Competitive and Sustainable Growth (GROWTH) Programme

SAMARIS

Sustainable and Advanced MAterials for Road InfraStructure

SPECIFICATION FOR THE USE OF CORROSION INHIBITORS FOR THE REHABILITATION OF CONCRETE HIGHWAY STRUCTURES

DELIVERABLE D25a

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ABSTRACT

Corrosion inhibitors are chemicals that act by direct action on the steel surface to reduce the rate of corrosion. The brief of the SAMARIS project focused on surface-applied penetrating corrosion inhibitors used as part of a maintenance or repair strategy. The guidelines that resulted are based on research on amino alcohol-based surface-applied inhibitors.

The mechanism of corrosion inhibitor action significantly influences its effectiveness in certain situations (e.g. combined effect of chloride level and existing level of surface corrosion damage). Specification of a rehabilitation strategy for a project involves balancing available resources against the satisfactory control of risk. This judgement must be made by the specifier. Therefore, the specifier should investigate if the project limitations are within the boundaries of efficiency of the corrosion inhibitors intended to be used or if effectiveness needs to be addressed in the specific project by monitoring. When required, to satisfy the specifier's requirements in respect of control of risk, performance monitoring is recommended. In summary, specifiers should be aware that there are circumstances where the use of corrosion inhibitors is appropriate, usually as part of a corrosion protection strategy rather than a stand-alone solution, and effectiveness should be performance-monitored whenever required.

A significant issue generally identified for effective highway structure maintenance is the role of monitoring and this is particularly highlighted in the case of repair strategies that incorporate corrosion inhibitors. Corrosion inhibitors can best be used to achieve or extend a defined service life in one of three ways. They may either defer the initial time to depassivation; and/or reduce the rate of existing corrosion to acceptable levels; and or control incipient anodes. The acceptable rate of corrosion is dependent on the particular circumstances of the project and is a function of service life requirement and the acceptable deterioration level. Highway structure maintenance is best achieved, if resources permit, by monitoring the existing state and deterioration rate of structural elements leading to planned interventions rather than sole reliance on intermittent repair of significant and advanced defects; this early intervention approach makes the most of the inhibitor performance and also offers a reduced maintenance cost over the service life through more proactive decision making.

The use of corrosion inhibitors should provide a cost effective solution if used in appropriate circumstances and as part of an integrated repair strategy that controls risk in structured way. Such an innovative technique – in the sense that it has not got too long an established track record, having been used for a little over a decade – brings with it uncertainty in a number of areas and this requires control of risk. Although control of risk is a normal part of practice it is an especially significant step in innovative practice until such time as the specifier can draw on a significant database of comparable situations.

This report presents guidelines for those managing highway infrastructure and specifiers of repair strategies incorporating inhibitors. It briefly outlines the principles of an integrated repair strategy to indicate the context, gives an overview of significant factors influencing the choice of inhibitors as a potential part of a strategy, sets out a methodology for trial performance tests and specification guidelines for inhibitor-based repair and subsequent performance monitoring.

EXECUTIVE SUMMARY

Background

Reinforced concrete bridges are required to maintain their serviceability over long periods of time, typically 120 years. Although this service life expectation was stated or implied, it did not explicitly form part of the specification process during the period when much of the developed world's current highway infrastructure was constructed. For a considerable period reinforced concrete was regarded as a maintenance-free material but corrosion of steel in concrete bridges, initiated by chloride ingress, or less commonly by carbonation, has become a major problem for highway authorities. Highway authorities worldwide have been required to commit substantial resources to repair contracts. Of equal significance are the collateral costs associated with traffic delays and increased journey times caused by road closure and lane restrictions. Traditional repair techniques involve many stages and are time consuming; the failure of traditional repairs is especially irritating when time and investment is a precious commodity. This aspect has been a driver for the development of innovative techniques for supplementing repair methods of the extensive existing stock of highway infrastructure assets in a time- and cost-efficient manner. One such technique is the use of surface-applied corrosion inhibitors.

Surface-applied corrosion inhibitors are applied to the mature hardened surface during rehabilitation procedures and diffuse through the cover concrete. These inhibitors are typically based either on mixtures of alkanolamines and amines or organic acids. Amino alcohol-based inhibitors are typically dual acting inhibitors (ambiodic or 'mixed' inhibitors). They act on both cathodic and anodic sites on the steel surface, the action of which is usually interdependent. Inhibitor action is typically to act as a barrier to newly arriving chlorides unless the concentration of chlorides becomes too high for the barrier to remain effective – this breakdown might happen where corrosion was already advanced at time of first inhibitor treatment. Thus in a sense the inhibitor appears to raise the chloride ion threshold level necessary to initiate corrosion and to decrease the rate of corrosion where the propagation stage has been reached. Inhibitors are best used to extend (or help to achieve) the required service life by deferring the initial time to depassivation, and/or through reducing the rate of corrosion once corrosion is propagated, or retard incipient action (ring anode). It must be emphasised that corrosion inhibitors are not used to totally stop corrosion - they 'buy time' by extending the time to first repair or next significant maintenance intervention (Figure I).

The sooner the inhibitor is introduced after corrosion propagation the more effective it is because it forms a protective layer which is best achieved on surfaces that are not heavily corroded. Indeed application before propagation could be the optimum time, as part of a proactive preventative maintenance strategy program. The ongoing action of the inhibitor near the reinforcement in treated structures is to provide a reservoir from which any local breakdowns may be rehabilitated to ensure protection. The reservoir is a finite resource and in time (years, perhaps decades) it will require renewal if further extensions of satisfactory service life are required.

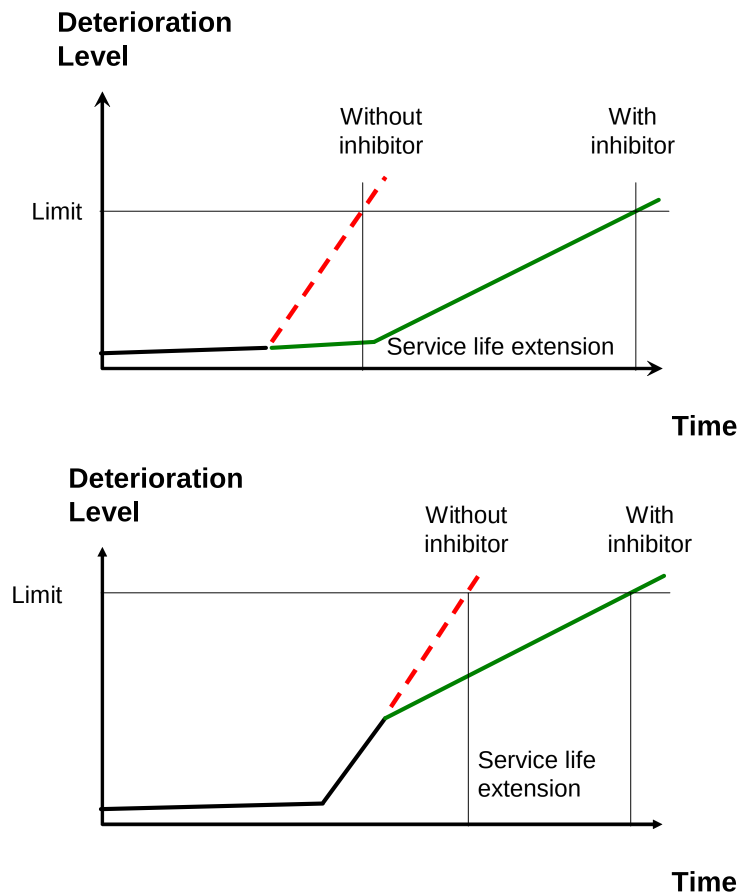


Figure I: Concept of service life extension through use of surface applied corrosion inhibitor on an existing reinforced concrete structure

Context for use - a structured engineering judgement maintenance strategy

The use of corrosion inhibitors can provide a cost-effective and time-efficient component of a repair strategy for highway structures. However such an innovative technique – in the sense that it has not got too long an established track record, having been used for a little over a decade – brings with it uncertainty in a number of areas and this requires control of risk. The specifier of a repair strategy needs decision-making tools that take account of the potential benefits of innovative techniques while controlling the risks. SAMARIS Report D31 provides a structured approach to deciding on an optimum repair strategy for an individual structure, and how this can be assessed against the needs of the network as a whole, while making provision for the use of innovative techniques. The principles outlined in that report form the context for the appropriate use of corrosion inhibitors as outlined in the guidance on the use and specification of inhibitors in this report.

Initial assessment

Having identified the need and determined the objectives of a maintenance intervention the possible use of corrosion inhibitors can be included in the initial consideration of options. The initial assessment of this option should take account of the condition of the structure and the environment to which it is exposed, now and into the future. This will determine:

- Whether corrosion inhibitors merit consideration as a viable option alone;
- Whether corrosion inhibitors merit consideration as a viable option in tandem with other techniques, such as protective coatings or hydrophobic impregnations;
- Whether the constraints that exist (e.g. corroded condition of the reinforcement or exposure conditions) preclude consideration of inhibitors.

In considering corrosion inhibitors as a potential component of a repair strategy it must be clear what role they are intended to play in achieving the objectives of the repair:

- Delay the onset of corrosion and/or
- Reduce (or prevent increase in) the existing rates of corrosion and/or
- Retard incipient action

An initial desk study assessment of corrosion inhibitor appropriateness should be conducted taking account of the following issues:

a) Extremes of in-service and application environmental conditions. The inhibitor must be capable of absorption without impedance by environments characterised by prolonged extremes of temperature (e.g lower than –5°C, more than 40°C). At very low temperatures the physical nature of the yet-to-be applied material may change (e.g. crystallisation) whereas at very high temperatures a volatile material may preferentially evaporate from the surface layers rather than diffuse into the concrete. Manufacturers' recommendations must be referred to.

b) Degree of saturation of concrete. Absorption and diffusion characteristics are critically dependent on the moisture state of the concrete. Concrete that is saturated will inhibit the process. Another factor to be considered is washout of inhibitor. Concrete that is cyclically wetted (e.g. tidal zone) may not be able to sustain an effective concentration of inhibitor during the penetration process.

c) Chloride levels. The concentration of inhibitor that diffuses to form a reservoir at the reinforcement must be adequate relative to any chloride presence, both at the time of the repair and in subsequent years. A very significant consideration is the relative inhibitor to chloride concentration. Thus long-term effectiveness will be critically dependent on the relative inhibitor to chloride concentration, at any given time. This will be a function of material properties and exposure conditions. On the one hand, the ratio will depend on the inhibitor's ability to penetrate the cover concrete and be retained in the zone of reinforcement. On the other hand it will be a function of the exposure to chlorides and the material resistance to chloride ingress. Allied to these factors is the state of the reinforcement at time of inhibitor application - see (e) below. By way of guidance, a moderate chloride level, qualitatively classified in this context as being less than 1% chloride, by weight of cement, at the level of the reinforcement, is a potentially significant level in ranking the inhibitor-based repair option. As chloride levels fall below this value there is an increasing possibility that an inhibitor-based rehabilitation strategy will show promise. The option is of greater interest at the preliminary review stage if chloride levels are low – at high chloride levels success if not assured. In cases where the existing or expected future chloride level is high, increased consumption of the inhibitor may be considered together with performance monitoring. Very high chloride levels, qualitatively classified in this context as being in excess of 2%, by weight of cement, are likely to be too high for the inhibitor to be effective at typically recommended dosages. These comments are inextricably linked to the corroded state (if any) of reinforcement at time of treatment with inhibitor – the corroded state may be a function of chloride level. See also e) below.

d) Permeability characteristics of carbonated concrete. There is evidence of successful use of inhibitors in carbonated concrete but one note of caution may be addressed: fully carbonated concrete might be highly permeable. On one hand such concretes allow easy penetration of the inhibitor but on the other hand they may present a challenge if the exposure conditions change and water or contaminants easily permeate and reduce the effectiveness of the adsorbed layer on the reinforcement and hence reduce the required satisfactory service life of the treated structure. In such specific cases an additional protective measure in the form of a suitable coating may be required to seal the surface.

e) Corroded state of reinforcement at time of repair. The state of the reinforcement at time of repair will have a very significant bearing on the likelihood of corrosion inhibitors being effective. The more corroded the surface the greater the difficulty for the inhibitor in forming a protective layer. If the layer cannot be fully formed (e.g. with inadequate concentration of inhibitor at the reinforcement level), the exposed sections may present a risk of increased local pitting corrosion.

f) Ecological constraints. The initial assessment of using corrosion inhibitors has to take account of environmental or health and safety constraints. For example rehabilitation of bridges over waterways may have to take account of chemical containment issues; water impounded for drinking water supply may have significant constraints associated with it.

The desk study may indicate that corrosion inhibitors are a potentially viable option. Based on the information from this desk study, and the specifier's requirement to balance available resources against the satisfactory control of risk, a decision can be made on whether the conditions exist for an immediate decision for using the corrosion inhibitor technique; or whether an alternative technique should be used; or whether a preview of corrosion inhibitor effectiveness is recommended.

Preview study option

It can be argued that with any repair strategy to reduce corrosion activity, verification of performance is the only way of ensuring that the expectations of the specifier and client are met. Given the multitude of factors that can influence corrosion activity in structures treated with inhibitor, or using any other electrochemical technique verification of expectations has special significance. It is strongly recommended therefore that a preview study be conducted. A preview study can verify that, in the particular circumstances of a project, the inhibitor penetration is satisfactory and that its effect is adequate and potentially sustainable for the period intended. The test area, or areas, should be representative of the structural element being assessed for delay of depassivation, corrosion rate reduction and/or retardation of incipient action.

The next stage should be the definition of performance criteria to attain repair strategy objectives and against which a preview study may be used to evaluate applicability on the structure in question. This could be a maximum value of reduction of corrosion rate (corrosion current density) or as a percentage reduction from pre-treated levels over a defined time assuming that base corrosion rates are not too low to begin with. Analysis of preview results will lead to a decision on ratification or modification of the proposed repair strategy.

Full scale maintenance intervention

Following execution of the preview study the results may be used to confirm or suitably modify the final repair strategy if warranted. From this a specification for implementation of the repair strategy may be drawn up mindful of the following:

- Manufacturer's guidelines to specifiers
- Materials Safety Data Sheet valid in the place of use
- Health and Safety Regulations valid in the place of use
- Ecological constraints particular to the project location

The repair should then be executed with adequate quality control and assurance measures.

Post-repair monitoring option

Serious consideration should be given to the opportunity presented at time of rehabilitation for post-repair monitoring as an integral part of the maintenance strategy. The period that an inhibitor remains effective will depend upon the overall corrosion management strategy. Hence the monitoring of corrosion performance plays a huge role in determining the effectiveness of corrosion inhibitors or any other repair strategy. Although this point is not unique to repair strategies based on corrosion inhibitors but it is emphasised in this context as an example of cost-effective good practice. Active monitoring of the investment in the initial inhibitor application repair strategy may be used to maintain satisfactory service life in a planned way rather than only reacting to future signs of significant deterioration.

The concept of active management of rehabilitation is illustrated in Figure II. This shows how the active monitoring of the investment in the initial inhibitor application repair strategy may be used to maintain satisfactory service life in a planned way rather than only reacting to future signs of significant deterioration. The corrosion inhibitor repair strategy is based on the integrity of the monomolecular layer thickness being available to maintain the integrity of the protection. Inevitably a time will come, perhaps over a decade later, when the effectiveness will diminish if chlorides and water are allowed to diffuse through the concrete. Rather than allowing deterioration to then accelerate, a managed system will flag that renewal of inhibitor is required. This should be a cost effective solution to the life cycle management of the structure.

Monitoring of each and every structure may not always be necessary. It may be a case that a 'family' of similar structures with similar problems might be identifiable, for example on a stretch of motorway. In such cases it may be adequate, and more cost effective, to limit the active monitoring to a subset of the family of structures.

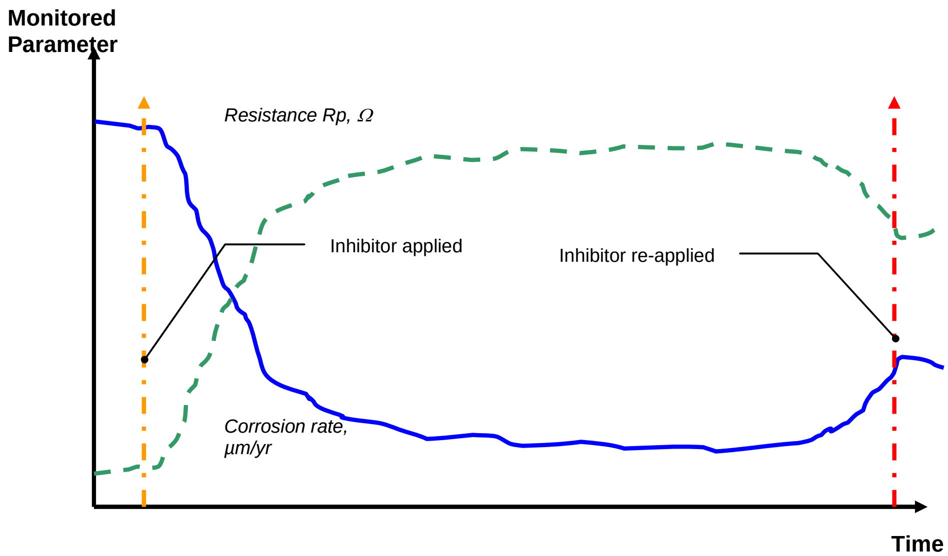


Figure II: Example of a monitored repair strategy based on corrosion inhibitors

If a post-rehabilitation monitoring system is in place the inhibitor may be reapplied when prompted by indications from the post-repair monitoring as a continuation of proactive management. This could be a decade or more later.

Summary flowchart

A summary flowchart is presented in Figure III.

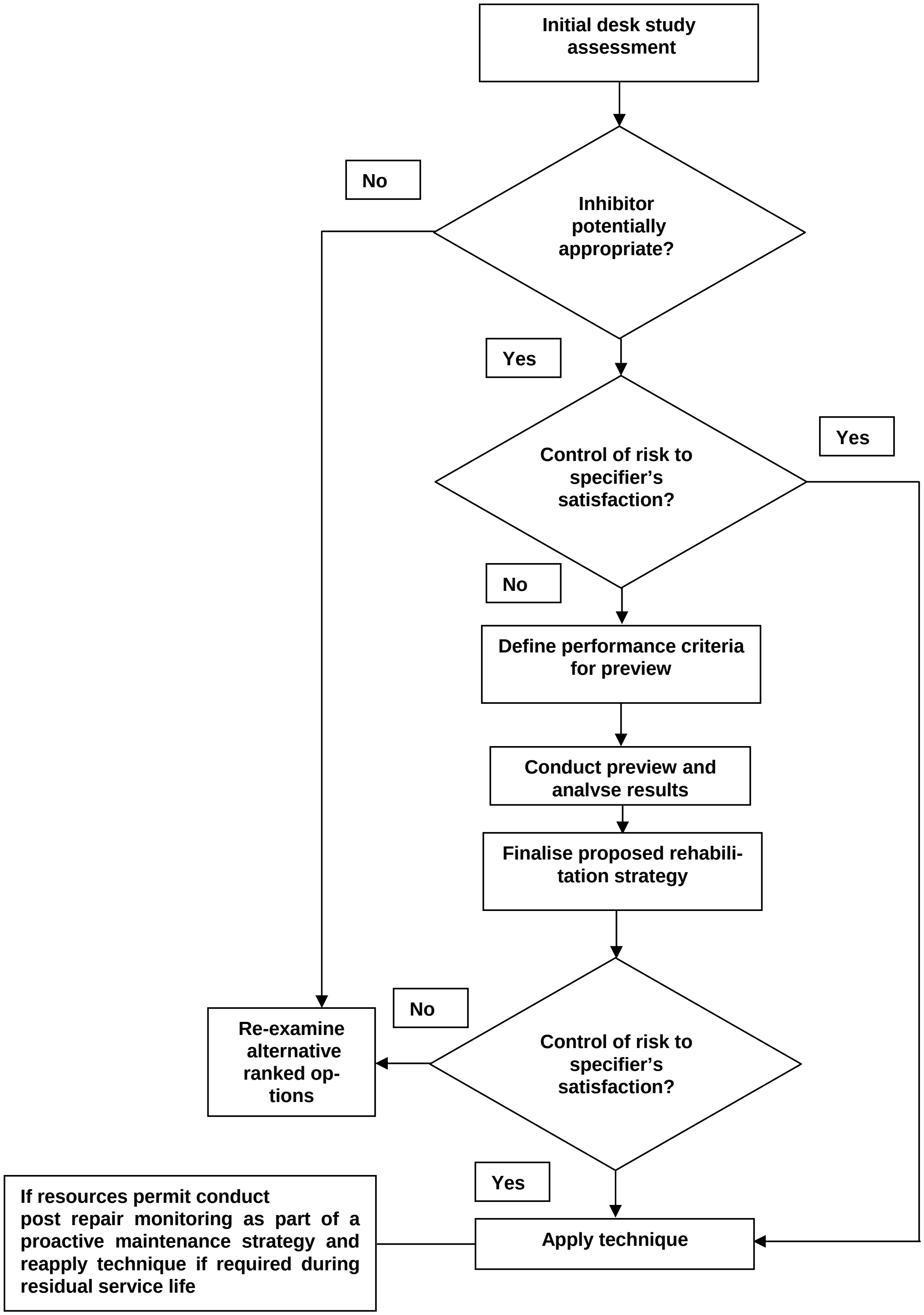


Figure III: Summary Flowchart

The use of corrosion inhibitors should provide a cost effective solution if used in appropriate circumstances and as part of an integrated repair strategy that controls risk in structured way. Such an innovative technique – in the sense that it has not got too long an established track record, having been used for a little over a decade – brings with it uncertainty in a number of areas and this requires control of risk. Although control of risk is a normal part of practice it is an especially significant step in innovative practice until such time as the specifier can draw on a significant database of comparable situations.

FOREWORD AND ACKNOWLEDGEMENTS

Work Package WP13 of the SAMARIS project was concerned with the appropriate use of corrosion inhibitors in repair strategies for rehabilitation of highway structures. Research was concentrated on amino alcohol-based surface-applied inhibitors. This led to a template set of guidelines for the effective use of such corrosion inhibitors. Its findings were informed by literature review, laboratory studies and field trials. This report forms part of a set of deliverables from Work Package WP13, reported as D17a, D17b, D21 and D25a.

SAMARIS Report D25a (this report) presents guidance for specifiers using corrosion inhibitors in the maintenance of highway structures. The guidelines are based on a review of corrosion inhibitors conducted through literature review and a laboratory study of the mechanism of corrosion inhibitor action and the factors that influence its effectiveness (SAMARIS Report D17a); findings from laboratory studies on concrete specimens, with particular reference to the influence of chloride concentration, inhibitor concentration, permeability and influence, if any, of inhibitor on the properties of concrete (SAMARIS Report D17b); and the findings of field trials in which the effectiveness of inhibitor was studied (SAMARIS Report D21). These documents are summarised in Table I.

Table I: List of SAMARIS Work Package WP13 Deliverables

Report Reference	Title
D17a	Test of effectiveness of corrosion inhibitors in laboratory trials – Part A
D17b	Test of effectiveness of corrosion inhibitors in laboratory trials – Part B
D21	Test of effectiveness of corrosion inhibitors in field trials
D25a	Specification for the use of corrosion inhibitors for the rehabilitation of concrete highway structures

In a wider context, the integration of corrosion inhibitors as part of a repair strategy is presented in SAMARIS Report D31 (of Work Package WP12), to which the end user is also referred. It is entitled ‘Guidelines on selection of innovative techniques for the rehabilitation of concrete highway structures’.

The information presented in this report is structured as follows:

- Outline of the principles of an integrated repair strategy decision process, as set out in Report D31;
- Initial assessment based on significant factors influencing the effectiveness of inhibitors in a repair strategy;
- Requirement for feasibility trials of performance;
- Specification issues for full scale inhibitor-based repair, where adopted;
- Advice on subsequent performance monitoring as part of the repair strategy.

The SAMARIS reports dealing specifically with corrosion inhibitors were produced by the Work Package WP13 team of contractors and subcontractors to the contract. The Work Package was led by University College Dublin. The other contractors were Sika, Transport Research Laboratory and ZAG – Slovenian National Building and Civil Engineering Institute. Subcontractors were Cardiff University, C-Probe Systems Limited and Structural Healthcare Associates.

The input of the following individuals, from the above organisations respectively, in synthesising the results of the research conducted by the participants is particularly acknowledged: Dr. Mark Richardson and Dr. Ciaran McNally; Michel Donadio, Beat Marazzani and Patrick Mulligan; Dr. Malcolm McKenzie; Dr. Andraž Legat; Dr. Bob Lark; Graeme Jones. The work of Dr. Richard Woodward, Transport Research Laboratory, in the preparation of the Work Package WP12 related report referred to in Section 1 – 'Guidelines on selection of innovative techniques for the rehabilitation of concrete highway structures'– is also acknowledged.

1. OVERVIEW OF AN INHIBITOR-BASED REPAIR STRATEGY

1.1 Context

Reinforced concrete bridges are required to maintain their serviceability over long periods of time, typically 120 years. Although this service life expectation was stated or implied, it did not explicitly form part of the specification process during the period when much of the developed world's current highway infrastructure was constructed. For a considerable period reinforced concrete was regarded as a maintenance-free material but corrosion of steel in concrete bridges, initiated by chloride ingress, or less commonly by carbonation, has become a major problem for highway authorities. This problem is manifest by numerous examples of premature deterioration of reinforced concrete structures in a fraction of their intended service life. The Federal Highway Administration (1970) issued a training manual for bridge inspectors in the early 1970's in the context of more than one in six bridges being reported as deficient.

Highway authorities worldwide have been required to commit substantial resources to repair contracts. Of equal significance are the collateral costs associated with traffic delays and increased journey times caused by road closure and lane restrictions, as illustrated in Figure 1.1. Traditional repairs involved many stages including removal of damaged and contaminated concrete, preparation and treatment of reinforcement, patch repair with pre-bagged cementitious repair mortar, reprofilling concrete surfaces with levelling mortar and, perhaps, application of a protective coating. This aspect has been a driver for the development of more stringent specifications for new works and innovative techniques for repair of the extensive existing stock of highway infrastructure assets in a time- and cost-efficient manner.

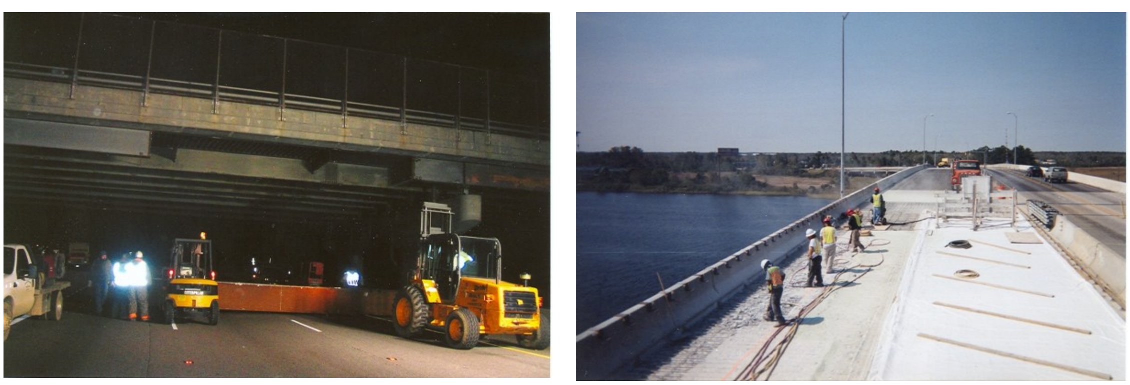


Figure 1.1: Road closures and lane restrictions during repair of highway structures

Innovative techniques include desalination, re-alkalisation and the use of corrosion inhibitors. Whilst these repair / maintenance strategies, and those based on cathodic protection, all have their benefits, their initial cost, downtime for repair, effective life and impact on life-cycle costs need consideration in a structured way that also takes account of the attendant risks associated with innovative techniques.

Kulash (1990) described the goals and recent developments in the Strategic Highway Research Programme (SHRP). The two major goals included improving the durability of concrete in highway structures and the rehabilitation and protection of concrete bridges. The work included developments in eight key areas, one of which was the use of corrosion inhibitors. Corrosion inhibitors may be mixed-in when specified in new works or may be surface applied to concrete as part of a repair strategy on existing elements, as illustrated in Figure 1.2. The appropriate use of a corrosion inhibitor may provide an alternative cost-effective solution compared to the other techniques mentioned above.

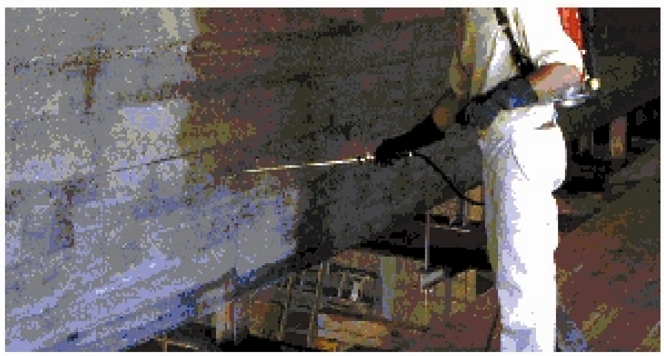


Figure 1.2: Surface application of corrosion inhibitor to an existing reinforced concrete structure

Penetrating corrosion inhibitors are applied to the mature hardened surface during rehabilitation procedures and diffuse through the cover concrete. These inhibitors are typically based either on mixtures of alkanolamines and amines or organic acids. Amino alcohol-based inhibitors are typically dual effect inhibitors (or 'mixed' inhibitors). They act on both cathodic and anodic sites on the steel surface to provide protection. Inhibitor action is typically to act as a barrier to newly arriving chlorides unless the concentration of chlorides becomes too high for the barrier to remain effective – this breakdown might happen where corrosion was already advanced at time of first inhibitor treatment. Thus in a sense the inhibitor appears to raise the chloride ion threshold level necessary to initiate corrosion, to extend the time to corrosion and to decrease the rate of corrosion where the propagation stage has been reached.

1.2 Surface-applied corrosion inhibitors

The satisfactory service life of a reinforced concrete structure is typically dependent on two phases – the initiation period and propagation phase of corrosion. The initiation period is the time taken for depassivation of the protective oxide film to occur; this can be caused by the arrival of chlorides in sufficient quantities or a carbonated front from carbon dioxide diffusing through the concrete cover. The propagation phase is the period of active corrosion from time of initiation to the time at which the lack of durability demands intervention due to growth of corrosion products causing build-up of tensile forces in the concrete cover that result in the need to repair cracking and spalling concrete.

Corrosion inhibitors are chemicals that, in small concentrations, act by direct action on the steel surface to reduce the rate of corrosion (ISO, 1989). The action of corrosion inhibitors depends on the characteristics of the particular compound. Surface-applied corrosion inhibitors are penetrating corrosion inhibitors. Surface-applied corrosion inhibitors, are usually applied during rehabilitation procedures and diffuse through the cover concrete. The mechanism by which the surface-applied inhibitors penetrate the concrete is a combination of capillary absorption and diffusion of vapour and liquid states. Surface applied corrosion inhibitors therefore are a concrete cover treatment that rely on direct action on the steel rather than chemical treatments, such as silanes, that rely on effecting a barrier to further ingress of depassivating agents.

Inhibitors are best used to extend (or help to achieve) the required service life by deferring the initial time to depassivation, and/or through reducing the rate of corrosion once corrosion is propagated, or retard incipient action (ring anode). The concept is illustrated in Figure 1.3, based on work by Laamanen and Byfors (1996). Mackechnie et al (2004) emphasise that, as illustrated, corrosion inhibitors are not used to totally stop corrosion - they ‘buy time’ by extending the time to first repair or next significant maintenance intervention.

The different types of corrosion inhibitors are nitrites, phosphates, amines and amino alcohols (also known as alkanalomines) and carboxylates, each with a particular mechanism. Nitrite inhibitors include sodium nitrite and calcium nitrite. Calcium nitrite is an anodic inhibitor which oxides ferrous ions to ferric ions, which then precipitate in the alkaline pH of concrete. Ferric ions are insoluble in aqueous alkaline solutions and block the transfer of ferrous ions into the electrolyte. Nitrite ions can penetrate into concrete by absorption and diffusion if applied to the surface by spraying or ponding. Amino alcohol compounds are water are water soluble, which allows them to migrate within concrete structures when water is applied. These inhibitors can be applied to existing reinforced concrete structures and will then be carried by water into the proximity of the reinforcing steel. Amines or alkanolamines have quite high vapour pressure under atmospheric conditions and may diffuse or migrate into concrete (Elsener, 2001). Amino alcohols such as ethanolamine and dimethylethanolamine control corrosion by attacking cathodic activity, blocking sites where oxygen picks up electrons and is reduced to hydroxyl ion. They absorb at anodic sites as well.

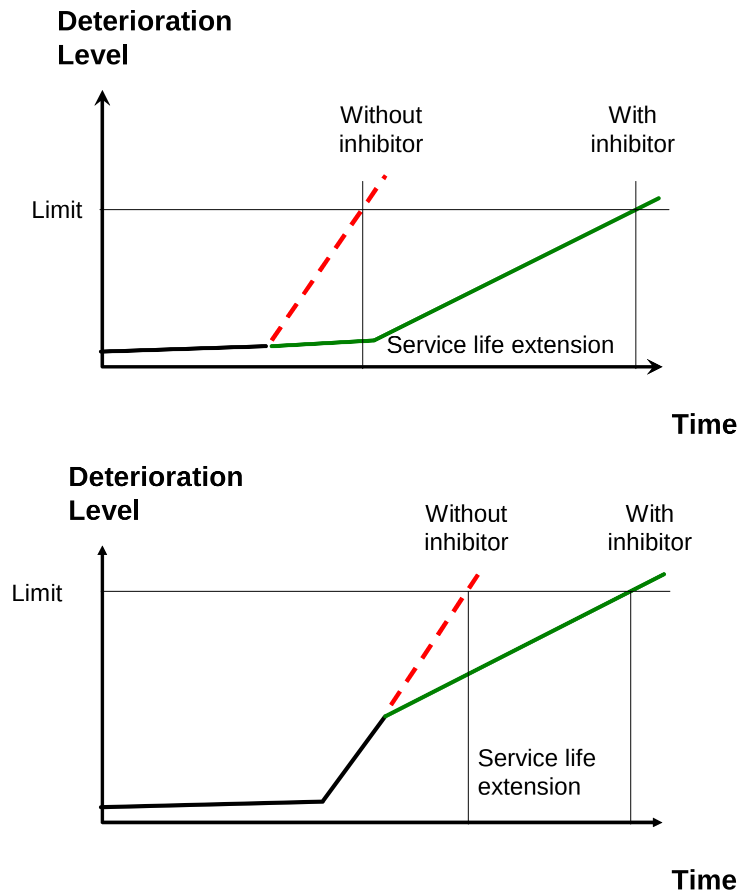


Figure 1.3: Concept of extending service life by use of inhibitors

Regarding the role of inhibitors in the life cycle cost of a structure, the relationship between cumulative cost and time is illustrated in Figure 1.4. Inhibitors can minimise the cost by extending the period during which damage is minimal and repair costs are not accumulating. Equally once corrosion is propagated the repair costs in a given time-step will be proportional to the rate of damaging corrosion. Inhibitors can reduce the corrosion rate and hence the cumulative cost in a particular period.

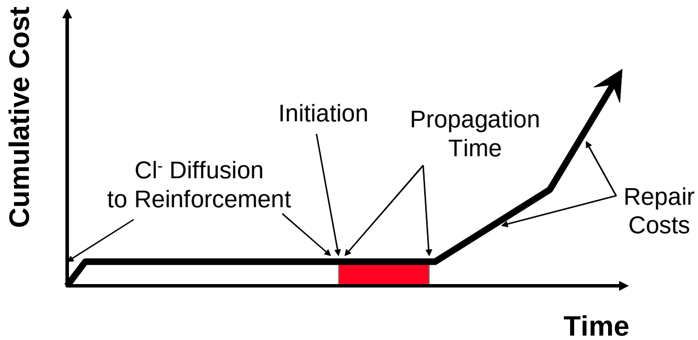
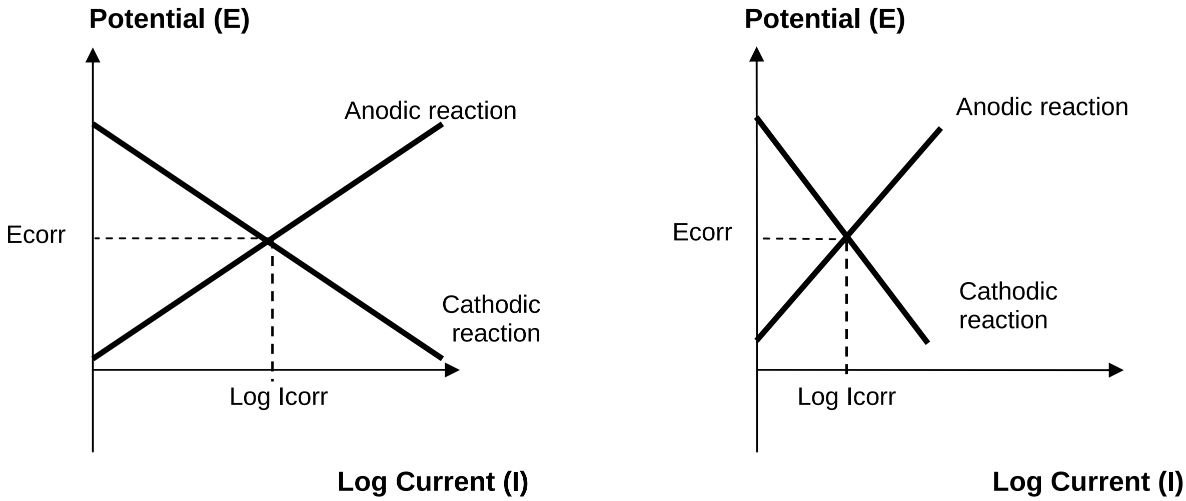


Figure 1.4: Relationship between repair cost and time in a corroding structure

Some inhibitors particularly influence the anodic or cathodic sites where corrosion has propagated. Others influence both. A good insight into the anodic and cathodic action of an inhibitor may be gained by consideration of polarisation curves and 'Evans Diagrams'. These curves graph the relationship between electrical potential and current. The anode will initially have a certain potential difference with the electrolyte and so too will the cathodes. An electrode potential is generated between the reinforcing steel, embedded in the concrete matrix, and a reference electrode. The potential is a mixed potential between anodic and cathodic sites of the reinforcing steel electrode that is naturally occurring when reinforcing steel is embedded in concrete. The corrosion process occurs at the potential where the rates of anodic and cathodic reaction are equal. An 'Evans Diagram' is used to plot the relationship of potential and current in a manner that shows both the anodic and cathodic reactions on one side of the axis. From this an equilibrium of current value can be determined and the potential that the metal adopts as it corrodes is determined by the point of intersection of the curves. A simplified form of the relationship between the potential (E_{corr}) and the current (I_{corr}) in reinforced concrete structure, where the curves are represented by straight lines, is presented in Figure 1.5.



(a) Before inhibitor application **(b) After inhibitor application**

Figure 1.5: 'Evans Diagram' illustrating circumstances in which corrosion rate is reduced without a change in potential

It is particularly significant to note that the effect of an inhibitor which influences both the anodic and cathodic reactions is to reduce the corrosion current without changing the potential. This has important implications for monitoring the effect.

A literature review, reported in SAMARIS Report D17a, indicated the following:

1. The use of inhibitors can extend the service life under certain conditions through delay of depassivation and/or reduction of corrosion rate once propagated.
2. Beneficial inhibitor action is thought to be due to a number of factors including the formation of a protective layer on the reinforcement; an increase in the chloride ion threshold necessary to initiate corrosion by binding chloride to the quaternary salt; displacement of chloride ions and other potentially deleterious ions on the reinforcement surface; and gel formation leading to a pore blocking effect.
3. Circumstances of particular relevance to the effectiveness of surface-applied corrosion inhibitors are:
   a. free chloride ion content at the level of the reinforcement,
   b. concentration of free chloride ions at rebar level in case of fully carbonated concrete,
   c. inhibitor to chloride concentration ratio,
   d. concrete permeability,
   e. environmental conditions prior to, during as well as after application, especially the moisture state of the concrete.
4. The influence of surface-applied inhibitor on the mechanical properties of mature concrete is not thought to be significant but this is distinct from the case of mixed-in (admixture) inhibitors which can influence the hydration process.

Laboratory tests conducted in simulated pore water as part of the SAMARIS Project confirmed that, for corrosion inhibitors based on amino alcohols, passivation due to the inhibitor is reached by the formation of an adsorbed layer on the steel surface. This has important implications for the specifier who must consider achievement of this in practice. The ratio of inhibitor/chloride concentration is a very important parameter and so there are chloride-rich environments in which inhibitors may not be appropriate.

Regarding formation of the protective layer, if the steel reinforcement is heavily corroded the critical concentration ratio is strongly dependent on the steel surface conditions: after the initiation of corrosion this ratio must be quite high for the retardation of corrosion. Therefore one must have conditions in which a suitable concentration of inhibitor is available at the reinforcement post-repair. Indeed it is recognised that if the steel is heavily corroded complete repassivation is practically impossible. The sooner the inhibitor is introduced after corrosion propagation the more effective it is. Indeed an optimum time might be before corrosion propagation to delay its onset.

The ongoing action of the inhibitor near the reinforcement in treated structures is to provide a reservoir from which any local breakdowns may be rehabilitated to ensure protection. This has two implications. Firstly, if the conditions are such that local rehabilitation of breakdowns is not possible the localized corrosion damage can be relatively serious. Secondly, it raises awareness that the reservoir from which ongoing support is provided is a finite resource and that in time, perhaps years, perhaps decades, it will require renewal if further extensions of satisfactory service life are required. The long-term concentration of the inhibitor near the reinforcement may decrease over time due to leaching and evaporation. It is a crucial parameter for the effectiveness of the inhibitor as part of a repair strategy. In the case of ambiodic inhibitors if insufficient is present the inhibition cannot be complete; in the case of anodic inhibitors a lack of concentration encourages pitting corrosion.

Thus repair strategies based on electrochemical techniques must be selected in the context of specific expectations regarding future performance in terms of serviceability and time to next significant maintenance intervention.

1.3 Outline of a structured engineering judgement maintenance strategy

The use of corrosion inhibitors can provide a cost-effective and time-efficient component of a repair strategy for highway structures. However such an innovative technique – in the sense that it has not got too long an established track record, having been used for a little over a decade – brings with it uncertainty in a number of areas and this requires control of risk. Until such time as the specifier can draw on a significant database of comparable situations the effect of conditions outside the proven range needs careful consideration. It is a normal part of engineering judgement and should not represent a barrier to the use of innovative techniques. However the specifier of a repair strategy needs decision-making tools that take account of the potential benefits of innovative techniques while controlling the risks. SAMARIS Report D31 provides a structured approach to deciding on an optimum repair strategy for an individual structure, and how this can be assessed against the needs of the network as a whole, while making provision for the use of innovative techniques. The specifier of repair strategies using corrosion inhibitors will find it a useful resource.

The overall process proposed in SAMARIS Report D31, illustrated by the flowchart in Figure 1.6, involves a number of stages. These include:

- Identify the maintenance need, typically based on inspection reports;
- Formulate a clear set of objectives of what any remedial treatment is designed to achieve. (Final decisions could involve compromise between conflicting objectives that are difficult to quantify);
- Identify a range of potential remedial strategies based on the assessments of the current condition of the structure and the objectives of the maintenance;
- Specify the decision making criteria such that the reasoning behind the final decision, or range of options, can be clearly presented in relation to the defined objectives and can be independently reviewed;
- Select preferred option based on the technical and non-technical factors of relevance in the objectives for the repair. The relative importance of each factor (primary or secondary) needs to be decided so that an appropriate weighting (numerical or subjective) can be used to combine the factors and establish a preferred option;
- Control of risk where the preferred option is innovative may involve specification of particular actions. These may seem to represent additional costs but could form part of an integrated maintenance strategy (e.g. active monitoring of corrosion inhibitor effectiveness post-repair);
- Rank project for comparison with other projects;.
- Apply repair technique(s).

The system recognises that remedial treatments should be considered as part of an overall maintenance strategy rather than as a single action. Also, unless the structure is nearing the end of its useful life, the maintenance intervention adopted will have implications for future maintenance. It is also recognised that often a choice must be made between an initially cheaper but less durable option against an initially more expensive but more durable alternative. It is usual to take this into account by considering the whole life cost of a particular maintenance strategy.

The choice of a particular option will depend on the cause of the deterioration, the current condition of the bridge, the consequences of further deterioration, the remaining life required for the bridge, and available funding, particularly with respect to competing demands for maintenance of other structures. The use of innovative techniques, such as corrosion inhibitors, is likely to involve additional effort. This could take the form of a detailed assessment of the potential technique in relation to the specific repair need and a documented justification of its recommendation. It may also involve feasibility studies prior to a full scale application and monitoring the success of the technique. If there are a number of similar structures currently needing, or likely to need maintenance, it may be realistic to use a small number as a test bed for an innovative technique. Results from this trial set can then be applied to the rest as appropriate.

The principles outlined in Figure 1.6 form the context for the appropriate use of corrosion inhibitors as outlined in the guidance on the use and specification of inhibitors in Section 2 and 3 of this report. The specifier who is considering a corrosion inhibitor based repair strategy is encouraged to refer to SAMARIS Report D31 for a full presentation of the principles summarised in this Section.

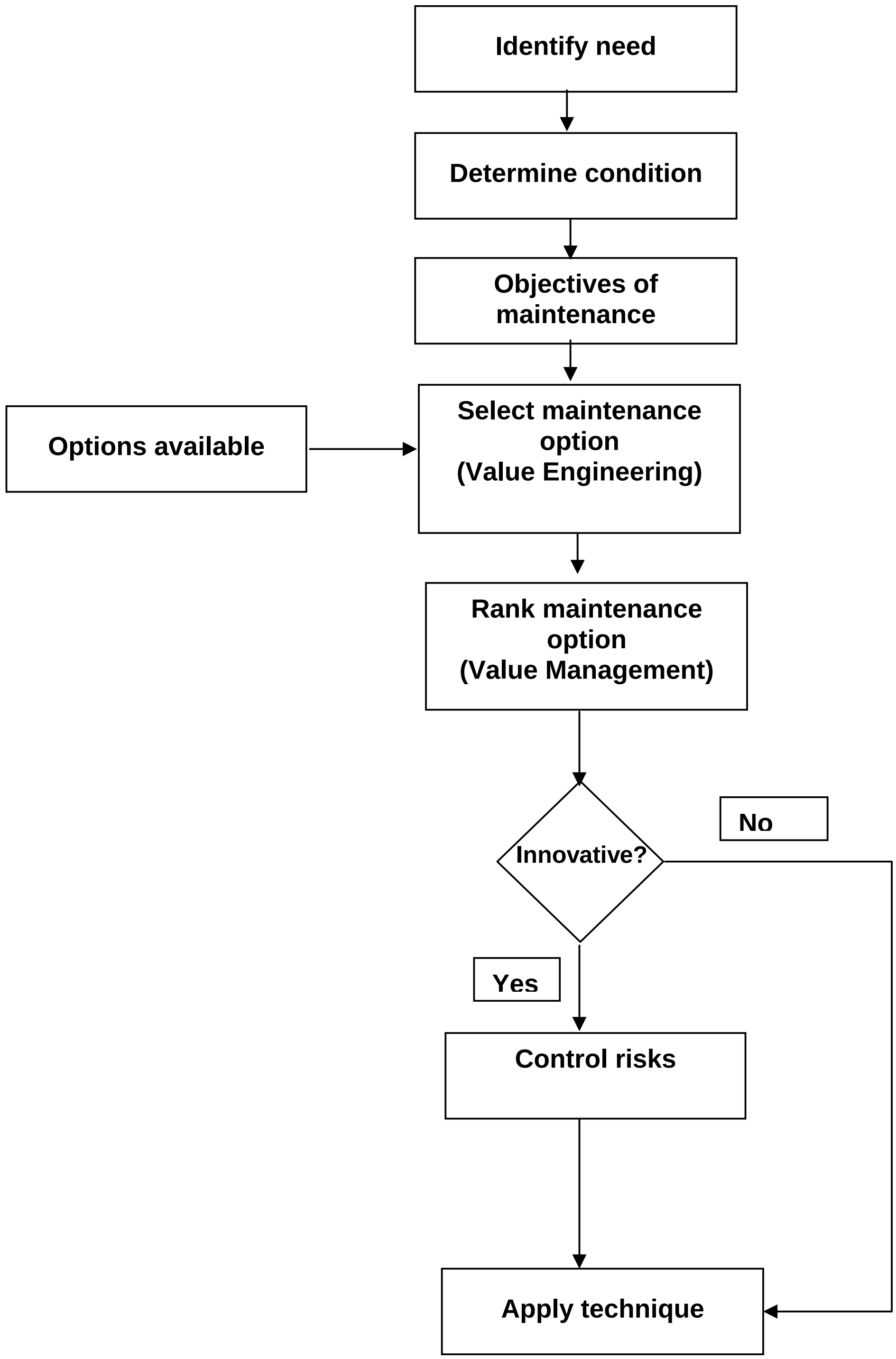


Figure 1.6: Flow chart illustrating proposed general principles of a structured engineering judgement maintenance strategy, including innovative techniques (from SAMARIS Report D31)

2. GUIDANCE ON APPROPRIATE USE OF INHIBITORS

2.1 Initial assessment

2.1.1 Fundamentals

Having identified the need and determined the objectives of a maintenance intervention the possible use of corrosion inhibitors can be included in the initial consideration of options. The initial assessment of this option should take account of the condition of the structure and the environment to which it is exposed. This will determine:

- Whether corrosion inhibitors merit consideration as a viable option alone;
- Whether corrosion inhibitors merit consideration as a viable option in tandem with other techniques, such as protective coating;
- Whether the constraints that exist (e.g. corroded condition of the reinforcement or exposure conditions) preclude consideration of inhibitors.

In making this initial assessment of feasibility the specifier should be mindful of the mechanism of the surface-applied inhibitor. It is required to penetrate through the cover concrete such that it reaches the reinforcement in sufficient concentration in a reasonable time period after application. The concentration that builds up at the reinforcement must be adequate relative to any chloride presence, both at the time of repair and in subsequent years. The inhibitor must be capable of forming an effective monomolecular layer on the reinforcement for the duration of the planned period until next maintenance intervention. Failure to satisfy these conditions will prevent its effective use.

2.1.2 Environmental considerations

The inhibitor must be capable of absorption by the concrete and subsequent diffusion through the cover to the reinforcement, irrespective of orientation. This could be impeded by environments with extremes of temperature. At very low temperatures the physical nature of the yet-to-be-applied material may change (e.g. crystallisation) whereas at very high temperatures a volatile material may preferentially evaporate from the surface layers rather than diffuse into the concrete. Manufacturer's recommendations must be adhered to. Indicative extremes of temperature are indicated in Table 2.1. Preliminary advice should be sought from the manufacturers of materials being considered if sustained extreme environmental conditions are considered to be a potential drawback in an otherwise favourable situation.

Table 2.1: Preliminary consideration of environmental suitability

Environment	Indicative Temperature	Potential Consequence
Sustained low temperatures	≤ -5°C	Alteration in the physical nature of the inhibitor with implications for its mobility in concrete. Application to be carried out at above +5°C to allow proper penetration. The temperature limit of –5°C is only applicable for the storage condition of the material. – consult manufacturers for preliminary advice.
Frequent high temperatures	≥ 40°C	Potential loss of volatile material to the atmosphere in preference to migration through concrete – coating the concrete surface may be an option to reduce evaporation loss. Consult manufacturers for preliminary advice.

2.1.3 Moisture state of concrete

Absorption of the inhibitor by the concrete surface layers is a significant first step in getting a sufficient concentration taken up to act as a driving force in the diffusion process. Absorption and diffusion characteristics are critically dependent on the moisture state of the concrete. Concrete that is saturated will inhibit the process. Another factor to be considered is washout of inhibitor. Concrete that is cyclically wetted may not be able to sustain an effective concentration of inhibitor during the migration process. Such environments would typically include tidal exposure. Indicative advice is presented in Table 2.2. Preliminary advice should be sought from the manufacturers of materials being considered if in doubt.

Table 2.2: Preliminary consideration of moisture state of concrete

Moisture State	Indicative Example	Possible Consequence
Permanently saturated	Elements of highway structures predominantly below the water level of a lake	Inhibitor take up by absorption would be low and subsequent penetration would not be assisted by capillary action and would be very slow. However, note that corrosion would be low in these areas if oxygen access is equally restricted.
Frequent and regular wetting cycles	Elements of coastal highway structures within the tidal zone	Potential washout of inhibitor right after application not leaving enough time for correct penetration, leading to inadequate concentration at the reinforcement.

2.1.4 Chloride level within the concrete

The concentration of inhibitor that diffuses to form a reservoir at the reinforcement must be adequate relative to any chloride presence, both at the time of the repair and in subsequent years. This cannot be over-emphasised. The concentration of inhibitor required to form a mono-molecular protective layer and to displace chloride ions from the reinforcement surface is extremely small. Displacement of chloride ions must also be considered: there may be a competitive surface adsorption reaction between inhibitors and chloride ions. A critical consideration is the relative inhibitor to chloride concentration, both at the time of application and in the subsequent years of expected satisfactory service life. Some degree of conservatism must therefore be applied in pursuing the corrosion inhibitor option at the initial assessment phase. Generally it may be expected that:

a) inhibitors will be most effective if applied before significant build up of chloride concentration at the reinforcement

and

b) additional measures to limit further chloride ingress are recommended in chloride-rich environments.

Preliminary advice should be sought from the manufacturers of materials being considered - a very significant consideration is the relative inhibitor to chloride concentration. Thus long-term effectiveness will be critically dependent on the relative inhibitor to chloride concentration, at any given time. This will be a function of material properties and exposure conditions. On the one hand, the ratio will depend on the inhibitor's ability to penetrate the cover concrete and be retained in the zone of reinforcement. On the other hand it will be a function of the exposure to chlorides and the material resistance to chloride ingress. By way of preliminary guidance, considerations for the desk study phase are presented as a guide in Table 2.3. It may be noted that a moderate chloride level, qualitatively classified in this context as being less than 1% chloride, by weight of cement, at the level of the reinforcement, is a potentially significant level in ranking the inhibitor-based repair option. The inhibitor-based option is of greater interest at the preliminary review stage if chloride levels are low (and reinforcement is not severely corroded) – at high chloride levels success is not assured. Very high chloride levels, qualitatively classified in this context as being in excess of 2%, are likely to be too high for the inhibitor to be effective at typically recommended dosages. This is further supported by the findings of Mackechnie et al (2004).

It may be a case in certain instances of high chloride level that higher dosages of inhibitor on the surface may lead to adequate inhibitor/chloride concentration ratios at the reinforcement. This might be valid in particular if the stage of corrosion is not yet too advanced. Morlidge (2005) has shown that a penetrating corrosion inhibitor, applied in accordance with the inhibitor manufacturer's recommendations but at a higher consumption than typically recommended to reinforced concrete specimens prior to corrosion initiation by ingressing chloride ions, has been able to delay significantly the onset of corrosion even when the chloride content at the reinforcement was in excess of 5% at the end of the test period. -.Such an approach however introduces more uncertainties, given the current state-of-the-art. This requires further consideration of control of risk – results from preview studies (Section 2.3) may provide supporting evidence but one must be mindful of potentially pushing the technique beyond its effective window. It is worth bearing in mind that a higher dosage represents a diminishing return – although it improves the inhibitor/chloride concentration ratio and increases the reservoir of inhibitor in the concrete it does not increase the protective layer on the reinforcement.

Table 2.3: Preliminary consideration of chloride level at the reinforcement

Chloride State	Indicative Free Chloride Ion at Level at Reinforcement	Possible Consequence
Low	≤ 0.5 % Chloride ion by mass of cement	Corrosion inhibitor potentially viable as a preventive maintenance strategy before any significant active corrosion takes place.
Moderate	≤ 1 % Chloride ion by mass of cement	Corrosion inhibitor may be effective if a satisfactory inhibitor to chloride ion concentration ratio is achieved in the particular circumstances of the project. Protective measures to prevent further chloride build up are recommended in chloride-rich environments.
High	1 – 2 % Chloride ion by mass of cement	Corrosion inhibitor dosage level may have to be increased beyond typical manufacturer's recommendation <u>and</u> additional protective measures required. May take the technique beyond its recommended effectiveness window, introducing higher risk.
Very high	> 2 % Chloride ion by mass of cement	Corrosion inhibitor unlikely to be a successful component of the repair strategy.

A related consideration in chloride-rich environments is of course the state of the reinforcement at time of repair. The surface is more likely to be heavily corroded in high chloride level environments leading to more onerous requirements for sustained inhibitor effectiveness. This is considered further in Section 2.1.6. Consideration at initial assessment stage may need to specifically take account of chloride level data in combination with data on corrosion activity, such as a potential survey.

2.1.5 Carbonated concrete

Carbonation levels in highway structures tend to be low due to the exposure conditions. Hence there is more attention paid in this report to chloride-induced corrosion. Good results with inhibitors have been reported in carbonated concrete. For example Bavarian and Reiner (1994) found adequate amounts of the penetrating corrosion inhibitor at the level of the reinforcement in studies up to 10 months after application in specimens treated with the inhibitor before and after carbonation. The corrosion rates of the treated specimens, both pre- and post-carbonated, showed much lower values of corrosion rates in comparison to the control samples. Mackechnie et al (2004) provide further evidence of successful use of inhibitors in carbonated concrete but caution that carbonation-induced corrosion may be indicative of fairly dry, permeable concrete. On one hand such concretes allow easy penetration of the inhibitor but on the other hand they may present a challenge if the exposure conditions change and water or contaminants easily permeate and reduce the effectiveness of the adsorbed layer on the reinforcement and hence reduce the required satisfactory service life of the treated structure. In such specific cases an additional protective measure in the form of a suitable coating may be required to seal the surface. Once again it should be noted that the earlier the intervention the better, from the viewpoint of the state of the reinforcement at time of treatment with inhibitor. The advice is summarised in Table 2.4.

Table 2.4: Preliminary consideration of treatment of carbonated concrete

Carbonation State	Concrete Permeability	Possible Consequence
Cover fully carbonated	Moderate	Inhibitor potentially effective.
	High	Inhibitor potentially effective initially but reservoir may not be retained in concrete reducing effectiveness over time. Consider additional measures such as a suitable coating.

2.1.6 Corroded state of reinforcement

The state of the reinforcement at time of repair will have a very significant bearing on the likelihood of corrosion inhibitors being effective. The more corroded the surface the greater the difficulty for the inhibitor in forming a uniformly effective mono-molecular protective layer. If the layer cannot be fully formed the exposed sections may corrode locally at a high rate. The layer may naturally breakdown in spots over time but will be reinstated by the reservoir of inhibitor in the concrete. Obviously the inhibitor-based repair will be most effective if the reinforcement is not heavily corroded and the demands on the reservoir are kept to manageable levels. A qualitative assessment of the likely situation is presented in Table 2.5 using Millard's (1992) qualitative assessment of corrosion rates in reinforced concrete structures.

Table 2.5: Preliminary consideration of the corroded state of reinforcement

Existing Corrosion	Indicative Corrosion Rate* over a sustained	Possible Consequence

Rate	period	
Low to Moderate	< 5 µm/year	Best scenario possible with inhibitor used as part of a proactive preventive maintenance strategy.
Moderate to High	5 – 10 µm/year	State of reinforcement is potentially suitable for consideration of corrosion inhibitor treatment.
High	10 - 100 µm/year	State of reinforcement will depend on where in this range the corrosion rate lies. Effectiveness of the inhibitor will be correspondingly influenced with higher risk as corrosion rate increases in the range. Corrosion monitoring is then recommended in case of higher corrosion rates.
Very High	> 100 µm/year	Reinforcement may be heavily corroded. If this is the case, corrosion inhibitor is unlikely to be a successful component of the repair strategy.

Notes*: Values in the table may also be expressed in the the approximate range < 0.5 $\mu A/cm^2$ to > 10 $\mu A/cm^2$.

Values measured in practice can be very variable and influenced by localised corrosion.

2.1.7 Ecological constraints

The initial assessment of using corrosion inhibitors has to take account of environmental or health and safety constraints. For example rehabilitation of bridges over waterways may have to take account of chemical containment issues; water impounded for drinking water supply may have significant constraints associated with it.

The advice of the manufacturers of proposed products should be sought at an early stage if these issues are flagged.

2.2 Objective criteria

The flow chart in 1.6 illustrated the proposed general principles of a structured engineering judgement maintenance strategy, as proposed in SAMARIS Report D31. It highlights the need for the objectives of the maintenance intervention to be clearly set out. Following from this, in the case of certain structures, it may be appropriate to frame performance-based specifications to ensure achievement of the objectives. Even if this specification approach is not used it is important to assess by objective criteria whether or not the overall objectives of the repair strategy are likely to be attained.

The incorporation of corrosion inhibitors in a repair strategy involves a strategy whereby one or more of the following objectives will be required:

a) defer the initial time to depassivation,
   and/or
b) reduce (or prevent increase in) the existing rates of corrosion once corrosion is propagated,
   and/or
c) retard incipient action (ring anode).

The performance criteria set out in Table 2.6 give guidance on criteria for assessing the effectiveness of an inhibitor repair strategy. These criteria could be used as part of the preview study (Section 2.3) and post-repair management of service life (Section 2.5). If used as part of a preview study the measurements should extend over a realistic period to allow a true capture of the effect of the inhibitor and sufficient corrosion rate measurements to ensure that they are representative and do not only reflect extreme values. Ideally the measurements would extend over a year to reflect seasonal variations in corrosion activity.

Table 2.6: Example of performance criteria for assessment of corrosion inhibitor effectiveness in respect of the repair objective

Objective	Indicative Performance Criteria
Defer the initial time to depassivation	< 5 μm/year loss of steel (or < 0.5 μA/cm^2)
Reduce the rate of corrosion	65% reduction from pre-treated levels over a defined time period or < 5 μm/year loss of steel (or < 0.5 μA/cm^2)
Retard incipient action (ring anode)	No increase in loss of steel prefer Decrease to < 5 μm/year loss of steel (or < 0.5 μA/cm^2)

2.3 Preview study

2.3.1 Outline requirements

In the context of the specifier's requirement to balance available resources against the satisfactory control of risk, the initial assessment of repair options, referred to in Section 2.1, may either rule out corrosion inhibitor-based repair strategies or may indicate that conditions exist that could prove favourable for their use. It may be argued that with any repair strategy to reduce corrosion activity, verification of performance is the only way of ensuring that the expectations of the specifier and client are met. Given the multitude of factors that can influence corrosion activity in structures treated with inhibitor, verification of expectations has special significance. It is strongly recommended therefore that a preview study be conducted and, indeed, that post-repair management of service life (Section 2.5) would include monitoring. A preview study can verify that, in the particular circumstances of a project, the inhibitor penetration is satisfactory and that its effect is adequate and potentially sustainable for the period intended. An example of a preview study is illustrated in Figure 2.1 and described in SAMARIS Report D21.

Figure 2.1: Preliminary measurements in a preview study on the crown of an arch highway structure (from SAMARIS Report D21)

The preview area, or areas, should be representative of the structural element being assessed for delay of depassivation, corrosion rate reduction and/or retardation of incipient action and must be selected in tandem with suitably comparable untreated control areas.

A specification should be drawn up for the preview study based on the manufacturer's guide to specifiers for a preview study, if available, or based on recommendations for the full scale rehabilitation.

The methodology should follow the requirements of the manufacturer's guide to specifiers in respect of handling, environmental conditions at time of application, surface preparation, mixing and application. Aspects of this are further elaborated in Section 2.4. In addition the contractor should conduct qualification tests on an area of approximately 1 m^2 to demonstrate adequate standards of surface preparation and application procedure.

2.3.2 Verification of inhibitor penetration

The preview study should demonstrate the ability of the corrosion inhibitor to penetrate through the concrete such that an adequate concentration of inhibitor will build up at the reinforcement. The penetration is influenced by the permeability of the concrete, the moisture state and the ambient conditions. This can be verified on site in the case of amino alcohol based inhibitors by the contractor using an on-site test with the assistance of the manufacturer. The depth profile concentration of inhibitor can be estimated using a qualitative test.

Quantitative testing is possible but is considerably more expensive and could only be conducted off site using specialist analytical methods. It could be conducted by independent well equipped laboratory with assistance of the manufacturers because some knowledge of material composition is required. It should be borne in mind that the purpose of the preview test is to verify that the combination of concrete quality and environmental conditions permit satisfactory penetration rates. Qualitative tests are adequate for this purpose.

The concrete should be profile tested for inhibitor presence after a suitable period of penetration. The minimum period between application and test should be approximately one month.

2.3.3 Verification of inhibitor effectiveness

The extent and duration of the monitoring should be adequate to detect stable trends. Badly corroded reinforcement with a high rate of corrosion pre-treatment may initially show a dramatic reduction in corrosion rate. This however might not be sustainable if the monomolecular layer cannot be maintained on a heavily corroded surface. On the other hand steel that is corroding at a much lower rate, but which is deemed to require remedial action, may not exhibit a significant reduction after treatment but the new rate may be perfectly adequate in the context of the repair strategy. Percentage efficiencies are important but the starting (base) condition requires definition: expectations can be formulated from that point for post-application effectiveness. For example halving the corrosion rate could more than double the satisfactory service life. This highlights the usefulness of performance criteria, such as that presented in Table 2.6.

The site measurements must cover an adequate duration to detect a stable picture of inhibitor effect but must also be numerous enough to allow a reliable trend to be detected despite inevitable temporal changes in readings.

The monitored characteristics of the corrosion activity must take account of the mechanism of action of the inhibitor. Classification of inhibitors is typically based on the action of the inhibitor – anodic, cathodic or ambiodic (‘mixed’). The amino-alcohol inhibitors central to the SAMARIS project research were ambiodic. Their effect on the characteristics of a corrosion cell is illustrated in Figure 5 (b). This schematic Evans Diagram depicts how corrosion current could reduce by changes in the anodic and cathodic activity but that the electrode potential could remain at its original level. Thus half-cell potential mapping alone would be inadequate to detect the effectiveness of the inhibitor but can be used to appreciate the thermodynamic conditions that are being exerted on the steel surface. Alternative monitoring methods, such as those based on linear polarisation resistance would be required to specifically define reductions due to inhibition.

2.4 Full scale maintenance intervention

2.4.1 Finalising the repair strategy

Once the preview study is complete an evaluation of the results will allow a clear assessment to be made of the appropriateness of a repair strategy based on corrosion inhibitors. Key issues confirmed or not in the study will have been the ability of the inhibitor to penetrate in a timely manner in the combined circumstances of the concrete quality and environment; the effectiveness of the inhibitor in creating the conditions where corrosion activity is trending to levels that are appropriate in the context of the repair objectives; and perhaps a better assessment of whether additional protective measures are necessary. Evaluation of the preview findings against the performance criteria may indicate a clear picture one way or another. There will of course be occasions when further consideration must be given to aspects of the findings. This may bring the final planning back into the 'control of risk' phase where compromises may have to be made between competing demands, based on engineering judgement.

Once the decisions on the repair strategy are made the specification for the full scale intervention may be finalised.

2.4.2 Specification

General

The specification for the final repair option should take full account of the corrosion inhibitor manufacturer's guidelines for specifiers, product data sheets and materials safety data sheets valid in the place of use. Local health, safety and ecological regulations may also need to be taken into account.

Full use should be made of quality assurance procedures in the chain of activities related to execution of the repair strategy.

Storage and handling

The manufacturer can advise on requirements for maintaining the materials in good condition and action to take if the materials are subjected to extremes of temperature prior to use.

Qualification tests

The contractor should conduct qualification tests on an area of approximately 1 m^2 to demonstrate adequate standards of surface preparation and application procedure, if this has not already been cleared for the contractor involved at the preview.

Surface Preparation

It is important that the surface be as receptive as possible to absorbing the inhibitor. Corrosion inhibitors are designed for use on sound, clean and absorbing concrete surfaces. Material that is cracked or spalling needs to be repaired before application of the inhibitor. The manufacturer will advise on specification clauses. Generally it is necessary to ensure that the surface is free of any existing coatings and surface contaminants (oil, algal growths, etc.) and that it is sound. Mechanical cleaning is generally required in the form of abrasive blast cleaning or high pressure water jetting.

Some additional consideration may need to be given to specification clauses in the case of aesthetic finishes so that these are not inadvertently damaged by inappropriate cleaning methods prior to inhibitor application.

Application

The manufacturer's requirements must be followed. Advice will be available on dosage rates, the site conditions at time of application and the methodology to be used. Dosage rates of 500 g/m^2 and not less than 300 g/m^2 in case of very dense concrete are typical. The rates recommended by the manufacturers are based on the need to provide a driving force for the initial effect of the inhibitor and to build up a reservoir of material around the reinforcement which will be available during the intended lifetime of the repair. The actual effectiveness will be influenced by free chloride ion concentration - an adequate inhibitor to chloride concentration ratio must be achieved, depending on the particular circumstances of the project.

In general it may be noted that the inhibitor shows the best initial absorption on dry surfaces, whereas required subsequent coats of the inhibitor are best applied to semi-dry surfaces. In addition the dosage prescribed by the manufacturer will require that the inhibitor be applied in a number of coats (e.g. 2 or 3). Each must be absorbed (matt dry surface) before application of the next coat. Drying times can vary from less than an hour to several hours depending on concrete porosity and ambient conditions. Therefore weather conditions at time of application should be as favourable as possible. Rain, frost and extremes of temperature are to be avoided. This should be clear in the specification. The method of application should be clear – for example spray or roller may be permitted whereas ponding of horizontal surfaces may not.

Additional measures (if required)

Corrosion inhibitors can have a useful role to play in the maintenance of aesthetic concrete, delaying the onset of spalling that can negate the initial significant investment in these surfaces. It would be normal to wash down such surfaces after inhibitor application, however it is also important to guard against washout of inhibitor during this process. The manufacturer can advise on the restriction regarding elapsed time after inhibitor application, maximum water pressure and temperature. As a guide the minimum elapsed period after application may be of the order of 2 days.

Another issue that may arise is the protection of certain building materials from spillages or contact with spray of corrosion inhibitor. This is more likely to be an issue on repairs to buildings rather than highway structures but the specifier should be mindful of any manufacturer's recommendations in this regard.

If the addition of a protective coating and/or reprofiling is to be carried out after the application of inhibitor the manufacturer's advice should be followed on appropriate specification clauses for cleaning down the surface without loss of inhibitor.

Consideration may be given to quality control procedures for detection of inhibitor penetration during the full scale repair, where this is deemed appropriate.

2.5 Post-repair management of service life

The best way to manage the service life of any repaired structure is to monitor its performance. Comprehensive corrosion monitoring involves collecting data from tests using equipment such as electrical resistance probes or linear polarisation techniques, with embedded (Figure 2.2) or surface mounted probes (Figure 2.3). How long an inhibitor remains effective will depend upon the overall corrosion management strategy. Hence the monitoring of corrosion performance plays a huge role in determining the effectiveness of corrosion inhibitors. This point is not unique to repair strategies based on corrosion inhibitors but it is emphasised in this context as an example of cost-effective good practice.

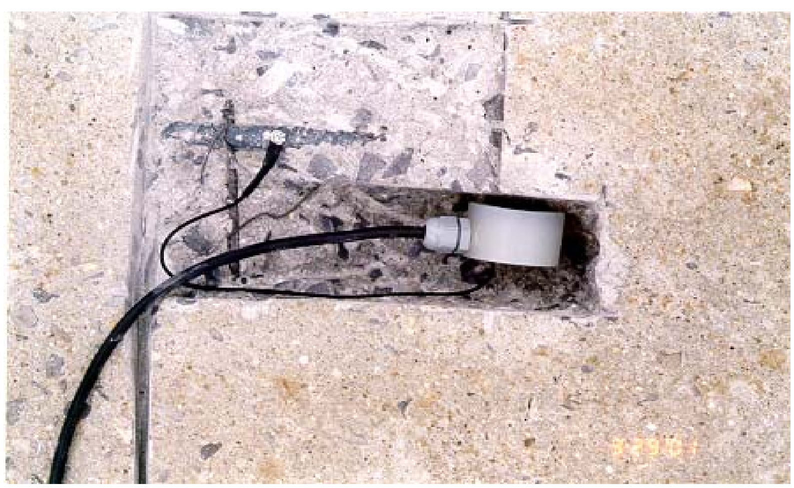


Figure 2.2: Example of an embedded probe to monitor ongoing performance

Figure 2.3: Example of a surface monitoring

A note of caution must be sounded on monitoring. Care should be taken with some surface monitoring methods that rely on perturbation currents or pulses that may create a harsh regime for the monomolecular film to survive in. Experienced operators are essential to the achievement of sound data. Transparency of monitoring parameters will allow analysis of data that show apparent poor performance of the inhibitor to truly attribute the effect on the treatment and not the monitoring method. This is also important for embedded monitoring systems but can be found more often with surface techniques.

The concept of active management of rehabilitation is illustrated in Figure 2.4. This shows how the active monitoring of the investment in the initial inhibitor application repair strategy may be used to maintain satisfactory service life in a planned way rather than only reacting to future signs of significant deterioration. The corrosion inhibitor repair strategy is based on the integrity of the monomolecular layer thickness being available to maintain the integrity of the protection. Inevitably a time will come, perhaps over a decade later, when the effectiveness will diminish if chlorides and water are allowed to diffuse through the concrete. Rather than allowing deterioration to then accelerate, a managed system will flag that renewal of inhibitor is required. This should be a cost effective solution to the life cycle management of the structure.

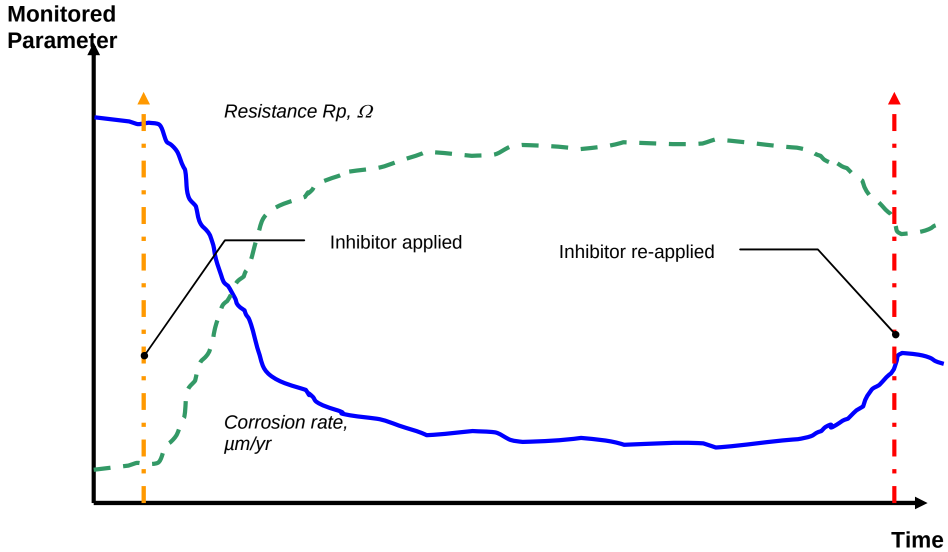


Figure 2.4: Example of a monitored repair strategy based on corrosion inhibitors

Monitoring of each and every structure may not always be necessary. It may be a case that a 'family' of similar structures with similar problems might be identifiable, for example on a stretch of motorway. In such cases it may be adequate, and more cost effective, to limit the active monitoring to a subset of the family of structures, provided that these are representative of the infrastructure in question. These can be assimilated into a single management system that will allow remote access to data and reporting. Monitoring is only useful where the data can be seen to have integrity and the data and reporting is used as the basis of good management practices.

3. SUMMARY GUIDANCE FOR SPECIFIERS

The appropriate use of corrosion inhibitors involves the following steps in the context of the summary flowchart in Figure 3.1.

1. Use should be made of a structured approach in the decision process on an optimum repair strategy for an individual structure, and how this can be assessed against the needs of the network as a whole, while making provision for the use of innovative techniques. Such an approach is proposed in SAMARIS Report D31 and is summarised in Section 1.3 of this report.
2. In considering corrosion inhibitors as a potential component of a repair strategy it must be clear what role they are intended to play in achieving the objectives of the repair:
    a) delay the onset of corrosion and/or
    b) reduce existing rates of corrosion and/or
    c) retard incipient action
3. An initial desk study assessment of corrosion inhibitor appropriateness should be conducted taking account of issues such as:
    a) Extremes of in-service environmental conditions
    b) Degree of saturation of concrete
    c) Chloride levels
    d) Permeability characteristics of carbonated concrete
    e) Corroded state of reinforcement at time of repair
    f) Past performance
    g) Ecological constraints
4. Based on this desk study, and the specifier's requirement to balance available resources against the satisfactory control of risk, decide whether the conditions exist for an immediate decision for using the corrosion inhibitor technique; or whether an alternative technique should be used; or whether a preview of corrosion inhibitor effectiveness is recommended.
5. Definition of performance criteria to attain repair strategy objectives and against which a preview may be evaluated.
6. Draw up specification for a preview.
7. Conduct a preview study to verify that, in the particular circumstances of a project, the inhibitor migration is satisfactory (typically qualitative assessment, if available, but quantitative is also possible though it is very much more complex) and that its effect is adequate and potentially sustainable for the period intended.

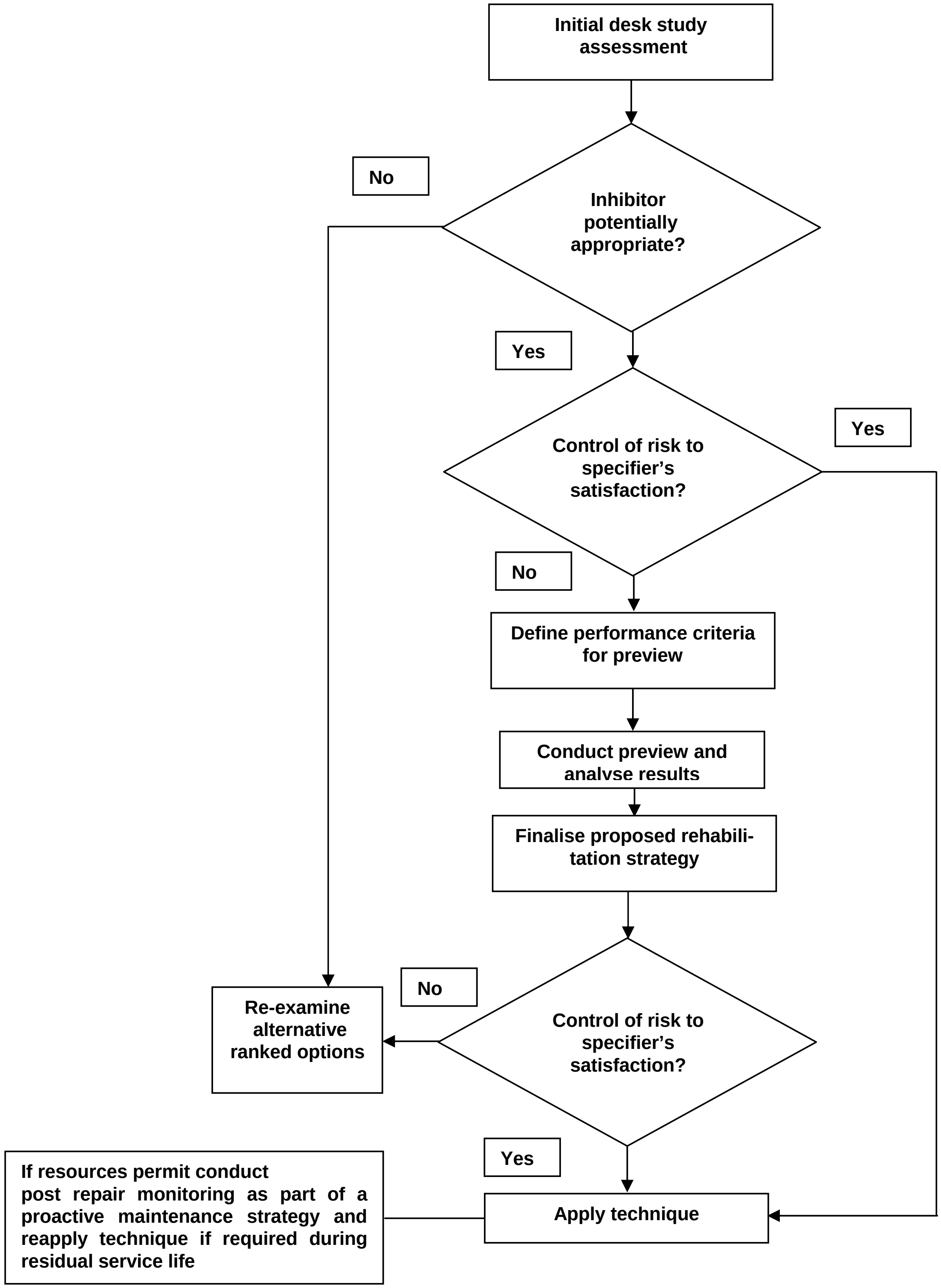


Figure 3.1: Summary flowchart of guidance for specifiers

8. Analysis of preview results and modification of final repair strategy if warranted.
9. Draw up specification for implementation of repair strategy, mindful of critically evaluating the following using sound engineering judgement:
    a) Manufacturer's guidelines to specifiers
    b) Materials Safety Data Sheet valid in the place of use
    c) Health and Safety Regulations valid in the place of use
    d) Ecological constraints particular to the project location
10. Apply technique with adequate quality control and assurance
11. Make provision for post-repair monitoring and data management reporting as an integral part of the maintenance strategy if possible
12. Reapply inhibitor when prompted by indications from post-repair monitoring (e.g. 10 to 15 years later).

REFERENCES AND SELECTED BIBLIOGRAPHY

Berke, N.S., Weil, T.G., (1994), "World wide review of corrosion inhibitors in concrete" Advances in Concrete Technology (editor: Malhotra, V.M.), CANMET, Montreal, pp. 891-914.

Broomfield, J., (1997), "The pros and cons of corrosion inhibitors", *Construction Repair*, Vol. 11, No. 4, pp. 16-17.

Broomfield, J.P., (1999), "Corrosion inhibitors for steel in concrete", *Concrete*, Vol. 33, No. 6, pp. 44-47.

COST Action 521 - Final report Part 3.3 Surface applied inhibitors, (2003).*Corrosion of steel in reinforced concrete structure*

Elsener, B., (2001), "Corrosion inhibitors for steel in concrete", European Federation of Corrosion Publication No. 35, W.S. Manney & Son, 68pp.

Elsener, B., Cigna, R., (2003), "Surface applied inhibitors in maintenance", *Corrosion of steel in reinforced concrete structures*, COST Action 521, Final Report, (Cigna, R., Andrade, C., Nurnberger, U., Polder, R., Weydert, R., Seitz, E.), pp. 148-159.

Eydelnant, A., Miksic, B., Gelner, L., (1993), "Migrating corrosion inhibitors for reinforced concrete", *ConChem Journal*, No. 2/93, pp. 38-42.

Fadayomi, J. (1997), "Corrosion inhibitors", *Concrete*, Vol. 31, No. 8, pp. 21-22.

Federal Highway Administration, (1970), "Bridge inspectors training manual 70", U.S. Department of Transportation, Bureau of Public Roads, Washington D.C.

Fedrizzi, L., Azzolini, F., Bonora, P.L., (2005), "The use of migrating corrosion inhibitors to repair motorways' concrete structures contaminated by chlorides", *Cement and Concrete Research*, Vol. 35, pp. 551-561.

Gianetti, F. (1998), "Corrosion Inhibitor (Part 1)", *Concrete Engineering International*, March, pp. 31-36.

Gonzalez, J.A., Ramirez, E., Bautista, A., (1998), "Protection of steel embedded in chloride-containing concrete by means of inhibitors", *Cement and Concrete Research*, Vol. 28, No. 4, pp. 577-589.

Heiyantuduwa, R., Beushausen, H.D., Alexander, M.G., (2003), "The effectiveness of corrosion inhibitors in concretes subjected to chloride attack and carbonation", *BFT*, Issue. 8.

Holloway, L., Nairn, K., Forsyth, M., (2004), “Concentration monitoring and performance of a migratory corrosion inhibitor in steel-reinforced concrete”, *Cement and Concrete Research*, Vol. 34, pp. 1435-1440.

International Standards Organisation, (1989), “Corrosion of metals and alloys, basic terms and definitions”, ISO 8044.

Kulash D.J, (1990), “SHRP’s Concrete and Structures Research: Goals and recent developments”., Proceedings, Strategic Highways Research Programme and Traffic Safety on two Continents, Gothenburg, Sweden, 27-29 Sept 1990, VTI Report 1990 352A, pp. 69-82.

Laamanen, P.H., Byfors, K., (1996), “Corrosion Inhibitors in Concrete: AMA (Alkanolamines) - based Inhibitors - State of Art Report”, Nordic Concrete Research, No. 19, pp. 29-40.

Mackechnie, J.R., Alexander, M.G., Heiyantuduwa, R, Rylands, T., (2004), “The Effectiveness of Organic Corrosion Inhibitors for Reinforced Concrete”, Department of Civil Engineering, University of Cape Town, Research Monograph No. 7, 32pp.

Maeder, U., (1996), “A New Class of Corrosion Inhibitors for Reinforced Concrete”. Proceedings, Third CANMET/ACI International Conference on Concrete in Marine Environment, (editor Malhotra, V.M.) St. Andrews by-the-Sea, New Brunswick, Canada, ACI SP163-10, pp. 215-232.

Maeder, U., Wombacher, F., Marazzani, B., (2005), “Surface-applied corrosion inhibitors for concrete repair strategies”, Proceedings, 16th International Corrosion Congress, Beijing, 19-24 September 2005.

Malik, A.U., Andijani, I., Al-Moaili, F., Ozair, G., (2004), “Studies on the performance of migratory corrosion inhibitors in protection of rebar concrete in Gulf seawater environment”, *Cement & Concrete Composites*, Vol.26, pp. 235-242.

Millard, S.G. (1992), “Corrosion rate measurement of in situ reinforced concrete structures”, Proceedings, Institution of Civil Engineers, Structures and Buildings, No. 92, pp. 389-396.

Montani, R., (1997), “Concrete repair and protection with corrosion inhibitor”, Water Engineering and Management, November, pp. 16-21.

Monticelli, C., Frignani, A., Trabanelli, G., (2000), “A study on corrosion inhibitors for concrete application”, *Cement and Concrete Research*, Vol. 30, pp. 635-642.

Morlidge, J.R., (2005), "The use of surface applied FerroGard 903 corrosion inhibitor to delay the onset of chloride induced corrosion in hardened concrete", BRE Client Report No. 224-346,. 35 pp.

Ngala, V.T., Page, C.L., Page, M.M., (2002), “Corrosion inhibitor systems for remedial treatment of reinforced concrete. Part 1: calcium nitrite”, *Corrosion Science*, Vol.44, pp. 2073-2087.

Ngala, V.T., Page, C.L., Page, M.M., (2003), "Corrosion inhibitor systems for remedial treatment of reinforced concrete. Part 2: sodium monofluorophosphate", *Corrosion Science*, Vol. 45, pp. 1523-1537.

Nmai, C.K., (2004), "Multi-functional organic corrosion inhibitor", *Cement & Concrete Composites*, Vol. 26, pp. 199-207.

Nmai, C.K., Farrington, S.A., Bobrowski, G.S., (1992), "Organic-Based Corrosion-Inhibiting Admixture for Reinforced Concrete", *Concrete International*, Vol. 14, No. 4, pp. 45-51.

Page, C.L., Ngala, V.T., Page, M.M., (2000), "Corrosion inhibitors in concrete repair systems", *Magazine of Concrete Research*, Vol. 52, No. 1, pp. 25-37.

Soeda, K., Ichimura, T., (2003), "Present state of corrosion inhibitors in Japan", *Cement & Concrete Composites*, Vol. 25, pp. 117-122.

Tritthard J., (2003), "Transport of a surface-applied corrosion inhibitor in cement paste and concrete", *Cement and Concrete Research*, Vol.33, No. 6, pp. 829-834.

Vaysburd, A.M., Emmons, P.H., (2004), "Corrosion inhibitors and other protective systems in concrete repair: concepts or misconcepts", *Cement & Concrete Composites*, Vol. 26, pp. 255-263.

Wombacher, F., Maeder, U., Marazzani, B., (2004), "Amino alcohol based mixed corrosion inhibitors", *Cement & Concrete Composites*, Vol. 26, pp. 209-216.

Figures

Tables