning and executing works, as opposed to codes of practice in the pure sense. The requirements of these stages are further described in the informative sections (Annex B), supporting the main text. The key stages include establishing the condition of the structure, the form of construction and the exposure and service environments, assessment of defects, planning of possible repair options, detailed design of selected repair works, execution of the repairs and acceptance of the works. These stages mirror the main sections of Part 9 as shown in Table 8.

Table 8 Main technical contents of ENV 1504-9

Section	*Title*
4	Minimum requirements before protection and repair (including assessment of defects and causes)
5	Objectives of protection and repair (including choice of appropriate action)
6	Basis for the choice of products and systems
7	Properties of products and systems required for compliance with the principles of protection and repair
8	Maintenance following the completion of protection and repair
9	Health, safety and the environment

The activities and requirements of each stage are not necessarily prescribed. However, the general principle and required outcome of the activity is stated. For example, no procedure for the investigation and testing of a structure is given, but the outcome of this stage is an assessment of the current condition and future requirements of the structure including the nature, extent and cause of defects.

The logic of the standards is illustrated in Figure 6 below:

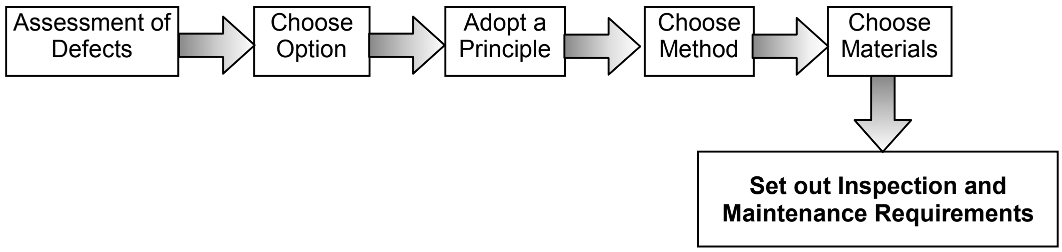

Figure 6 Logic of European Standard ENV 1504

As illustrated, each stage in assessing viable repair options and adopting inspection requirements uses definitions from the European Standard. Examples of these definitions are provided in Table 9 below.

Table 9
Practical examples for application of terms used in the European Standard on concrete repair principles[68]

Term	*Example*
Options (appropriate action to be taken)	Do nothing Re-analysis and downgrade Reduce further deterioration Strengthen or repair
Principles (of protection and repair)	Reduce ingress of water and salts Restore the concrete of an element to its original shape and function
Methods (of protection and repair)	Cathodic Protection (CP) Surface impregnation Apply mortar by hand Apply sprayed concrete Re-alkalisation
Products and systems	Coatings Mortars Injection resins

Further to this, suggested principles and methods have been put forward and categorised, examples of which are given in Table 10 below.

Table 10
Examples of principles and methods for dealing with reinforcement corrosion defects (from DD ENV 1504:1997) [7]

Principle no.	*Principle*	*Example of methods based on the principles*	
3[CR]	Concrete restoration	3.1	Applying mortar by hand
		3.2	Recasting with concrete
		3.3	Spraying concrete or mortar
		3.4	Replacing elements
7[RP]	Preserving or restoring Passivity	7.1	Increasing cover with additional concrete or mortar
		7.2	Replacing contaminated or carbonated concrete
		7.3	Re-alkalisation
		7.4	Chloride extraction
8[IR]	Increasing resistivity	8.1	Reducing moisture content by surface coating or over-cladding
9[CC]	Cathodic control	9.1	Reducing oxygen supply at the cathode by saturation or surface coating
10[CP]	Cathodic Protection (CP)	10.1	Applying an appropriate electrical potential
11[CA]	Control of anodic areas	11.1	Applying coatings containing zinc to the reinforcement
		11.2	Applying barrier coatings to the reinforcement
		11.3	Applying inhibitors which penetrate to the reinforcement from the concrete surface

A.3 OPTIONS FOR REPAIR

Part 9 requires an assessment be carried out and it is valid at the time the repair objectives and work is executed. After this, an option for repair can be selected. There are six options identified, ranging from do nothing to demolition:

- Do nothing for a certain time
- Re-analysis of structural capacity
- Prevention or reduction of further deterioration
- Improvement, strengthening or refurbishment of all or part of the concrete structure
- Reconstruction of part or all of the concrete structure
- Demolition of part or all of the concrete structure

The standard states that costs and funding have to be taken into account when considering alternative repair options, this alone demands client, or structure owner, input.

Methods of removal of concrete and reinforcement bars from structures are included. The draft states that the method used to remove concrete should not cause micro-cracking in the remaining concrete, and that any reinforcement should be removed in a way which does not damage reinforcement bars left behind. Mechanical methods of concrete removal are permissible, but for the last 50mm removed only light, hand operated hammers will be acceptable to avoid cracking. This may result in a change in methods to more sensitive techniques such as high pressure water jetting, or hydro-demolition[69].

APPENDIX B BIBLIOGRAPHY

List of key texts referred to in report.

[1] Sheffield University Centre for Cement and Concrete, Mott MacDonald Special Services Division, DEW-Pitchmastic PLC (1999), "Concrete repair materials and protective coating systems", Nuclear repair contract BL/G/31221/S, IMC Reference CE/GNSR/5020.

[2] Tuutti, K., "Repair Philosophy for Concrete Structures" pp.159-169, Proceedings of the international conference on concrete durability and repair technology, University of Dundee, Scotland, UK, 8-10 September 1999.

[3] Davies, H., "repair and maintenance of corrosion damaged concrete: materials strategies" pp721-733. Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[4] van Gemert, D., "Durability of Rehabilitation" pp549- 558. Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[5] Walker, M., "An overview of rehabilitation methods and selection of an appropriate system". Pp169-180. Proceedings of the international seminar on controlling concrete degradation, University of Dundee, Scotland, UK, 7 September 1999

[6] Etebar, K., "Integrity of repaired concrete under repeated loading conditions" pp 493-502 Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[7] ENV 1504 (1997), "Products and Systems for the Protection and Repair of Concrete Structures – Definitions, requirements, quality control, evaluation of conformity", Part 9, "General Principles for the Use of Products and Systems".

[8] P C Hewlett (editor): Lea's Chemistry of Cement and Concrete, Fourth Edition

[9] A M Neville: Properties of Concrete, Fourth Edition

[10] D W Hobbs (editor): Minimum requirements for durable concrete. Carbonation- and chloride-induced corrosion, freeze-thaw attack and chemical attack. British Cement Association

[11] Concrete Society Technical Report No. 54: Report of a Working Party, "Diagnosis of deterioration in concrete structures", 2000.

[12] BRE Digest 444 "Corrosion of steel in concrete: Part 1 Durability of reinforced concrete structures." February 2000.

[13] Broomfield, John P.(1997), "Corrosion of Steel in Concrete". Understanding, investigation and repair.

[14] Report of a Working Party, "Repair of concrete damaged by reinforcement corrosion", Concrete Society Technical Report No. 26, October 1984.

[15] BRE Digest 363 Sulphate and acid resistance of concrete in the ground, January 1996 (and imminent revision)

[16] Thaumasite Expert Group Report (TEGR) The Thaumasite form of sulfate attack: risks, diagnosis, remedial works and guidance on new construction. Report of the Thaumasite Expert Group, DETR, January 1999

[17] BRE Digest 330 Alkali silica reaction. 1999

[18] Concrete Society Technical Report No 30. Alkali-silica reaction: minimising the risk of damage to concrete, 3r[d] Edition, 1999

[19] Concrete Society Technical Report No.33: Report of a Concrete Society Working Party, "Assessment and repair of fire-damaged concrete structure", 1990.

[20] Concrete Society Technical Report No.38: Report of a Concrete Society Working Party, "Patch Repair of Reinforced Concrete – subject to reinforcement corrosion. Model Specification and Method Measurement."

[21] Pomeroy, C.D., "Benefits of Concrete as a Construction Material", pp 1-12 Proceedings of the international conference on protection of concrete, University of Dundee, Scotland, UK, 11-13 September 1990

[22] Somerville, G., "Whole Life Design for Durability and Sustainability. Where Are We Going, and How Do We Get There?" pp 1-19 Proceedings of the international conference on concrete durability and repair technology, University of Dundee, Scotland, UK, 8-10 September 1999.

[23] Rostam, S. & Faber, M., "Rehabilitation Strategies – A Multi-Disciplinary Challenge to the Engineering Profession".pp865-876 Proceedings of the international conference on concrete repair, rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[24] Mays, G.C. (1999), "Materials for the protection and repair of concrete: progress towards European standardisation", pp.482-491, Proceedings of the international conference on concrete durability and repair technology, University of Dundee, Scotland, UK, 8-10 September 1999

[25] BRE Digest 444 "Corrosion of steel in concrete: Part 2 – Investigation and assessment. February 2000."

[26] Department of Transport (1986), "The Investigation and Repair of Concrete Highway Structures". Department of Transport Highways & Traffic Departmental Advice Note BA 23/86, November 1986.

[27] Kamijoh, T., "Repair of Salt-Damaged Concrete Structures" pp425-439 Proceedings of the international conference on protection of concrete, University of Dundee, Scotland, UK, 11-13 September 1990

[28] Johnstone, R R "The maintenance of concrete trunk road bridges in Scotland" pp735-745. Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[29] BRE Digest 444 "Corrosion of steel in concrete: Part 3 – Protection and remediation." February 2000.

[30] Henriksen, C. & Michaux, C., "Prediction of Service Life and Choice of Repair Strategy" pp611-619 Proceedings of the international conference on concrete durability and repair technology, University of Dundee, Scotland, UK, 8-10 September 1999

[31] Rowe, D.P., Roberts, M.B. & Gardiner, R.P. "Cost-Optimised Maintenance of RC Highway Structures" pp357-369 Proceedings of the international conference on concrete durability and repair technology, University of Dundee, Scotland, UK, 8-10 September 1999

[32] BS15686: Part 1 2000 Buildings and constructed assets service life planning. General principals

[33] BS15686: Part 2 (May 2001): Buildings and constructed assets service life planning. Service life prediction procedures

[34] BS6270:Part 2: 1985 Cleaning and surface repair of buildings: Concrete and precast concrete masonry, British Standards Institution.

[35] BS8221: 2000 Code of practice for cleaning and surface repair of buildings. Part 1: Cleaning of natural stones, brick, terracotta and concrete. Part 2: Surface repair of natural stones, brick and terracotta, British Standards Institution.

[36] Johnson, R.A., Leek, D.S., King, E.S., Dunne, H.B. (1995), "Underground Service Reservoirs: Waterproofing and Repair Manual", CIRIA report 138, CIRIA.

[37] Kay, E.A. (1989), "Concrete society working party on patch repair of concrete", The Proceedings of the 3rd International Conference on Deterioration and Repair of Reinforced Concrete in the Arabian Gulf, Volume II, Bahrain, 21-24 October 1989.

[38] Vassie, R R., "The effectiveness of repairs to a corroded reinforced concrete bridge deck" pp640-652. Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[39] Hewlett, P C & Oliver, M S, "Certification of concrete repair materials and installation methods" pp803-813 Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[40] Emberson, N.K. & Mays, G.C., "Design of Patch Repairs: Measurements of Physical and Mechanical Properties of Repair Systems for Satisfactory Structural Performance", pp 937-954 Proceedings of the international conference on protection of concrete, University of Dundee, Scotland, UK, 11-13 September 1990

[41] Kruger, D. & Penhall, E., "Polymers in Concrete: A Protective Measure", p653-664 Proceedings of the international conference on protection of concrete, University of Dundee, Scotland, UK, 11-13 September 1990

[42] Williams, J.T. & Parker, A.J., "Reinforced Concrete: Structural Considerations and Choice of Products for Repair" p819-830, Proceedings of the international conference on protection of concrete, University of Dundee, Scotland, UK, 11-13 September 1990

[43] Currie, R.J. & Robery, P.C. (1994), "Repair and Maintenance of Reinforced Concrete", Building Research Establishment Report 254, BRE.

[44] P H Perkins: Repair, Protection and Waterproofing of Concrete Structures, Third Edition, 1997. E&FN Spon.

[45] Mays, G.C. & Barnes, R.A. (1996), "Sprayed concrete repairs – their structural effectiveness", Sprayed Concrete Technology, The Proceedings of the ACI/SCA International Conference on Sprayed Concrete/Shotcrete, 10-11th September 1996. ISBN 0 419 22270 7.

[46] Mangat, P.S., O'Flaherty, F.J. (1996), "Long term performance of sprayed concrete repair in highway structures", Sprayed Concrete Technology, The Proceedings of the ACI/SCA International Conference on Sprayed Concrete/Shotcrete, 10-11th September 1996. ISBN 0 419 22270 7.

[47] Martech, "Electrochemical Treatment for Reinforced Concrete, The Martech Systems and Support Service", Martech Ltd.

[48] Concrete Society technical Report No 36. Report of a joint Concrete Society and Corrosion Engineering Association Working Party: Cathodic Protection of Reinforced Concrete.

---

[49] McKenzie, M. "Cathodic Protection of Reinforced Concrete Bridges" p641-651 Proceedings of the international conference on protection of concrete, University of Dundee, Scotland, UK, 11-13 September 1990.

[50] McKenzie, M. & Chess P.M. (1988), "The Effectiveness of the Cathodic Protection of Reinforced Concrete". UK Corrosion 88 with Eurocorr 88. Brighton 3-5 October 1988.

[51] Sergi & Page – 'The effects of cathodic protection on alkali-silica reaction in reinforced concrete" Department of Transport and TRL Limited, Issue 310, 1993.

[52] Page, Sergi & Thomson (1992) "Development of alkali-silica reaction in reinforced concrete subjected to cathodic protection." 9th International Conference, 1992. Westminster.

[53] King, E.S. & Ecob, C.R. (1993), "Review and Specification of Concrete Repair Materials".

[54] DTI Link Project TIO-49 (1997), "Draft Specification for Concrete Repair in Highway Structures based on Long Term Performance Criteria", Draft v4, May 1997.

[55] Emmons, P.H. & Vaysburd, A.M. (1996), "System Concept in Design and Construction of Durable Concrete Repairs", p.69-75, Construction and Building Materials, Vol.10, No.1.

[56] Morgan, D.R. (1996), "Compatibility of concrete repair materials and systems", pp.57-67, Construction and Building Materials, Vol.10, Number 1.

[57] Department of Transport Highways and Traffic Departmental Standard BD27/86: materials for the repair of concrete Highway Structures, 1986

[58] Sopko, S J "Repair and Protection: Two case histories", p683-691 Proceedings of the international conference on concrete repair , rehabilitation and protection, University of Dundee, Scotland, UK, 27-28 June 1996

[59] Emmons, P.H. & Vaysburd, A.M. (1993), "Factors affecting durability of concrete repair – The contractor's viewpoint", Proceedings of 5th international conference on structural faults and repair, Vol.2 Extending the Life of Civil & Building Structures, University of Edinburgh.

[60] Cromie, J.A., Abu-Tair, A.I., Lyness, J.F., McFarlane, B., McCullough, W.P. (1999), "The independent assessment of electrochemical chloride extraction treatment on a 30-year-old motorway bridge", The Structural Engineer, Vol.77, No's 23 & 24, 7 December 1999.

[61] Cabrera J. G & Al-Hasan, A S. 1997. "Performance properties of concrete repair materials" Construction and Building Materials, Vol 11, Numbers 5-6.

[62] Mangat, P.S. & O'Flaherty, F. (1999), "Long term performance criteria for concrete repair materials", pp.381-393, Proceedings of the international conference on concrete durability and repair technology, University of Dundee, Scotland, UK, 8-10 September 1999.

[63] Langlois, M., Pigeon, M., Bissonnette, B. & Allard, D. (1994), "Durability of concrete repairs – a field experiment", Third CANMET/ACI international conference on durability of concrete supplementary papers, Nice, France, 22-28 May, 1994.

[64] Saucier, F. & Pigeon, M. (1991), "Durability of new-to-old concrete bondings", Proceedings of ACI International conference on evaluation and rehabilitation of concrete structures and innovations in design, Hong Kong, ACI SP-128, Vol 1, p.p.689-707, 4-6 December 1991.

[65] BS EN 1504 Part 1: "Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity". Part 1: Definitions. BSI 1998.

[66] Draft BS EN 1504 Part 10: "Product and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity". Site Application of products and systems and quality control of the works.

[67] Robery, P.C. (2000), "Concrete Repair Materials Specification Impact of EN 1504 Series", Concrete Society Meeting, Institution of Structural Engineers, 9 May 2000.

[68] Davies, H. & Kay, E.A. (1996), "The European Standard on Concrete Repair Principles", p.52, Construction Repair: Concrete Repairs 6.

[69] Application of new European standards to concrete repair, New Civil Engineer , 19/11/1998

Printed and published by the Health and Safety Executive
C1.10 12/03

HSE
BOOKS

MAIL ORDER
HSE priced and free
publications are
available from:
HSE Books
PO Box 1999
Sudbury
Suffolk CO10 2WA
Tel: 01787 881165
Fax: 01787 313995
Website: www.hsebooks.co.uk

RETAIL
HSE priced publications
are available from booksellers

HEALTH AND SAFETY INFORMATION
HSE Infoline
Tel: 08701 545500
Fax: 02920 859260
e-mail: hseinformationservices@natbrit.com
or write to:
HSE Information Services
Caerphilly Business Park
Caerphilly CF83 3GG

HSE website: www.hse.gov.uk

RR 175

£10.00

ISBN 0-7176-2783-7

9 780717 627837