

**Deterioration of reinforced concrete
in a marine environment: repair costs
and maintenance strategies**

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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted in partial fulfilment for the Degree of Master of Science in Applied Science at the University of Cape Town. It has not been submitted before for any degree or examination at any other University.

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Abstract

This dissertation comprises an investigation into the rate at which reinforced concrete structures deteriorate in the Cape Peninsula due to reinforcement corrosion, the reasons for this deterioration, and the accompanying repair costs. The costing of repair work is calculated per m² of reinforced concrete and is based on quoted labour rates and material rates of repair materials supplied by four major suppliers in the Western Cape. Formulas are included which enable a person using the data listed in tables and figures to calculate what repair costs will be in future, and also enable the calculation of monthly/annual deposit amounts in order to save sufficient money for future maintenance at a specified date. Life cycle costing and decision models for the maintenance of concrete structures are discussed and guidelines for the establishment of optimal maintenance cycles are included. Based on the results of the life cycle costing exercise the importance of planned preventative maintenance is highlighted. Finally, locally and internationally available maintenance management computer systems are reviewed.

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Introduction

Although reinforced concrete structures can be expected to show good durability for years, certain structures in the Cape Peninsula are currently experiencing major problems with deterioration of reinforced concrete caused primarily by reinforcement corrosion.

The main causes of this problem are identified as a lack of understanding of the corrosion mechanisms by the engineer at the design stage, poor workmanship at the construction stage and the lack of knowledge and application of maintenance management strategies by owners of the structures⁽¹⁾. This combined with the external environment in the Cape Peninsula (i.e. high percentages of airborne chlorides) have resulted in inadequate specifications for durability of structures in this high risk exposure zone. (A good example of a structure that has deteriorated severely is the Muizenberg promenade where cover was specified to be 20 mm⁽²⁾.)

The importance of recognising the critical role played by the environment in the deterioration of concrete is outlined in brief in chapter 1. In chapter 2 a guideline to predict the service life of reinforced concrete (r.c.) elements in the Cape Peninsula is presented which can not only be used to see how r.c. structures will deteriorate with time but can also be used to determine the remaining life i.e. time before 'replace only' is the sole repair solution.

Options for repairing deteriorated structures are discussed in chapter 3, as well as the tools presently available and under development to diagnose corrosion problems in existing structures. These various repair methods and materials are then costed. The costing is based on the cost of materials and labour required to repair 1m² of r.c. in each of the deterioration categories. A guideline is also included which can be used to diagnose chloride and CO₂ contaminated structures.

In chapter 4 formulas are included which enable owners of structures to establish the cost of repairs at some point in time in the future, and how much they should save annually/monthly in a deposit account in order to have sufficient funds to

carry out repairs at a later stage.

Chapter 5 is entirely devoted to how decision models have come about, how they can be used on r.c. structures to establish when is the best time to effect repairs on a deteriorating structure and how life cycle costing applies to r.c. structures. An example has been given to illustrate how life cycle costing can be applied to the data collected in order to determine the most economic point in the deterioration cycle to initiate maintenance.

The last chapter contains the findings from an investigation into the field of computerized maintenance management systems and highlights the importance of planned preventative maintenance and the necessity of reliable construction and maintenance data. Also included is a list of computer packages currently available in South Africa and abroad (ascertained from the available literature) including a brief summary of the functions and features of each system.

Life and deterioration of reinforced concrete

Structures start to deteriorate at varying rates even during the construction period, and thereafter, due to exposure to the environment.

Steel is prevented from corroding in sound concrete by the formation of a thin layer of gamma ferric oxide on the surface of the steel. This layer will give protection, provided the pH of the concrete is at least 12 and the chloride-ion concentration is sufficiently low. Environmental processes may cause salts, oxygen, moisture or carbon dioxide to penetrate the concrete cover and eventually lead to corrosion of embedded steel reinforcement by depassivation of the gamma ferric oxide layer. As steel corrodes it expands in volume causing cracking, rust staining and spalling of the concrete cover. From the results in the next chapter it is clear that the problem occurs in all forms of concrete structures especially in coastal areas like the peninsula. The two most significant penetration processes are the following:

(1) ***Carbonation***

Initially concrete contains alkalis e.g. calcium hydroxide (CaOH_2) in the pore solution which ensures that the pH is about 12,5 or higher. Carbonation is caused by atmospheric carbon dioxide (CO_2) diffusing into concrete and reacting with CaOH_2 to form carbonate. This formation of calcium carbonate reduces the concrete alkalinity with time, and when the pH value around the steel bar falls below about 10 corrosion can start⁽³⁾.

(2) ***Chloride-ion ingress***

Chloride-ions diffusing into concrete break down the passivating layer on the steel when they exceed a certain threshold value of

concentration, and corrosion proceeds by means of an electrolytic process. Chloride salts may be present in concrete because calcium chloride was added at the time of construction as an accelerating admixture or because of impurities in the aggregates and/or mixing water, or because of ingress from seawater or spray in the case of marine structures. The chlorides form a strong electrolyte with the moisture contained in the pores of the concrete, reducing the resistivity thereof and accelerating the flow of electrons from the anodic area on the reinforcement to the cathodic area, thus forming sites of pitting corrosion attack. The subsequent rate of corrosion will be controlled by the level of moisture and oxygen present. In moist conditions corrosion cells are activated whilst oxygen fuels oxide formation on the steel reinforcement.

Although the freeze-thaw process and de-icing salts on highways also have a detrimental effect on concrete, these won't be discussed in detail in this dissertation because these processes of environmental attack are not really applicable to South African conditions.

The problem is to quantify the above two effects and predict how they will affect the life of a structure.

Due to the fact that different structures are designed to different codes and specifications and for different purposes, they have different design lives. Buildings for example are normally designed to last about 60 years and bridges some 120 years⁽⁴⁾. On the other hand, marine structures are designed to last between 30 - 60 years⁽⁴⁾. However, an extensive world-wide building boom in the sixties and seventies led to faster construction methods, less quality control, etc. and these structures are now showing signs of distress⁽⁴⁾. In addition, factors such as changes to cement chemistry, content and fineness may also have had an influence.

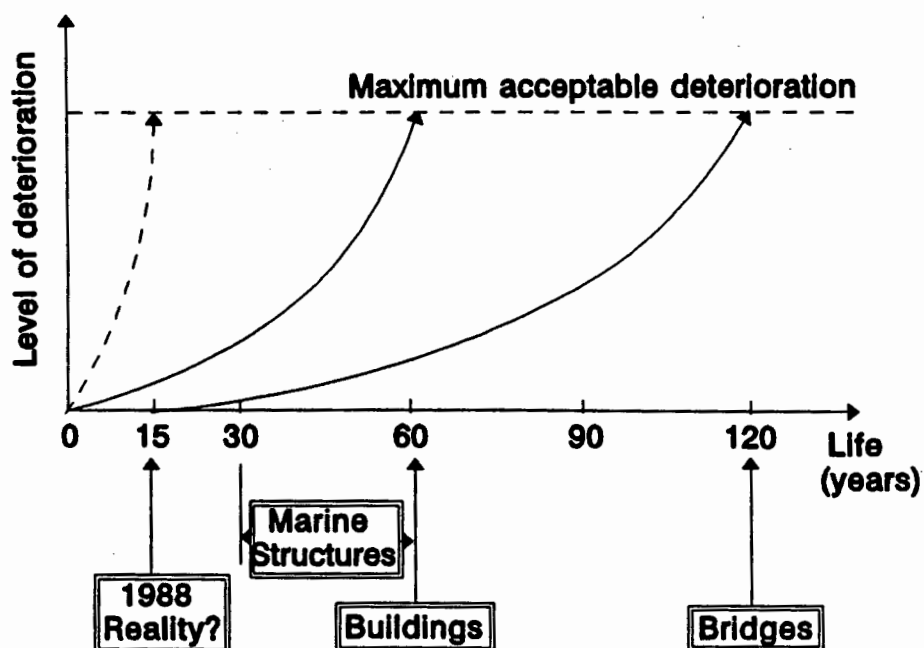


Figure 1 - Design Life for reinforced concrete structures⁽⁴⁾

From Figure 1 above it can be seen that many younger structures are showing signs of distress and are reaching a stage of maximum acceptable deterioration at an age of about 15 years. This is the reason for the fairly recent phenomenon that people are interested in mechanisms of deterioration, repair methods and costs because so many young structures are in advanced states of deterioration.

Reducing the rate of deterioration and repair

It is common knowledge that a structure should not be structurally loaded abnormally or in excess of the design load and there are certain precautions that can be taken in which this risk of failure can be reduced. Cracking resulting from intrinsic effects within the concrete is more likely to result in unserviceability, particularly in the case of water-retaining structures, than actual collapse. However, certain fundamental precautions both in the design process and during construction can minimize such intrinsic effects.

There is no cure for alkali-silica reaction once it has occurred. Repair techniques essentially involve short-term control of the situation, e.g. reductions in moisture content and temporary support and propping.

In the case of environmental attack mechanisms which pose a threat to the reinforcement, it is the concrete cover to the reinforcement which has traditionally been the prime defence. Ideally this cover concrete or covercrete should have low permeability to water, oxygen, chloride ions and water vapour. It is therefore unfortunate that the layer tends to be of poorer quality than the concrete in the heart of the member. Factors which may be beneficial in reducing penetration and thus reducing the rate of deterioration are the following:

- (i) increased depth of concrete cover;
- (ii) low water/cement ratio to minimize capillaries formed and to create a denser pore structure;
- (iii) high cement contents to provide a high level of alkalinity (note that this requirement may however conflict with those for reducing early thermal contraction and with conditions for minimizing the risk of alkali-aggregate reaction);
- (iv) efficient curing of adequate duration to assist hydration and densify the pore structure;
- (v) coatings or barrier treatments applied to the surface.

One repair method is complete reconstruction with members constructed from fresh concrete designed, placed and cured with the above factors in mind. However, it is usually more economical to consider local patching of the damaged area. The patching process may be multi-staged and the choice of material for reinstating the cover is often a difficult one. The options are cementitious, polymer-modified cementitious or epoxy resin mortars. The nature of these materials, the techniques for repair and their cost are addressed in later chapters. Of prime importance to the long-term stress characteristics of the repair is the bond to the concrete substrate. There is also a need to consider the level of mismatch between the properties of the repair material and those of the original concrete with regard to resisting structural loading, elastic, thermal and creep effects and assessing the

level of composite action between the two materials. An alternative method, particularly for protecting chloride-contaminated structures, is to use cathodic protection. This method of protection is also discussed and costed in a later section but essentially it is a small current applied to the reinforcement bars to render them passive again.

Cracking induced by environmental effects

The corrosion products of steel have an average volume up to 8 times greater than that of the original steel depending on the type of oxide, and as corrosion products form around the bar they exert high expansive forces⁽⁵⁾. These forces cause tensile stresses in the surrounding concrete and where such stresses exceed the tensile strength of the concrete it cracks⁽⁵⁾.

In this study only cracks large enough to be seen by the naked eye have been considered. This section looks only at those cracks that are induced by effects from the external environment. By investigating what causes these cracks one can modify the concrete to avoid the action that induced the crack. By following the flowchart below (*Ref. Figure 2*), one can see that the tendency of concrete to undergo environmentally induced cracking results from an interaction between the properties of the concrete and the characteristics of the environment.

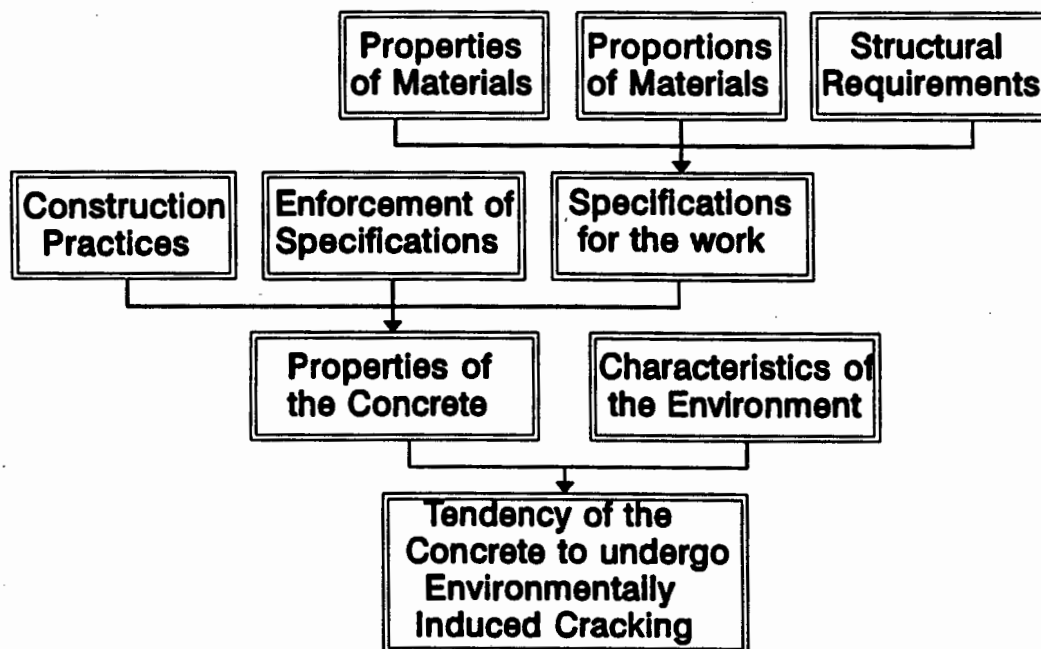


Figure 2 - Interaction between the properties of the concrete and the characteristics of the environment⁽¹⁾

There are a number of environmentally induced cracking mechanisms that have been sufficiently thoroughly studied so that not only are the mechanisms well understood but also the means of avoiding the consequences of the mechanisms are generally readily available. When cracking does occur from such mechanisms, it merely indicates failure to specify what should have been specified or failure to obtain what was specified. These mechanisms are divided into 8 categories discussed below⁽¹⁾:

- (1) **Unsound cement.** Concrete may crack due to internal expansion caused by reaction of moisture with unhydrated calcium oxide or magnesium oxide that was introduced into the concrete as a part of the cement. This will not happen if the cement used is sampled, tested, and inspected to ensure compliance with current specifications⁽⁶⁾.
- (2) **Freezing susceptibility of cement paste.** Concrete may crack due to internal expansion caused by freezing water in the capillary cavities in hardened cement paste.

- (3) **Alkali-silica reaction.** Concrete may crack due to internal expansion caused by reaction of alkalis in solution in the concrete (usually originating from the cement) with reactive silica in the aggregates. If the environment in which the concrete is to serve is moist and also includes sources of abundant alkalis, this can only be confidently avoided by not using aggregates containing deleterious amounts of ~~soluble~~ ^{reactive} silica.
- (4) **Plastic shrinkage.** Concrete may crack due to rapid evaporation of moisture during the early stages of hardening. This will not occur if the surface is prevented from drying during the critical period.
- (5) **Corrosion of reinforcement.** Concrete may crack due to internal expansion resulting from the corrosion of embedded corrodible metal. This will not occur if agents that promote corrosion are prevented from reaching the corrodible metal as will be the case if no such agents are present in the concrete or in the environment. If the concrete is exposed to a high chloride environment, metal items that can corrode should be embedded to a sufficient depth depending on the permeability of the concrete to the corrosive agents. It has been recommended⁽⁷⁾ that for marine exposures all steel, including stirrups and chairs, should be at least 75 mm from exposed faces and 100 mm from corners. It has been reported⁽⁸⁾ that chloride corrosion has been observed at distances up to 15 km inland from the coast in South Africa.
- (6) **Sulphate attack.** Concrete may crack due to internal expansion resulting from reaction of sulphates with aluminate hydrates of the cement. This will not occur if the quantity of such aluminate hydrates that can form in the cement is sufficiently low or if the amount of available soluble or dissolved sulphates is sufficiently low.
- (7) **Thermal contraction.** Concrete may crack due to expansion and contraction caused by temperature differentials in association with some form of member restraint. Larger concrete members tend to suffer from these effects more than smaller members.

- (8) ***Drying shrinkage.*** Concrete may crack when drying out occurs. Factors like the relative humidity and the temperature of the surrounding atmosphere play an important part here.

Having briefly discussed a few specific kinds of interaction between concrete properties and the environment, it is possible to tabulate the interacting properties⁽¹⁾. (*Ref. Table 1*)

Table 1 - Eight mechanisms that may cause environmentally induced cracking of concrete

Property of Concrete	Characteristics of Environment
<i>Unsound Cement</i>	
Excessive amounts of unhydrated CaO or MgO.	Moisture
<i>Freezing-and-Thawing</i>	
Saturated capillary cavities in hardened cement paste, inadequate air-void system.	Moisture and freeze/thaw
<i>Alkali-Silica Reaction</i>	
Excessive amounts of soluble silica in aggregates and of alkalis in concrete.	Moisture and excessive amounts of alkalis.
<i>Plastic Shrinkage</i>	
Premature surface drying in plastic state.	High evaporation rate
<i>Corrosion of Reinforcement</i>	
Corrodible metal and corrosion inducing agents. Corrodible metal and inadequate concrete cover.	Moisture Moisture and high amounts of corrosion inducing agents.
<i>Sulphate Attack</i>	
Aluminate hydrates in the cement.	Excessive amounts of dissolved sulphates in water or surrounding soil.
<i>Thermal Contraction</i>	
Coefficient of thermal expansion/contraction	Temperature differentials and rate of cooling.
<i>Drying Shrinkage</i>	
Drying shrinkage potential	Relative humidity and temperature

Seven of the mechanisms mentioned have one thing in common - they all involve moisture movement in the concrete produced by interaction of the concrete with the environment.

If the concrete were placed in an environment in which it dried out at the optimum rate and then remained dry, it would not manifest environmentally induced cracking due to the first six mechanisms.

This list is not exhaustive; there are many other interactions that can cause environmentally induced cracking e.g debonding of joints.

Thus, when the properties of the environment in which a concrete structure is placed are properly considered in selecting the materials and methods for initial construction or later repair work, the structure should interact with the environment without cracking (or at least the cracking should be well controlled, e.g. the use of distribution steel to limit shrinkage crack widths). One essential consideration is to prevent moisture movement from the exterior to the interior of a reinforced concrete (r.c.) element, which is the reason why repair materials have to bond properly and be relatively impermeable from outside, but have to still allow the concrete to breath i.e. let moisture out.

Although this chapter only deals with cracking as a deterioration mechanism, this is not the only form of deterioration of concrete. Other mechanisms like soft water attack, acid etching, abrasion, erosion, etc. all have a detrimental effect on concrete but for this project the work was limited to the corrosion of reinforcement mainly due to the ingress of chlorides and the cracking and spalling effects this process has on reinforced concrete.

CHAPTER 2

Service lives of reinforced concrete structures in the Cape Peninsula

No attempt has been made in this dissertation to try to predict durability of concrete structures from a fundamental basis. Rather, data has been collected on various deteriorating structures in the Western Cape, and separated into two categories, i.e. relating to mild or severe coastal exposure environments. Structures closer than 200 m from the sea have been classified to be in a severe coastal exposure climate and structures further away classified to be in a mild coastal exposure climate. An attempt was also made to avoid structures that had previously been painted or repaired so as to limit the amount of variables that have to be considered. This, however, was not totally possible so mention is made where a structure had previously been repaired. This collected data was then plotted on two sets of axes for the different climatic zones and fair curves were drawn which give an indication of deterioration trends in the Cape Peninsula and of what might happen in future.

The curves are divided into 10 categories, each representing a degree of deterioration, varying from "*no deterioration*" (category 9) to a "*replace-only*" solution (category 0). Below follows an explanation of the thinking that went into the plotting of these curves and how the structures were assessed.

The general deterioration curve

The progression of deterioration with time, the deterioration curve as well as the deterioration process, are described in graphic form in **Figure 3**.

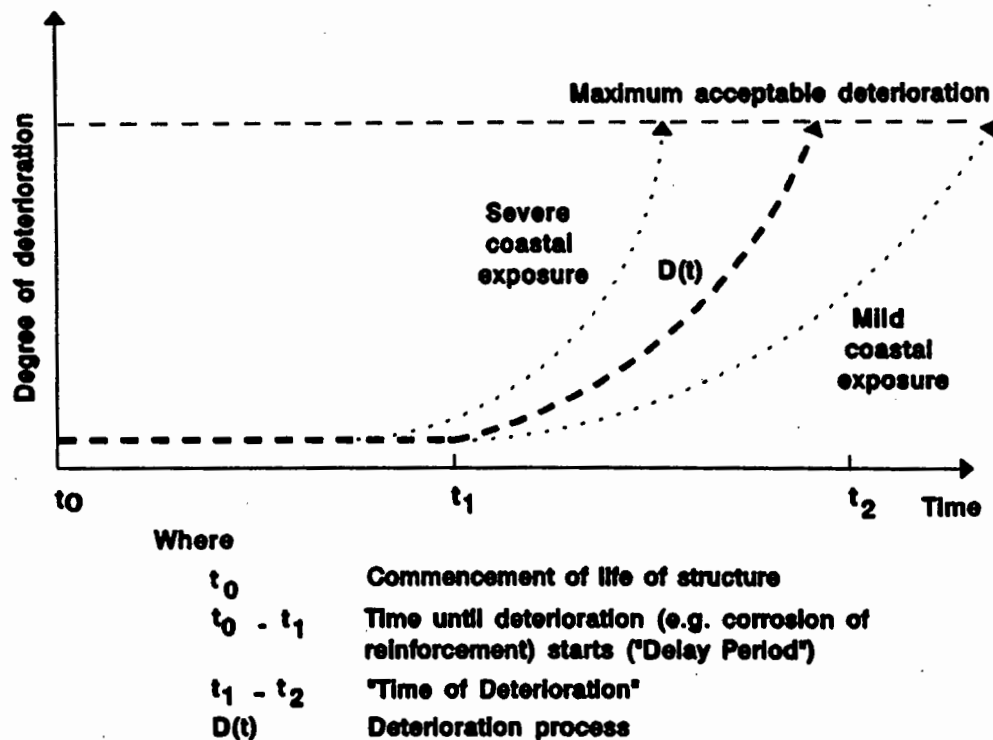


Figure 3 - General relation between deterioration and time (based on ref.⁽⁹⁾)

In order to make reasonable predictions of the service life of a structure one needs data with regards to:

- the actual state of the structure, by testing the current state of the concrete and the overall extent of deterioration;
- the detrimental factors on the structure e.g. changing climates, rainfall figures, etc.;
- the actual rate at which the deterioration process $D(t)$ proceeds.

The function $D(t)$ representing the rate of the deterioration process varies with the deterioration factor under consideration and can follow almost any path in the time/deterioration area, thus e.g., the branch $t_0 - t_1$ could be absent, the line between $t_1 - t_2$ could be straight, have a convex or concave curvature and could be continuous or discontinuous⁽⁹⁾.

For the reasons mentioned above it was decided to plot two separate curves i.e. one for each of the exposure zones.

Factors that have an influence on the deterioration rate of reinforced concrete structures in the Cape Peninsula

The factor that has the biggest influence on the rate of concrete deterioration is the external environment i.e. the amount of chlorides (and CO₂) in the air. The salt laden air in the peninsula causes concrete to deteriorate more rapidly than in a salt-free environment, and with the prevailing winds in the area chlorides are transported far inland to have a serious effect on structures remote from the sea⁽⁸⁾.

Some parts of a structure also deteriorate faster than others. Soffits of any element tend to deteriorate faster than any other area mainly due to the fact that moisture collects there and that the cover to reinforcement is normally the least there. In reservoirs the soffit of the ceiling slabs attract condensation which is a condition much worse than total submersion because more O₂ is available to "boost" the corrosion process. An example of the preceding statement can be seen at the Steenbras water treatment plant. On the inside of the structure where the concrete is totally submerged there is no spalling although the water's pH is sometimes as low as 3⁽²⁾ and should under normal circumstances be sufficiently low to induce depassivation of the reinforcing steel. The soffit of a bridge at the same treatment plant has spalled severely.

Other important factors are the cover to reinforcement, the quality of concrete used, the location of the element in the structure in question, whether the structure has been painted or not, etc.

From the above one can see that there are a great many variables that influence the rate of deterioration. It is almost impossible to find structures that are subjected to exactly the same conditions and that consist of exactly the same concrete. The drawing of a curve relating time to an amount of deterioration is therefore a difficult task. From interviews conducted during the course of this study it became evident that the general feeling in the industry was that structures had to be individually assessed and that there will never be such a thing as a general trend in the deterioration process.

No testing was carried out to establish the depth to which chlorides or the carbonation front has penetrated the structure. This means that the curves for the two exposure zones are not perfect due to the fact that the data is only based on visual assessments of structures.

The classification system

The chosen classification system used for dividing the extent of deterioration into different categories is the one from the North Carolina Department of Roads in the United States, now also used in South Africa by the Department of Transport in their Bridge Maintenance Management software package⁽¹⁰⁾ (see chapter 6 for further information). The classification system was modified slightly so as to classify r.c. elements that are not subjected to such great loads as bridges are.

The classification system is as follows (*Ref. Table 2*):

Table 2 - The classification system

RATING		CRITERIA AND GUIDELINES
9	Excellent	New Condition
8	Very Good	Minor shrinkage or temperature cracks
7	Good	Non-structural cracks, light spalling, no rust stains through cracks yet.
6	Satisfactory	More significant non-structural cracks, moderate spalling, no rust stains visible.
5	Fair	Some section loss due to minor spalling, scour, etc. Structural cracks with light rust staining.
4	Marginal	More general section loss due to deterioration, spalling, scour, etc. Structural cracks with moderate rust staining visible.
3	Poor	Advanced deterioration, spalling or scour exposing reinforcing steel. Structural cracks with severe rust staining.
2	Very poor	Significant structural cracks. Re-bar exposed or rusted.
1	Critical	In-depth study required to decide whether to repair/replace.
0	Beyond repair	Replace is the only reasonable solution

Assessment of existing reinforced concrete elements

The stability and durability of a concrete structure can only be assumed where it has an appropriate safety margin against expected forces and environmental influences during its intended lifetime⁽¹¹⁾. To assess deterioration in a concrete structure an inspection is needed - in serious cases involving testing by special techniques. The assessment of the current state of existing reinforced concrete (r.c.) structures carried out for this project involved a visual assessment and a search for information on the age, cover to the reinforcement, design concrete strength and any relevant repainting or repair data. For some of the structures, recent tests for carbonation depth, chloride diffusion, oxygen permeability and porosity had been carried out and these results were also used to get a clearer picture of the current state of a relevant structure. In general, however, this project concentrated on maintenance strategies in relation to visual assessments, and in-situ testing was therefore not carried out routinely.

The visual assessment involved inspecting the r.c. element or structure and rating it's sea-facing side holistically i.e. not only considering localised corrosion and spalling but looking at the sea-facing side of the structure in its entirety. The reason why the sea-facing side was rated was to provide uniformity of the data collected. A short summary was made of each structure's current state and this data was then entered on a data sheet (*Ref. Table 3 & 4*). On the data sheet the separate r.c. elements were then divided into the 10 categories as given above in the classification system.

The next step in the investigation was to obtain data on the age, cover to reinforcement and design concrete strength of each structure. Most structures that were assessed are owned by local authorities or other quasi-government organisation because they are the only organisations that usually have records of their structures.

After spending many hours at the Cape Town City Council offices sifting through old records, plans and drawings some of the information that was needed was found but for some of the older structures no references except age could be

found. In cases like these the author assumed that the structures were built according to the codes of the day i.e. concrete mixes of 1:2:4 or 3000 p.s.i. (20 MPa).

Due to the fact that not enough information could be found with regards to the above mentioned required data to make corrections to points on the curve, it was decided to ignore correction factors completely and plot age versus deterioration based on a visual assessment only. Following are two tables (*Ref. Table 3 & 4*) displaying data collected on deteriorating structures for the two coastal exposure categories and the curves that were drawn from the data (*Ref. Figure 4 & 5*), where the dotted lines indicate extremes and the dashed line indicates mean values of the points.

The younger structures in a mild coastal exposure climate start cracking and spalling significantly at an average age of 20 - 25 years and those in a severe exposure climate start at about 15 years. It is also clear, from the curves, that structures in a severe exposure climate deteriorate much faster, i.e. take 35 - 40 years to reach a stage of maximum acceptable deterioration, than those in a mild exposure climate. An interesting aspect of the two curves is that older structures in both of the deterioration categories seem to last longer than the younger ones, e.g. from the points on the mild coastal exposure curve it can be seen that no structures were found to be in a very poor or critical condition even though two structures were older than 90 years but, the younger structures look as if they will reach a stage of maximum acceptable deterioration after about 40 years.

Overall, when examining the curves, it is important to keep in mind that they merely indicate trends and are unadjusted for factors like cover thicknesses and concrete strengths. However, the curves are good indicators of time-spans to reach certain stages in the deterioration cycle and can be used very effectively in conjunction with the repair cost data collected and listed in Chapter 3 for future budgeting purposes. (Note that the flattening off of the curves does not indicate a slower deterioration rate, rather that older structures have lasted longer and deteriorated slower.)

Table 3 - Deteriorating structures in a mild coastal exposure

No	Structure	Location	Exposure (Severe/ Mild)	Age (y)	Classification (Ref. Table 2)	Cover to Reinforcement (mm)	Design Concrete Strength (MPa)
1	Old Mutual storage deck	Pinelands - Maitland	Mild	2	9 - No hairline cracking or discolouration	*	30
2	Shoprite R.C. framed building	Main Road, Mowbray	Mild	11	8 - Isolated hairline cracks	*	25
3	Lourens Muller (Portnet) bldg	Cape Town harbour	Mild	19	6 - Localised spalling on facade; little rust	*	*
4	Parking garage	Foreshore freeway	Mild	20	8/7 - Spalls at expansion joints; connections	*	35
5	Platteklouf reservoir	Platteklouf	Mild	22	7 - Still in good condition externally	*	*
6	R.C. framed bldg & Facade	Cavendish square, Claremont	Mild	24	6/5 - Facade spalling; exposing reinforcing	50	30
7	Elevated Freeway	N2, Over Sir Lowry Road	Mild	24	7 - Localised spalls, no rust staining	*	35
8	Apartment block	Blouberg Heights, Blouberg	Mild	26	5 - Before repairs were started	*	*
9	Greenpoint stadium	1 st Stage seating	Mild	27	6 - Cracking in places esp. soffits of beams	0 - 20	20
10	Greenpoint stadium	Gates - Perimeter wall	Mild	28	4 - Cover almost nil in most places	0 - 5	20
11	Greenpoint stadium	2 nd stage seating	Mild	30	5 - Better quality control on site i.e. cover OK	0 - 20	20
12	Greenpoint stadium	3 rd stage seating	Mild	34	4/3 - Severe corrosion of reinf. in places	0 - 20	20
13	R.C. framed building	Ebenezer Rd Depot, Foreshore	Mild	40	4 - Has been repaired; Reinf. exposed, rusted	*	*
14	Newlands rugby stadium	Newlands	Mild	43	3 - Insufficient cover & honeycombing	*	*
15	Steenbras Waterworks	Above Gordons Bay	Mild	50	3 - Soffit of bridge badly spalled & corroded	*	*
16	Snowflake building	Salt River	Mild	90	3 - Sev. cracking & rust staining (Bef. Repairs)	*	*
17	Klooknek reservoir	Camps Bay - Higgovale	Mild	102	3 - Severe spalling, steel gone in places	15 - 25	*

* = no details available

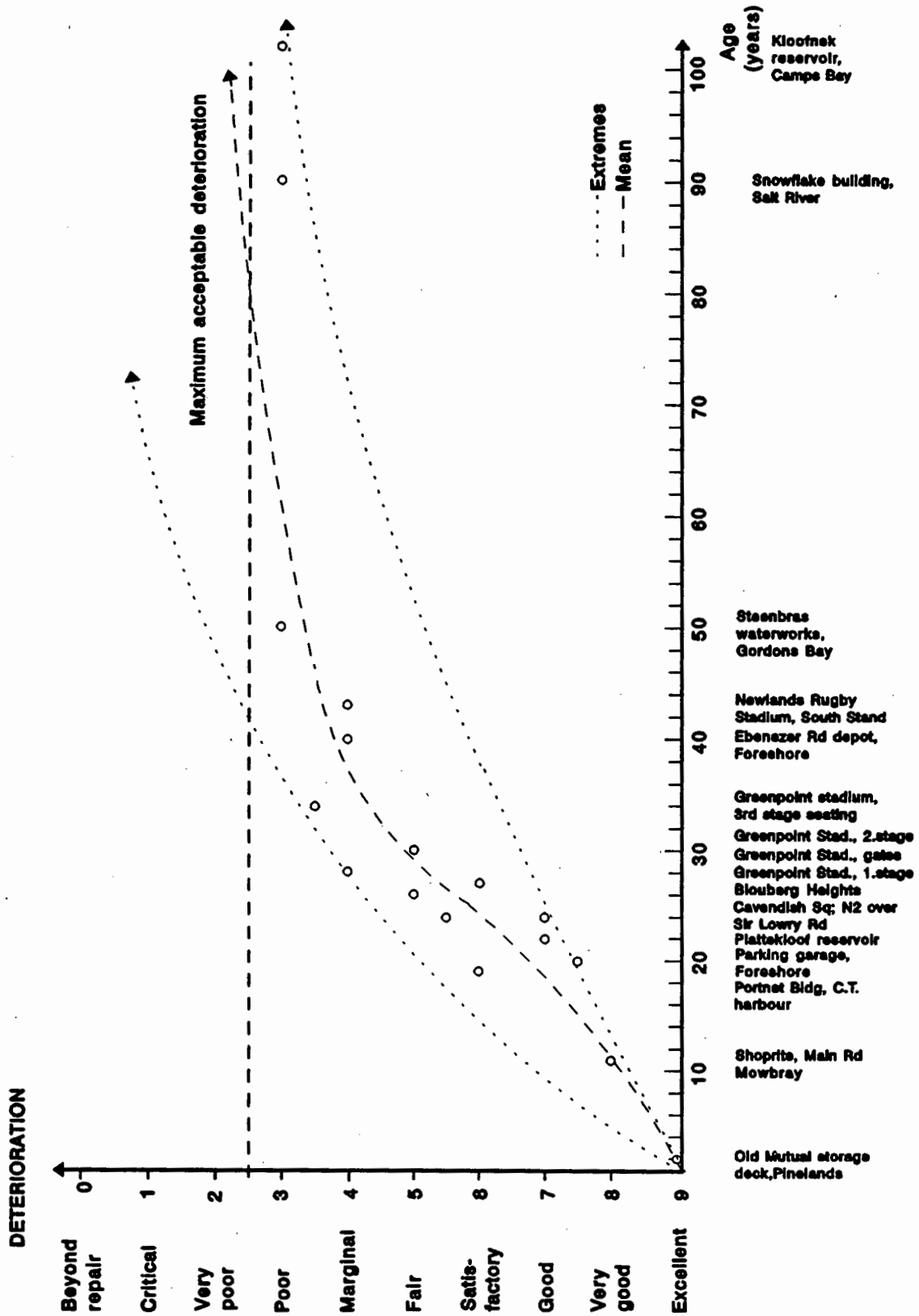


Figure 4 - Mild coastal exposure deterioration curve

Table 4 - Deteriorating structures in a severe coastal exposure

No	Structure	Location	Exposure (Severe/ Mild)	Age (y)	Classification (Ref. Table 2)	Cover to Reinforce- ment (mm)	Design Concrete Strength (MPa)
1	Concrete walkway	Muizenberg - St. James	Severe	6	9/8 - Very limited hairline cracks	100	35
2	Tidal pool	Strandfontein	Severe	13	8 - Concrete softening; hairline cracks	100	30
3	Harbour jetty	Saldanha	Severe	15	5 - Some spalling; Cl ions penetrated way in	*	*
4	Tidal pool	Maiden's Cove, Camps Bay	Severe	15	7 - Aggregates completely exposed	*	*
5	Ben Schoeman Terminal	Cape Town harbour	Severe	16	5 - Abrasion damage; structural cracks	*	*
6	Pumpstation	Camps Bay beach	Severe	17	8 - Isolated hairline cracks	75	35
7	Wind & Spray walls	Cape Town harbour	Severe	21	4 - Reinforcing exposed & rusted	0 - 10	*
8	Harbour jetty	Houtbay, Mariners Wharf	Severe	21	5 - Severe isolated spalling on soffit	25	*
9	Cat walks/Dolphin links	Cape Town harbour	Severe	28	3 - Soffits severely spalled; rusted	*	*
10	Promenade/walkway	Muizenberg pavilion	Severe	30	3 - Condition 3 years ago before repairs	0 - 30	*
11	San Michelle apartments	Clifton, 2nd beach	Severe	30	4/3 - Severe spalling in places	0 - 25	*
12	Road bridge	Glencairn - Simonstown	Severe	31	3 - On sea facing side; severe spalling	*	*
13	Tidal pool	Miller's Point	Severe	31	3 - Advanced deterioration; steel exposed	5 - 15	*
14	Road bridge	Over Zeekoeivlei	Severe	38	1 - Falling apart; rebuild/replace	60	20
15	Road/pedestrian bridge	Royal road, Muizenberg	Severe	40	4/3 - Spalling on soffits of beams	15	*
16	Diving tower	Sea Point pavilion	Severe	43	0 - Has been demolished and rebuilt	*	*
17	Breakwater	Sea Point pavilion	Severe	50	3 - Severe spalling; repaired 2 years ago	200	*
18	Service tunnel for pool	Sea Point pavilion	Severe	51	2/1 - Been repaired often; severely cracked	40	25
19	Sturrock dry dock	Cape Town harbour	Severe	52	5/4 - Abrasion damage; severe rust staining	*	*
20	Aquarium pools & frame	Beach road, Sea Point	Severe	56	1/0 - Rebar has rusted away completely	25	*
21	Tidal pool change rooms	Milton Rd pool, Sea Point	Severe	65	0 - Should be demolished; repairs stopped	20 - 30	20
22	Tidal pool	Camps Bay	Severe	69	3 - Severe abrasion damage; repaired often	*	*
23	Harbour jetty	Simonstown	Severe	75	1 - Very severe structural cracking	30 - 40	*

* = no details available

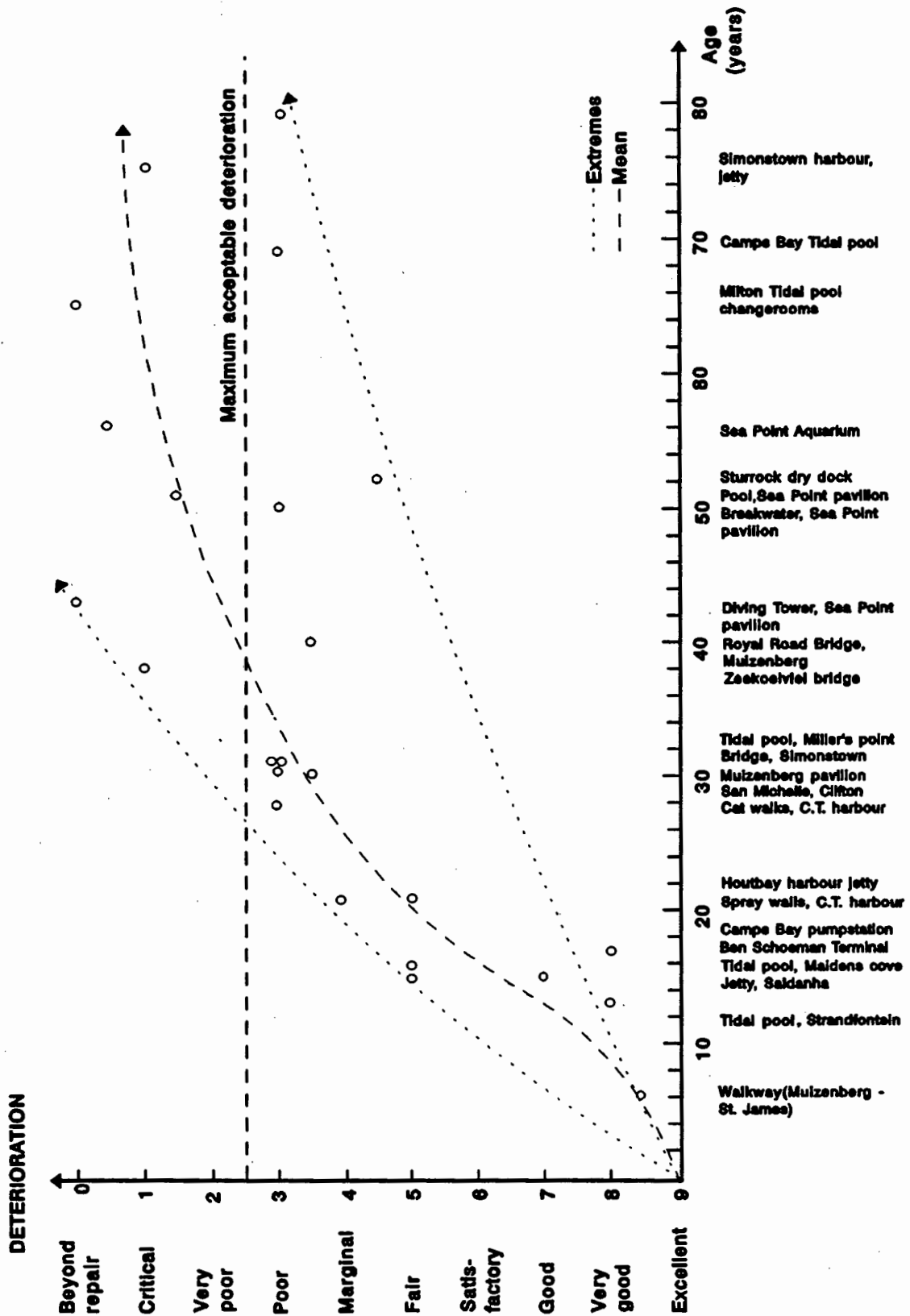


Figure 5 - Severe coastal exposure deterioration curve

CHAPTER 3

Maintenance options, repair methods & repair costs

After some time, most structures show signs of distress, whether cracking or spalling, due to environmental effects. It has been clearly shown in the preceding chapters that reinforced concrete, like other construction materials, is not maintenance free and the future will require the development of realistically costed maintenance policies allied to appropriate repair strategies. Furthermore, design codes need to be critically assessed as to their ability to help produce durable concrete structures. Maintenance policies applied to existing reinforced concrete elements or structures generally involve the decision to implement one of the following repair philosophies⁽¹²⁾.

- (1) **Leave alone** and accept the existing state of deterioration, monitor the deterioration state with time and provide structural propping as required. (This is the way it is mostly done at present.) This implies doing nothing other than incorporating measures to protect public safety and accepting a significant reduction in structural strength or structural serviceability (*Ref. Figure 6*)(e.g. Zeekoeivlei Bridge, Strandfontein and Royal Road pedestrian bridge, Muizenberg)

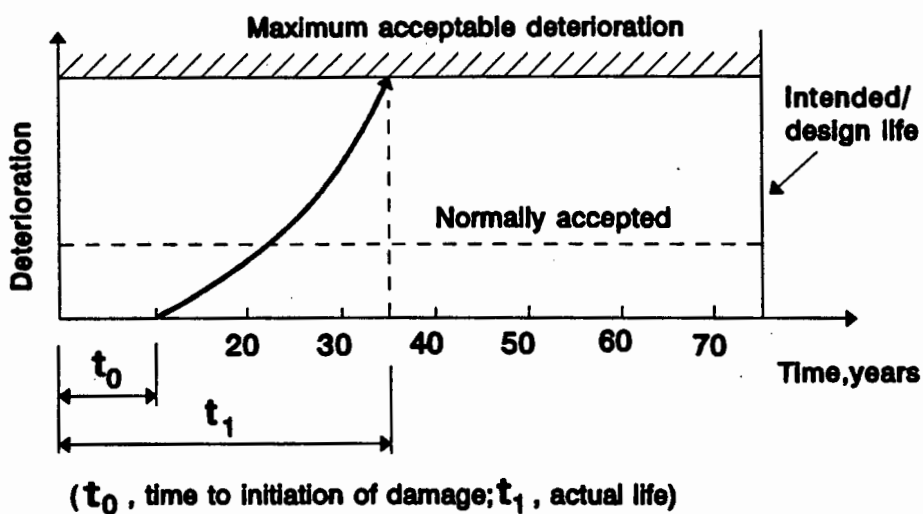


Figure 6 - 'Do nothing' repair philosophy⁽¹³⁾

- (2) Apply barrier coatings to inhibit further ingress of aggressive agents to prevent further corrosion.
- (3) Break out damaged areas to the reinforcement steel or beyond, treat the steel, restore with a high quality patch material and apply a barrier coating to the damaged and surrounding areas. These are essentially holding repairs to slow down the corrosion rate, accepting the need for further repairs at intervals in order to reach the original intended life of the structure (*Ref. Figure 7*) (e.g. Greenpoint Stadium, Sea Point Pavilion Pool).

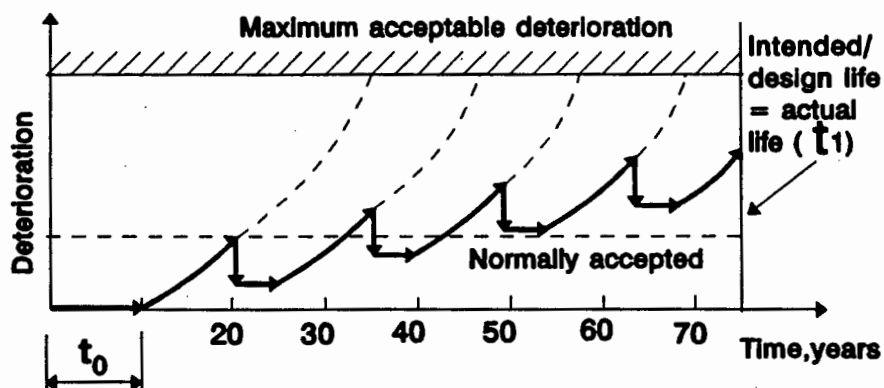


Figure 7 - Regular holding repairs⁽¹³⁾

- (4) Cathodically protect the reinforcement from corrosion. This will

enable the structure to survive for its intended life and beyond (*Ref. Figure 8*)

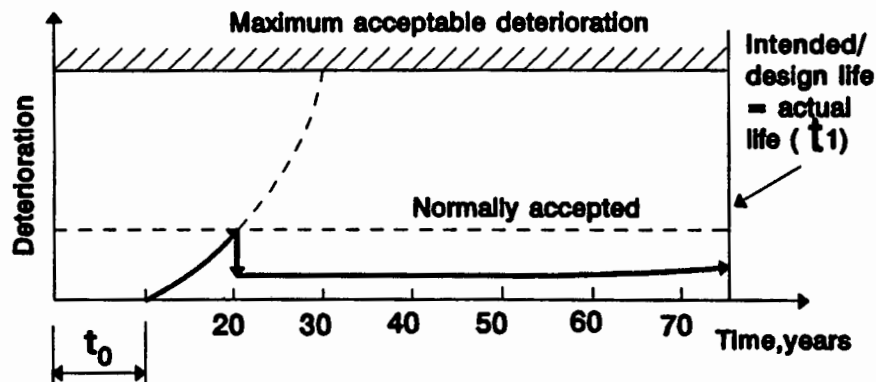


Figure 8 - Cathodic protection of member⁽¹³⁾

- (5) **Re-alkalisation of the concrete.** This method of repair draws the chlorides that have penetrated the concrete out again and restores the pH of the concrete to a level which renders the reinforcing steel passive again i.e. with the necessary surface protection no further corrosion should take place.
- (6) **Cut out the member and replace completely with new materials.**

Further options include demolition and/or the complete replacement of the structure. The choice will be closely allied to the funds available for maintenance and how these are distributed over time.

Whatever the decision, the strategy must be based on a thorough structural investigation, the prime aim of which must be to discover the cause of the distress or deterioration.

In order to make the whole concept of repair and maintenance more tangible and to be able to put costs to the various options, the various repair options have been elaborated below.

Life extension of deteriorated structures

From interviews with people that are involved with repair and renovation of reinforced concrete structures it soon became evident that there was a need to control future environmental ingress (chlorides and CO_2) as well as further corrosion development of reinforcement when one considered restoration. Traditional techniques of guniting or simply mortar patching damaged areas, have shown in most cases a very limited life before cracking recurred, due to the process of attack not having been controlled effectively.

Even now, renovation contractors are still patch-repairing deteriorated structures with inappropriate materials resulting in failures in time scales of less than two years⁽²⁾, particularly in the severe coastal climate of the peninsula area. It is vital to design the remedial approach based on the nature and extent of the attack process.

The current repair approach using barrier coatings and patch repairs is shown in **Figure 9**. The diagnosis depends on whether:

- (a) The depth to which the concrete has been carbonated is sufficient to reach the reinforcement and depassivate it;
- (b) The concentration of chloride ions in the concrete is sufficient to depassivate the reinforcement;
- (c) The reinforcement is already actively corroding.

CARBONATION

CHLORIDE DIFFUSION

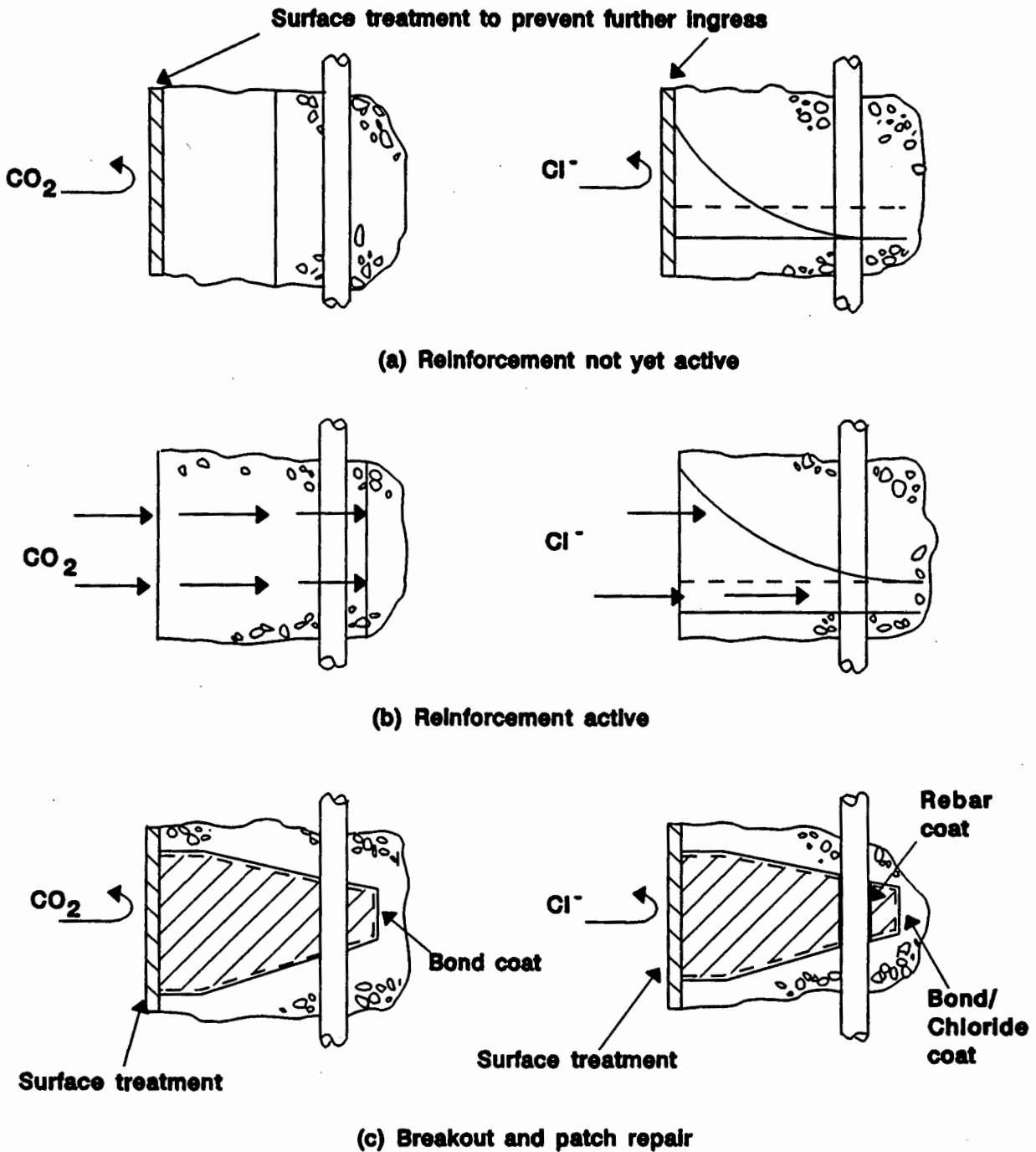


Figure 9 - Patch repair of deteriorated reinforced concrete⁽¹²⁾

Repair methods

This section serves as a more detailed explanation of the range of solutions to repair deteriorated reinforced concrete with associated costs as quoted by suppliers of the four major repair material suppliers in the Western Cape i.e. **FOSROC**, **SIKA**, **ABE**, and **PROSTRUCT**. Also included are actual costs to initiate the repair work as quoted by renovation & repair contractors.

(1) *Barrier Coatings*

Protective coatings or surface "enhancers" such as silanes are used as a barrier against further penetration of the carbonation front or chlorides when the reinforcement has not yet been depassivated or where an element has been repaired. Due to the fact that there are so many types of cementitious and polymeric materials available the author has included a table which is a summary of tests carried out at Taylor Engineering in England⁽¹²⁾. **Table 5** lists a few of the materials tested by them and their ability to control either CO₂ or chloride ingress. Certain coatings can become detached from the concrete due to water vapour building up in-situ with time. Therefore with less strongly bonding materials, it is necessary to consider vapour transmission through the barrier system as well.

Table 5 - Barrier coatings⁽¹²⁾
--

Type	Classification	CO ₂ Resistance	H ₂ O Vapour Transmission	Chloride Diffusion Resistance
Methacrylate	Coating	High	Moderate	High
Styrene Acrylate	Coating	High	Low/ Moderate	----
Ethylene ter-polymers	Coating	High	Moderate	High
Vinyl co-polymers	Coating	High	Moderate	----
Urethane	Low build coat	Very High	Very Low	Very High
Epoxy	Coating	Very High	Very Low	Very High
Bitumen	High build coat	Very High	Very Low	High
Emulsion	High build coat	Moderate	High	Poor
Chlorinated Rubber	Coating	High	Very Low	High
Alkyd	High build coat	Moderate	High	----
Cementitious	Slurry coating	Low	High	Very Low
Silane/siloxane	Surface enhancer	Very Poor	Very High	Very High

Due to the fact that there are so many barrier coatings available the selection of the correct repair material for the right application is not always an easy one. In the severe coastal environment silane/siloxanes are best to use due to their high chloride diffusion resistance. Some manufacturers however do not manufacture a silane/siloxane product but only a polymer modified cementitious material which has a low chloride diffusion resistance, so in selecting the correct repair or "protection" material one has find out what the various manufacturers supply. Then one can choose a product from a manufacturer which will resist the attack mechanism which one is attempting to counteract.

(2) ***Breakout damaged areas***

According to the PCI Guide: "*Diagnosing and repairing the surface of reinforced concrete damaged by the corrosion of reinforcement*"⁽⁵⁾ the edges of an area to be removed should first be sawn to a depth of at least 15 mm (using an angle grinder fitted with a masonry-cutting disc) to prevent feather edges in the repair material. Then the damaged concrete must be removed without damaging the remaining concrete. Light, power-driven chisels are suitable for most work and cold chisels with 2-kg hand-held hammers are to be used on smaller jobs.

When chiselling is finished, all detritus should be removed firstly with hand-held wire brushes and then with an industrial vacuum cleaner. The surface should be left rough and clean to facilitate adhesion of the repair material to be applied later.

Where the reinforcing steel is exposed and has also started corroding it is important to consider the state of the steel as well. First of all it should be assessed for structural function. Any steel that serves no structural function (e.g. fixing bars) should be cut out of the structure and discarded.

The remaining steel should then be inspected for the degree of corrosion. Where the uncorroded part of a bar is too small to carry the bar's design load, it should be cut out and replaced with a new bar. Replacement bars may be welded to or lapped with existing bars. It is then also very important to remove any corrosion products from partly corroded bars to be retained in the structure because these contain corrodents which if not removed can cause further corrosion within the repaired area or impair the bond between the existing surfaces and the material used for the repair.

The steel can be "cleaned" by either:

- Shot or sand blasting;
- Rotary wire brush, mechanically driven;

- Abrasive disc fitted to small angle grinder;
- Strips of emery cloth used by hand, especially for surfaces not easily accessible;
- High-pressure water jets with sand fed into the stream by a venturi.

As **Figure 9** shows, it is very important to also break out concrete behind the bar, where the chloride gradient has reached a critical level at the steel or beyond. Otherwise, even the repair will not stop adjacent chlorides behind the steel from reactivating the steel. A chloride barrier coat can also be applied to the broken-out surface if the chloride penetration is deep, but the life performance of such a coat is still unproven⁽¹²⁾.

A major problem, only fairly recently identified by research is that a patch itself can divert the corrosion process into an adjacent area - often referred to as "incipient" anodes⁽¹²⁾ (*Ref. Figure 10*). This problem can only be combatted by selecting repair materials which are compatible with the "old" concrete and thereby prevent differences in electric potentials.

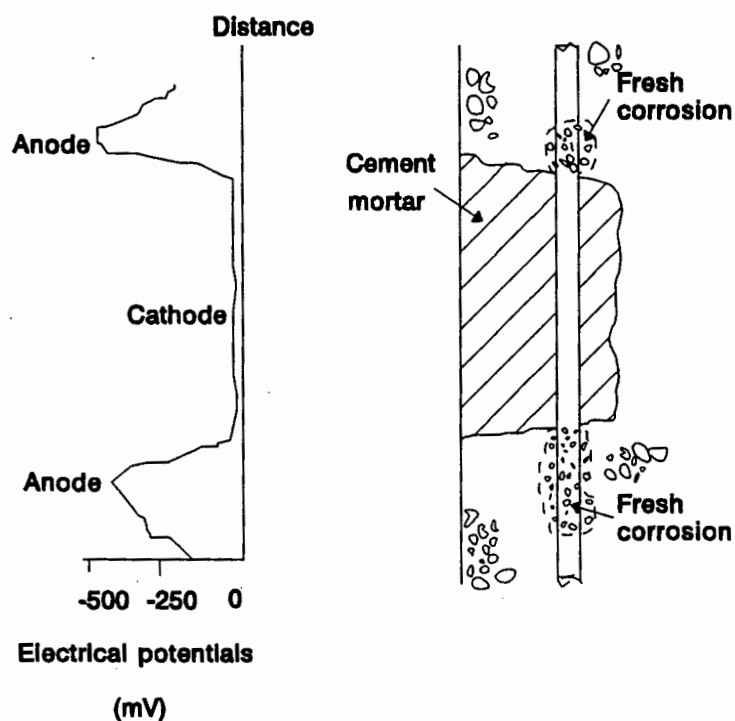


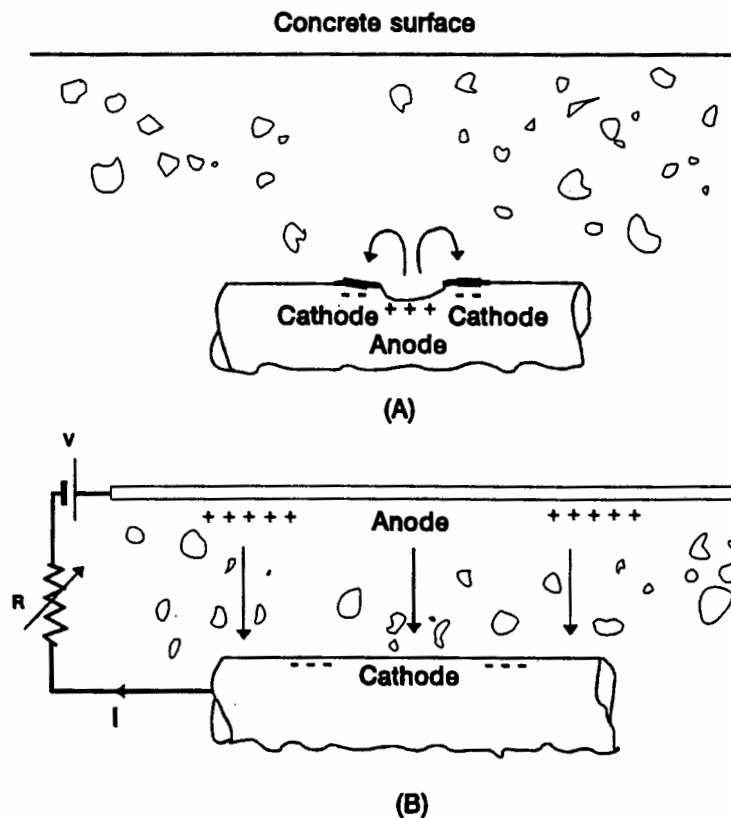
Figure 1 - "Incipient" anodes⁽¹²⁾

(3) ***Cathodic Protection***

Cathodic protection is a technique of steel protection that has been extensively used for many years to protect steel pipelines and tanks from corrosion and has in recent years been applied to the protection of reinforcing steel in concrete⁽¹³⁾. Since the development of conductive coatings (1980-82) the effectiveness of cathodic protection has been enhanced⁽¹⁴⁾. It became easier to install and is now applicable to many different types of concrete structures (i.e. docks; harbour facilities; marine terminals; bridge substructures such as piers, pier caps and beams; parking garages; etc.).

Corrosion of steel proceeds by the formation of an electro-chemical cell. With the concrete acting as a coupling electrolyte, an anodic reaction occurs at some point on the steel surface and cathodic reactions consume the dissolved electrons on the remaining portion of the steel surface. The presence of chloride ions will produce a local depassivation. By means of a small externally applied current, the electric potential between the steel and concrete is shifted to a non-critical level. Thus, the electrons impressed in the steel force the steel to act as a cathode in the electro-chemical cell. One method of cathodic protection is to apply an electrically conductive overlay to a bridge deck, for example, and pass an impressed current between the overlay and the reinforcement, thereby effectively repassivating the steel (*Ref. Figure 11*). The potential shift produced by the DC is critical to cathodic protection. Because of the high resistivity of the electrolyte concrete, a uniform distribution of the protection current throughout the structure is necessary⁽¹⁵⁾.

The key advantage of the system is that, once it is operational, it can totally arrest the corrosion process and thereby provide a permanent solution even though further chloride penetration may still occur. In fact, the concept works better if chlorides are present as the covercrete is more electro-chemically conductive.



(A) A freely corroding reinforcement bar

(B) A cathodically forced surface

Figure 2 - How cathodic protection works⁽¹³⁾

Surface treatment with barrier coatings is not effective once chlorides have penetrated the concrete⁽¹⁴⁾. Indeed after extensive research and testing, the Federal Highway Administration (FHWA) in the US issued the following policy statement⁽¹⁶⁾:

"Rehabilitation techniques such as overlays, sealers and waterproof membranes have been evaluated in both the laboratory and the field in an effort to protect the reinforcing steel from the corrosive effects of salt (chlorides).

*The **only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete is cathodic protection.*** " (Emphasis added)

Since this statement was published in 1982, significant technological breakthroughs have been achieved. Today cathodic protection is the most effective means of controlling corrosion of reinforcing steel in chloride-contaminated concrete⁽¹⁴⁾. (Whether it is the most cost effective method remains to be proven.)

The primary methods of cathodic protection currently in use are:

Electrically conductive mesh applied to the surface of the structure after a suitable and simple patch repair is effected. The mesh is then imbedded in a highly modified cementitious render, for example applied by guniting.

The use of an **electrically conductive paint** containing graphite, or **flame sprayed zinc**, with the current supplied via platinised titanium wire and carbon fibre.

The above mentioned repair options are the only three that will be costed in the following section and that is the reason why a more detailed explanation of re-alkalisation and replacement of entire members has been excluded.

Costing of repair work

In this study the material cost has been separated from the labour and access costs in order to get an indication of how the prices of various supplier's materials differ.

The labour and overhead rates used in this study for carrying out various items of work are actual costs extracted from a tender where six concrete repair contractors tendered for the same work/activities. The contracting companies were *Clifford Harris*, *Grinaker*, *Power Construction*, *Murray & Roberts (M&R)*, *Savage & Lovemore (S&L)* and *African Concrete*. A seventh rate was also included in the calculation of an average rate. This was the estimated rate that the consultants (i.e. *BKS*) used and against which all the tendered rates were compared. (Due to the confidentiality of the individual tender rates, no individual costs have been quoted in this dissertation but merely averages of the seven rates.)

The items in the cost estimate are based on each step normally taken in the repair of a damaged or deteriorated r.c. element/structure, carried out in accordance with the specifications for the specific work.

The variabilities of the individual rates are all fairly small (and thus ignored) except for the breaking out of contaminated reinforced concrete where the average cost quoted in the table can be very misleading because the actual quoted rates ranged from R 0.35 /litre to R 7.25 /litre.

This break out process (removal of defective reinforced concrete) has to be costed very accurately. The reason for this is that in practice it can be extremely time consuming and expensive to break out behind the steel, particularly if the concrete element was originally constructed of high strength concrete i.e. the concrete is then very hard. The rate of breakout to a depth of 25 mm behind the bar on a jetty deck beam soffit, for example, can be as slow as 1 m run per day⁽⁴⁾.

All the items likely to occur in the repair of structures in categories 9 to 2 are costed below (*Ref. Table 6*):

**Table 6 - Cost estimate of items in the repair process
(1994 Costs in the Western Cape)**

Item No.	Description	Unit	Rate inc VAT
1	High Pressure Water Jet cleaning	m ²	R 8.39
2	High Pressure Water-sand Jet cleaning	m ²	R 13.73
3	High Pressure Grit blasting	m ²	R 23.55
4	Removal of defective Reinforced Concrete within the following height ranges above existing ground level:		
	(i) 0 m up to 2.5 m	ℓ	R 3.06
	(ii) Exceeding 2.5 m	ℓ	R 3.08
5	Prime Reinforcing Bars with an approved coating	m	R 3.26
6	Apply Bonding Coat to raked out Concrete surface	m ²	R 1.14
7	Concrete repairs with a cementitious repair mortar within the following height ranges above existing ground level:		
	(i) 0 m up to 1.5 m	ℓ	R 10.11
	(ii) Exceeding 1.5 m up to 4.5 m	ℓ	R 12.26
8	Concrete repairs with an epoxy resin mortar within the following height ranges above existing ground level:		
	(i) 0 m up to 1.5 m	ℓ	R 23.03
	(ii) Exceeding 1.5 m up to 4.5 m	ℓ	R 31.50
9	Concrete crack preparation for crack injection (including installation of nipples) within the following height ranges above existing ground level:		
	(i) 0 m up to 1.5 m	m	R 61.33
	(ii) Exceeding 1.5 m up to 4.5 m	m	R 66.26

Item No.	Description	Unit	Rate inc VAT
10	Injection of an approved epoxy resin into cracks	ℓ	R 50.65
11	Application of skimming layer on surface of concrete to fill blowholes and smooth surface	m ²	R 20.52
12	Application of barrier coating to concrete surface: (i) Silane/Siloxane impregnator (ii) Primer & 2 coats Topcoat (iii) 2 coats Polymer modified cementitious coating or elastic coating	m ² m ² m ²	R 5.14 R 17.86 R 14.39

Comparative costing of various repair materials

For the purposes of this study it was necessary to arrange interviews with representatives of each of the 4 major suppliers of repair materials in the Western Cape. After having been advised by all four, it became possible to establish which materials are suitable for what application and the repair of each category of the classification system could be costed.

It is important to realise that each product has its advantages and disadvantages and that one pays for what one gets. The contractors that were interviewed were of the same opinion i.e. that **cost, ease of application and service & backup** were equally important; cost however, became the overriding factor when deciding what repair material to use. Other factors that are also to be considered are impermeability from outside & breathability from inside, volume stability, bond strength, testing carried out on the product in question, to name but a few⁽¹⁷⁾.

What came to light in this study was that the quality of a product was not given sufficient consideration in the choice of product for a particular application. Consultants normally specify the product that they are most familiar with and do not normally make any effort to attempt to assess which manufacturer's product is the most suitable for the particular application in question.

The different types of repair materials available are costed in **Table 7** below. Details like the mix proportions, application technique, curing of the repair etc. are beyond the scope of this work but can be found in ref.(5) as well as the product information manuals of the various suppliers.

**Table 7 - Cost comparison of repair materials
(1994 Costs in the Western Cape)**

Category	Description	FOSROC	SIKA	ABE	PROSTRUCT
9	Silane/Siloxane - clear	Nitocote SN502 (Impreg.) R 10.50/m ²	Sikaguard 70 (Impreg.) R 7.05/m ²		
	Plastic-Elastic Protective coatings	Nitocote Dekguard 'S' R 12.92/m ²	Sikaguard 550 Elastic Top R 10.94/m ²		Water repel dressing 670 R 4.84/m ²
	Polymer/Resin modified cementitious coating		SikaTop-Seal 107 R 12.18/m ² @ 1 mm thick	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ²
8	Cementitious levelling mortar & filling of hairline cracks	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikaguard 75 Epo Cem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.68/m ² @ 1.5 mm thick	Caulking compound 643 R 17.78/m ² @ 1 mm thick
	Plastic-Elastic Protective coatings	Nitocote Dekguard 'S' R 12.92/m ²	Sikaguard 550 Elastic Top R 10.94/m ²		Water repel dressing 670 R 4.84/m ²
	Polymer/Resin modified cementitious coating		SikaTop-Seal 107 R 12.18/m ² @ 1 mm thick	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ²
7	Crack and blowhole filler to smooth surface	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikaguard 75 EpoCem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.68/m ² @ 1.5 mm thick	Crackfiller 684/1 R 9.78/m ² @ 1.5 mm thick
	Application of Bonding agent on concrete	Nitobond HAR R 3.59/m ²	Sikacem 810 R 3.00/m ² @ 1.5 mm thick		
	Patching of light spalling	Renderoc GP R 44.00/m ² @ 10 mm thick	SikaRep R 34.20/m ² @ 10 mm thick	Durafill R 77.06/m ² @ 10 mm thick	Five Star Structural Concrete 528 R 70.84/m ² @ 10 mm thick

Category	Description	FOSROC	SIKA	ABE	PROSTRUCT
	Application of protective surface coating	Nitocote Dekguard Elastic R 24.11/m ²	Sikagard 550 Elastic Top R 10.94/m ²	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ² + HBC 684/4 R 3.89/m ²
6	Sealing of cracks (3 mm wide)	Conbextra EP 10 Tropical R 1.01/m	Sikadur 52 R 0.71/m	Epidermix 365 R 0.99/m	Crack Injection Resin 629 R 0.72/m
	Application of Bonding agent on concrete	Nitobond HAR R 3.59/m ²	Sikacem 810 R 3.00/m ² @ 1.5 mm thick		
	Patching of moderate spalling and cracks	Renderoc GP R44.00/m ² @ 10 mm thick	SikaRep R 34.20/m ² @ 10 mm thick	Durafill R 77.06/m ² @ 10 mm thick	Five Star Structural Concrete 528 R 70.84/m ² @ 10 mm thick
	Crack and blowhole filler to smooth surface	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikagard 75 EpoCem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.68/m ² @ 1.5 mm thick	Crackfiller 684/1 R 9.78/m ² @ 1.5 mm thick
	Application of protective surface coating	Nitocote Dekguard 'S' R 12.92/m ²	Sikagard 550 Elastic Top R 10.94/m ²	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ² + HBC 684/4 R 3.89/m ²
5	Anti-corrosive coating on steel: 12 mm bar - Zinc rich	Nitoprime Zincrich R 0.34/m	SikaTop Armatec 110 EC R 1.34/m		Zincrich primer 528 R 0.30/m
	- Resin modified cement			Durafer R 5.46/m @ 2 mm thick	
	Application of Bonding agent on concrete	Nitobond HAR R 3.59/m ²	Sikacem 810 R 3.00/m ² @ 1.5 mm thick		
	Patching of structural cracks and spalling	Renderoc HB R 221.32/m ² @ 40 mm thick	SikaRep R 139.80/m ² @ 40 mm thick	Durabed R 124.95/m ² @ 40 mm thick	Five Star Structural Concrete 528 R 283.36/m ² @ 40 mm thick

Category	Description	FOSROC	SIKA	ABE	PROSTRUCT
	Crack and blowhole filler to smooth surface	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikaguard 75 EpoCem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.68/m ² @ 1.5 mm thick	Crackfiller 684/1 R 9.78/m ² @ 1.5 mm thick
	Application of protective surface coating	Nitocote Dekguard 'S' R 12.92/m ²	Sikagard 550 Elastic Top R 10.94/m ²	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ² + HBC 684/4 R 3.89/m ²
4	Anti-corrosive coating on steel: 12 mm bar - Zinc rich	Nitoprime Zincrich R 0.34/m	SikaTop Armattec 110 EC R 1.34/m		Zincrich primer 528 R 0.30/m
	- Resin modified cement			Durafer R 5.46/m @ 2 mm thick	
	Application of Bonding agent on concrete	Nitobond HAR R 3.59/m ²	Sikacem 810 R 3.00/m ² @ 1.5 mm thick		
	Patching of structural cracks and spalling	Renderoc HB R 276.65/m ² @ 50 mm thick	SikaRep R 171.00/m ² @ 50 mm thick	Durabed R 156.19/m ² @ 50 mm thick	Five Star Structural Concrete 528 R 354.20/m ² @ 50 mm thick
	Crack and blowhole filler to smooth surface	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikaguard 75 EpoCem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.67/m ² @ 1.5 mm thick	Crackfiller 684/1 R 9.78/m ² @ 1.5 mm thick
	Application of protective surface coating	Nitocote Dekguard 'S' R 12.92/m ²	Sikagard 550 Elastic Top R 10.94/m ²	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ² + HBC 684/4 R 3.89/m ²
3	Anti-corrosive coating on steel: 12 mm bar - Zinc rich	Nitoprime Zincrich R 0.34/m	SikaTop Armattec 110 EC R 1.34/m		Zincrich primer 528 R 0.30/m
	- Resin modified cement			Durafer R 5.46/m @ 2 mm thick	

Category	Description	FOSROC	SIKA	ABE	PROSTRUCT
	Application of Bonding agent on concrete	Nitobond HAR R 3.59/m ²	Sikacem 810 R 3.00/m ² @ 1.5 mm thick		
	Patching of advanced spalling and structural cracks	Renderoc HB R 276.65/m ² @ 50 mm thick	SikaRep R 171.00/m ² @ 50 mm thick	Durabed R 156.19/m ² @ 50 mm thick	Five Star Structural Concrete 528 R 354.20/m ² @ 50 mm thick
	Crack and blowhole filler to smooth surface	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikaguard 75 EpoCem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.68/m ² @ 1.5 mm thick	Crackfiller 684/1 R 9.78/m ² @ 1.5 mm thick
	Application of protective surface coating	Nitocote Dekguard 'S' R 12.92/m ²	Sikagard 550 Elastic Top R 10.94/m ²	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ² + HBC 684/4 R 3.89/m ²
2	Anti-corrosive coating on steel: 12 mm bar - Zinc rich	Nitoprime Zincrich R 0.34/m	SikaTop Armatec 110 EC R 1.34/m		Zincrich primer 528 R 0.30/m
	- Resin modified cement			Durafer R 5.46/m @ 2 mm thick	
	Application of Bonding agent on concrete	Nitoprime 25/28 R 9.25/m ²	Sikadur 32 R 20.70/m ²		
	Patching of very advanced spalling and significant structural cracks	Nitomortar 'S' R 553.58/m ² @ 50 mm thick	SikaTop 122 R 377.00/m ² @ 50 mm thick	Epidermix 314 R 462.09/m ² @ 50 mm thick	Five Star Structural Concrete 528 R 354.20/m ² @ 50 mm thick
	Crack and blowhole filler to smooth surface	Renderoc FC R 7.24/m ² @ 1.5 mm thick	Sikaguard 75 EpoCem R 7.51/m ² @ 0.5 mm thick	Duraskim R 16.68/m ² @ 1.5 mm thick	Crackfiller 684/1 R 9.78/m ² @ 1.5 mm thick
	Application of protective surface coating	Nitocote Dekguard 'S' R 12.92/m ²	Sikagard 550 Elastic Top R 10.94/m ²	Duraflex R 40.27/m ² @ 2 mm thick	Conseal 511 R 3.85/m ² + HBC 684/4 R 3.89/m ²

Note to Items in Categories 5 - 2:

In the costing exercise, aspects like the minimum cover to the reinforcement after repairs are considered in calculations to determine the volume of repair concrete required for a specific area of spalled and damaged concrete and values for these are based on the values in the **Table 8** below (Taken from **SABS 0100⁽¹⁸⁾**).

**Table 8 - MINIMUM COVER TO REINFORCEMENT
AFTER COMPLETING REPAIRS⁽¹⁸⁾**

Exposure condition	Minimum cover (mm)
Severe	35
Very severe	50

[The above classification system equates to the mild and severe coastal exposure conditions in the classification system used in this dissertation.]

Repair cost examples for structures in different deterioration categories

Formula for costing:

$$\text{Cost} = \sum [\text{Material price} + \text{Labour rate} + \text{Access factor}]$$

where

- Σ - Sum of items listed under each category in **Table 7**
- Material price** - Actual costs calculated from quoted costs by manufacturers of repair materials (applied at recommended coverage rates & no. of coats specified in product information manuals)
(*Ref. Table 7*)
- Labour rate** - Actual costs quoted by contractors tendering for r.c. repair work (includes all labour costs, wastage, profit and costs of consumables e.g. paint brushes, trowels, rollers, solvents, gloves, etc.)
(*Ref. Table 6*)
- Access factor** - Cost of access to areas on structures to be repaired. Will vary to a large extent depending on the size of the structure and the location of areas to be repaired e.g. scaffolding for a 10 storey building will increase the cost of repair work by a large margin compared to repair work on ground level.

When doing an estimate of costs to repair r.c. the access factor will always have a major influence on the total cost. When repairs are initiated on a structure where scaffolding has to be used to access the areas that are deteriorating it is wise to do the best possible repair job using materials of superior quality to ensure a long life from the repairs. When repairs are done at ground level, areas that can easily be accessed without any scaffolding are cheap to repair and it is easy and cheap

to come back every couple of years. This means that one doesn't have to do as good a job here as on areas difficult (and expensive) to access. A good example is the Kloofnek reservoir which went out to tender in March 1994⁽¹⁹⁾. The repairs to the spalling soffit of the roof have to be carried out well because of the immense costs involved for access i.e. the reservoir has to remain operational during repairs, thus one half has to be sealed off from the other. Scaffolding has to then be erected to a height of 15 - 20 metres, and all scaffolding, materials and workmen, have to enter the reservoir through a 1.5 x 1.5 m opening in the roof. The actual repair job is small so material costs will amount to a minor percentage of the total cost. This highlights the importance of supervision on site whilst repair work is being carried out especially to areas that can not easily be accessed at a later stage.

Another factor that has to be individually assessed for every repair job is the actual total area affected or deteriorated. This is different for every structure and can normally only be measured once removal of defective concrete has commenced due to the fact that some deterioration may not be identified during a visual assessment of the structure. Normally, when contractors tender for repair work they specify this in their tender and give a rate/m² or a rate/£ so that the actual amount of work can be measured at a later stage once it is certain how much work is involved^(20, 21).

For the costing exercises in this study, extents of deterioration expressed in percentage terms were arrived at by purely a visual assessment of the structures and plotted on the two deterioration curves. These percentages varied so much i.e. from 50% - 90% for category 3 for example and 2% to 20% for category 6 that in the costing exercise of repair of 1 m² of r.c. averages of these percentages were used. This means that the costs arrived at to repair will only be the same for another structure if the extent of deterioration is exactly the same.

To estimate the linear metres of cracks to be injected with a crack injection resin also proved to be a very difficult task because each m² on a structure is different from the next. For purposes of this costing exercise it was taken to be an average of 1 m/m².

Two examples are given below which illustrate how the formula given above should be used (*Ref. Example 1 & 2*). The two examples show the total cost/m² to repair reinforced concrete in two different deterioration categories repaired with products from two different manufacturers (excluding access costs).

Example 1 - Repair of 1 m² of r.c. in deterioration category 7 with SIKA products [Percentage spalling/m² equals 10%]

(*Ref. Appendix 1 for cost build-up*)

- | | | |
|-----|--|--|
| (1) | High pressure water-sand jet cleaning of the surface to remove all paint, organic matter, loose concrete and dust | R 13.73 |
| (2) | Fill non-structural cracks and blowholes with Sikaguard 75 Epo Cem | R 25.23 |
| (3) | Apply a bonding agent, Sikacem 810 , on spalled areas to ensure strong bond between old concrete and repair mortar (10% of area) | R 0.41 |
| (4) | Patching of light spalling with Sikarep on horizontal and vertical surfaces and Sikarep LW on vertical and overhead surfaces (10% of area) | R 4.43 |
| (5) | Application of a protective surface coating i.e. Sikaguard 550 Elastic Top . | <u>R 25.33</u>
<u>R 69.13/m²</u> |

Example 2 - Repair of 1 m² of r.c. in deterioration category 4 with FOSROC products [Percentage spalling/m² equals 35%]

(Ref.
Appendix 2
for cost
build-up)

- | | | |
|-----|---|---|
| (1) | Removal of defective r.c. up to 20 mm behind the reinforcing bar | R 5.36 |
| (2) | High pressure water-sand jet cleaning of the surface to remove all paint, organic matter, loose concrete and dust | R 13.73 |
| (3) | High pressure grit blasting to remove all iron oxide (rust products) from reinforcing steel | R 3.11 |
| (4) | Apply anti-corrosive coating on the steel rebar, Nitoprime Zincrich | R 12.60 |
| (5) | Apply a bonding agent, Nitobond HAR , on spalled areas to ensure strong bond between old concrete and repair mortar (35% of area) | R 1.66 |
| (6) | Patching of advanced spalling and raked out areas with Renderoc HB (35% of area) | R 114.52 |
| (7) | Application of a thin surface coat to fill blowholes and little cracks to provide a smooth surface for a protective surface coating i.e. Renderoc FC | R 18.04 |
| (8) | Application of a protective surface coating, Nitocote Dekguard 'S' | <u>R 30.78</u>
<u>R 199.80/m²</u> |

The following table, (*Ref. Table 9*), is a summary of costs for repairs of each category, for each repair material - calculated in the same way as the examples 1 & 2 (*Ref. Appendix 1 & 2*). It should be noted that the work done to category 9 and 8 should not be categorised as repair work but rather as "protection". The third column lists the percentage of 1 m² that has spalled and is to be repaired. It is important to keep in mind that these percentages vary to a great extent and are different for every structure.

**Table 9 - Summary of costs to repair 1 m² of reinforced concrete
(1994 Costs in the Western Cape)**

Category	Description	%	FOSROC	SIKA	ABE	PRO-STRUCT	Average
9	Excellent	0	R 24.03	R 20.58	R 63.05	R 27.62	R33,82
8	Very good	0	R 72.27	R 67.09	R 105.59	R 71.26	R79,05
7	Good	10	R 86.56	R 69.13	R 110.59	R 74.70	R85,25
6	Satisfactory	15	R 140.04	R 132.96	R 176.17	R 140.04	R147,23
5	Fair	25	R 163.36	R 134.06	R 175.83	R 178.20	R162,86
4	Marginal	35	R 199.80	R 160.84	R 203.92	R 221.62	R196,55
3	Poor	45	R 236.24	R 187.63	R 232.01	R 265.04	R230,23
2	Very poor	60	R 499.19	R 400.77	R 496.44	R 330.17	R431,64

Costing of cathodic protection

In the calculation of the cost to install cathodic protection on 1 m² of concrete the most important factors that have to be taken into account, according to **Ref. (22)** are:

- The amount of reinforcing steel in the concrete element;
- The continuity of the reinforcing steel;
- The amount of spalling to date to be patched.

Of the three above the extent of civil engineering works is the overriding factor influencing costs. Although spalling is patched with a normal OPC concrete, the patching process could be very costly where the soffits of slabs or beams or columns have to be patched. Costs also increase where the cover to the reinforcing is very small. This means that the cover will have to be increased because the anode has to be a distance away from the cathode. Where cathodic protection is applied to the surface of a highway flyover costs are obviously far less because it is much easier to gain access and work on a flat surface.

Costs:

- (1) Titanium mesh (anode) - R 160.00 / m²
- (2) Cathodic protection hardware & design - R 50.00 - R 70.00 / m²
- (3) Civil works (patching, formwork, guniting)- R 100.00 - R 350.00 / m²
- (4) Power consumption - 40 - 100 watts / 1000 m² (i.e. 1 light bulb / 1000 m²) thus cost / m² is negligible.

Total cost / m²: R 300 - R 600 / m² ⁽²²⁾

Figure 12 is a graphic representation of the cost summary table i.e. **Table 9**. The x-axis has been adjusted to take into account the time it takes to move from one deterioration category to the next. The averages between figures 4 & 5 were used. This figure now clearly illustrates how costs increase as the amount of deterioration increases with time. When a structure is still in an excellent condition, it is fairly cheap to "protect" the structure from ingress of chlorides and CO₂. Costs start increasing in an accelerating manner from there as the amount of deterioration increases. From the points on the set of axes it can also be seen how costs suddenly rise when repairing category 6 due to the high labour cost involved with the crack injection process. Costs keep on increasing from category 6 onwards and once category 3 and 2 are reached one should consider permanently repairing by installing cathodic protection. In order to assess which option would be the cheapest one in the long-run one has to compare the total costs over the life of a structure (*Ref. Example 4 in Chapter 5*).

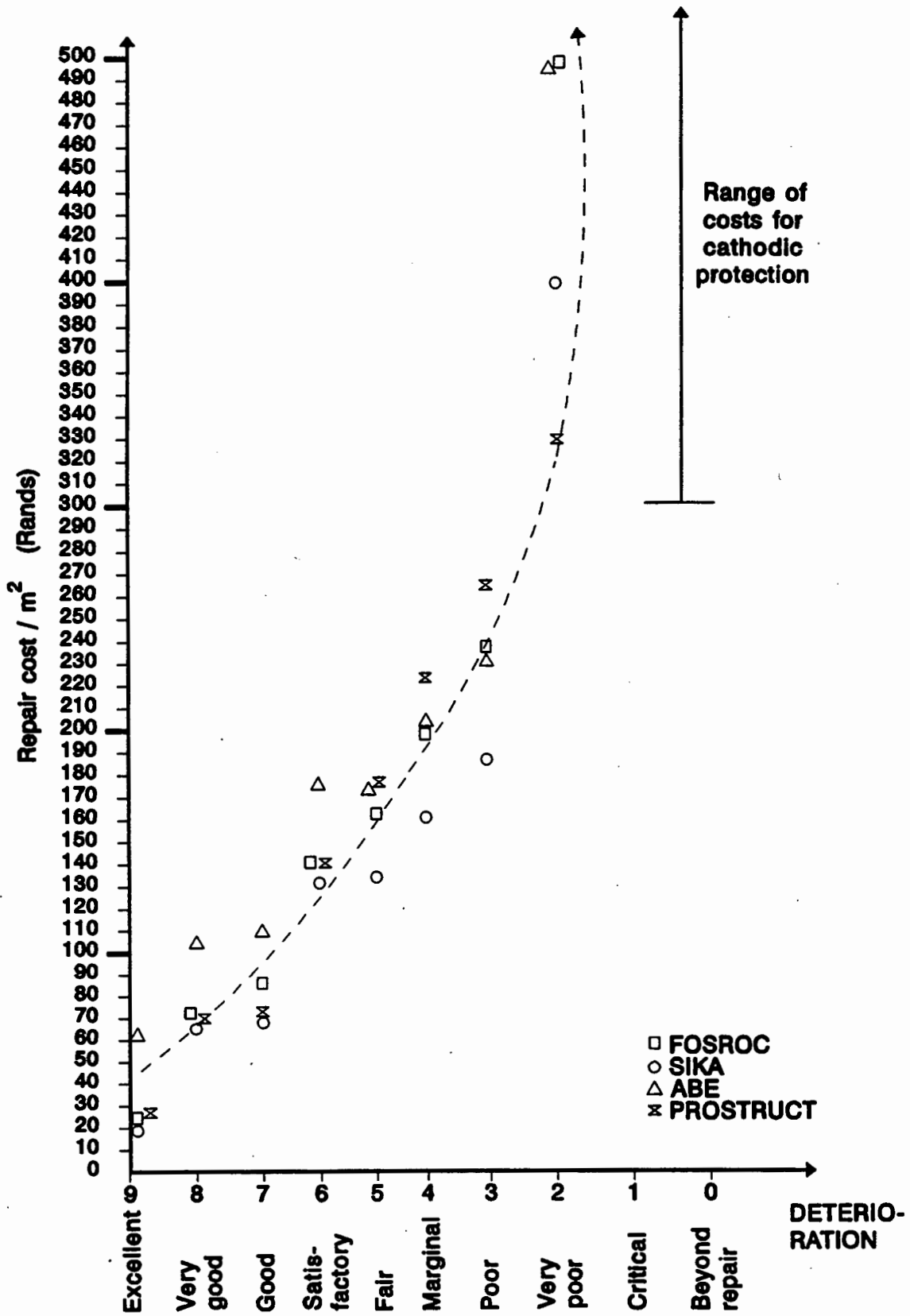


Figure 3 - Deterioration v. repair cost / m² of concrete

Minimising costs of short-term maintenance and repairs

This section has been included to connect the repair cost data from the summary graph (*Ref. Figure 12*) with the various maintenance options and methods i.e. it should serve as a degradation diagnosis guideline. By following the flowchart (*Ref. Figure 13*) one can initiate maintenance in the correct manner, at minimum cost.

For the repair of reinforced concrete in the various stages of the deterioration cycle it is important to realise that some materials are only suited for certain applications e.g. silane/siloxanes are only effective if the chlorides are still fairly far from the steel (have only penetrated the surface layer) due to the fact that they line pores in the concrete rather than block them. Silane/siloxanes do not work to prevent carbonation.

Table 5 should be considered when the decision is made as to what barrier coating is to be used and it is important that the decision takes into account the results from a chloride concentration profile and/or from a depth of carbonation test to ensure that penetration is not very deep.

The method of repair will depend on the state of a structure i.e. a structure can exhibit a great amount of cracking due for example to excessive shrinkage cracking at original construction but minimal chlorides could have penetrated due to it being situated in a wind- and rain-protected area. This means that raking out might not have to take place, merely crack injection and coating. Cracking could also be minimal on the other hand, but chloride diffusion very deep, to a point past the steel and having reached a concentration at the steel which is at or above the corrosion threshold level. This means that raking out of the chloride contaminated concrete will have to take place, as well as grit blasting of the corroded steel, followed by patching processes. In the case where chlorides have only penetrated to a depth of 50% - 70% of the covercrete it is important to keep in mind that if the chloride concentration is very high at the surface, sealing the surface will not always be the correct diagnosis because levelling of the concentration gradient will take place i.e. the chlorides will still reach the steel. The correct repair method will

then be raking out and patch repairing.

The reason why it is stated (in the flowchart) that repairs should be carried out 'as soon as possible' is twofold: firstly, the longer a r.c. structure is left to deteriorate, the deeper the chlorides (or the carbonation front) will penetrate the structure. It is important to keep in mind that in severe coastal exposure climates the rate of chloride diffusion is very high i.e. chlorides penetrate the surface layer within the first year after construction and reach the steel at a corrosion threshold level after 12 - 15 years⁽²³⁾. The second reason is clearly illustrated in **Figure 12** which shows that costs for repair work increase as the amount of deterioration increases which means that in the short-term it will always be cheaper to initiate repair work at the earliest possible stage in the deterioration cycle.

From the above it is clear how crucial it is to establish the depth of chloride ion diffusion and/or carbonation. Despite the fact that only a visual assessment was done, a full investigation cannot rely on this alone. It is also important to consider the environment before any repair work is carried out to counteract the factors that are causing the particular structure in question to deteriorate.

By considering all the factors and options listed in the preceding chapter when formulating maintenance and repair strategies the cheapest and most cost effective short-term solution will be pursued, with the exception of cathodic protection which is a long-term repair solution. It is however not sufficient to only consider these factors for long-term maintenance planning. In order to formulate a long-term maintenance strategy one firstly has to know how fast a particular r.c. structure will deteriorate (**Ref. Chapter 2**), formulas are necessary to calculate what repair costs will amount to at some predefined point in time in the future and formulas are necessary that enable budgeting for those future expenses. Then it also needs to be established when is the optimal point in the deterioration cycle to carry out periodic preventative maintenance and repairs so as to minimise costs over the life-span of a structure. These issues are now dealt with in the following chapters (**Ref. Chapters 4 and 5**).

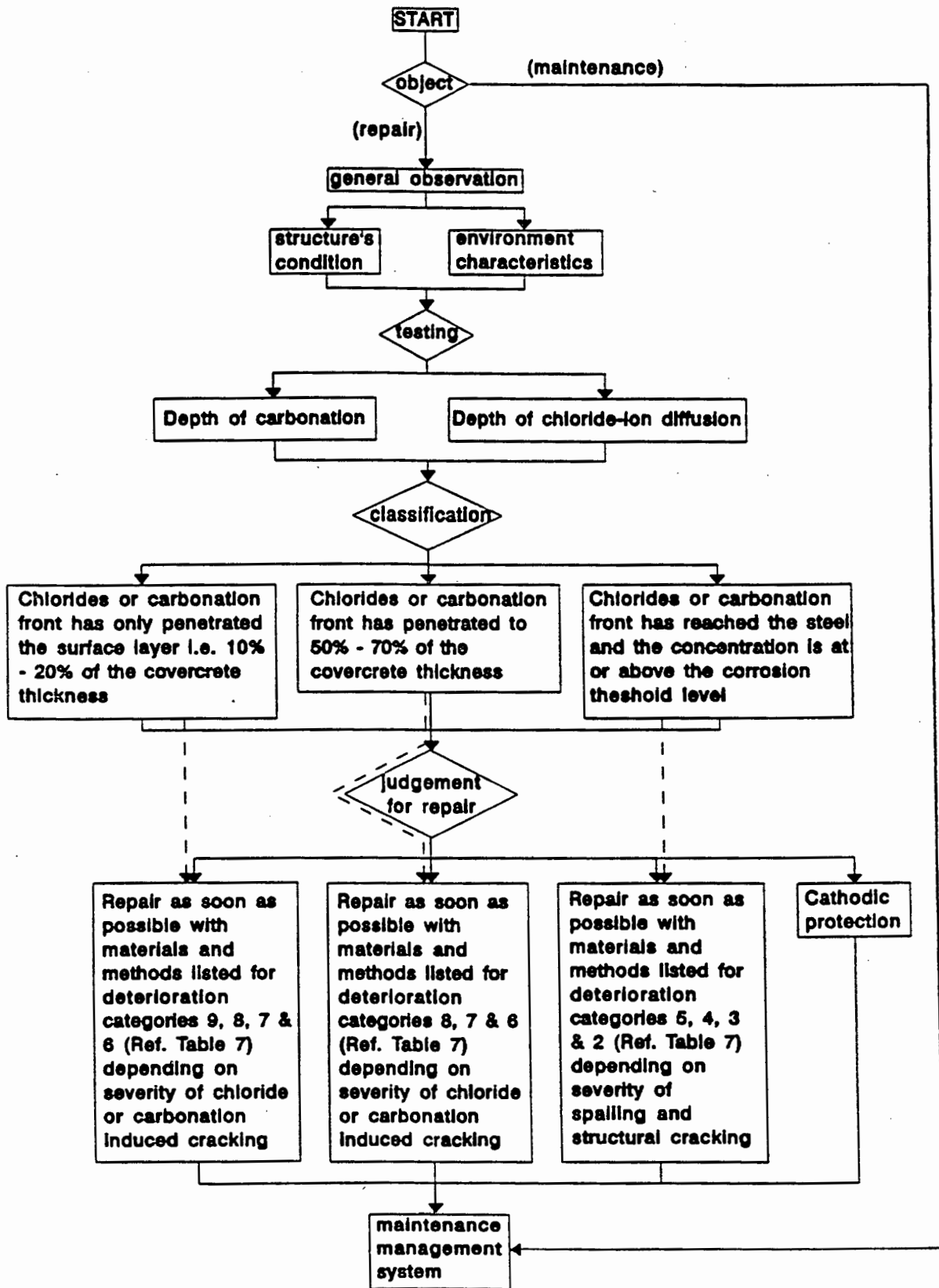


Figure 13 - Degradation diagnosis system for reinforced concrete structures

CHAPTER 4

Financial calculations for future maintenance & repair budgeting

In the past concrete structures were only repaired or maintained when any form of deterioration was noticed. This trend is however changing in that maintenance managers now have to make budgetary forecasts of maintenance expenditure envisaged for the next year⁽¹⁹⁾. This chapter links the cost and deterioration rate information collected and discussed in the previous chapters with mathematical formulas which can be used to establish what the repair costs will be in future, and gives aid in budgeting for periodic maintenance expenditure.

Future value of repair costs

The calculation of an estimated future value of the repair cost / m² of reinforced concrete involves the projection of the present cost. The compound interest equation that is used to compute the future value equivalent of the present price is⁽²⁴⁾:

$$S = P [1 + b]^n$$

- Where **S** - The projected estimated price (future value) for maintenance & repair / m² of r.c.
- P** - The present day price for maintenance & repair / m² of r.c.
- b** - The escalation index for building renovation (concrete work)
- n** - The number of years from the present until maintenance is to be carried out

Figure 4 & 5 in combination with Figure 12 can be used to establish values for 'P' and 'n'. From Figure 4, for example, it takes a structure in a mild coastal exposure climate about 24 years to reach a 'Satisfactory' condition after initial construction.

This means that if one chooses to repair once a particular structure has reached this state of deterioration it will cost an average of R 147.48/m² at present (*Ref. Figure 12*).

This value is then entered into the above equation to calculate a future value equivalent (where 'b' = 13.6% (average from Ref. (25))) i.e.

$$S = R \ 147.48 [1 + 0.136]^{24}$$

$$S = \underline{R \ 3146.39/m^2}$$

Budgeting - Calculation of annual deposit amounts to pay for future maintenance

A series of equations is used to calculate the monthly amounts required to be deposited in a bank account in order to save enough money to carry out maintenance at some specified date in the future. For purposes of this study this amount has been assigned the abbreviation 'D'.

In order to calculate the values of 'D' for each year a series of stages should be followed, starting with the calculation of an estimated future value of the repair cost / m² of reinforced concrete, i.e. 'S' (same as above).

The next stage involves the calculation of the relationship between the effective interest rate and the rate of increase or decrease of the renovation indices for concrete work. For this calculation the present worth formula is used to find the relationship between the two.

The formula used is⁽²⁴⁾:

$$w = \frac{[1+g]}{[1+i]} - 1$$

Where

- w - Adjusted interest rate
- g - Rate of increase or decrease of renovation indices
- i - Interest rate of deposit account

The next formula is used to calculate the first payment of a geometric gradient series. A geometric gradient payment series is a series of cash flow sequences that increase or decrease by a fixed percentage at each payment interval⁽²⁴⁾. This method of calculation is used because it enables the amount to be saved every year to be escalated by the increase or decrease in renovation costs. This is performed so that the amount paid into the deposit account each year escalates according to renovation costs, and does not remain static⁽²⁶⁾. If escalation were not carried out, the value of the last payment would not be equal to the first due to the time value of money.

The first payment is calculated and then used again to calculate the annual income necessary to collect enough money to pay for the maintenance & repairs.

This formula is⁽²⁴⁾:

$$R = S \left[1 + g \right] \left[\frac{1}{1 + w} \right] \left[\frac{w}{(1 + w)^n - 1} \right] \left[\frac{1}{(1 + i)^n} \right]$$

Where

- R** - First annual payment of geometric gradient
- S** - The projected estimated price (future value) for maintenance & repair / m² of r.c.
- g** - Rate of increase or decrease of renovation indices
- w** - Present worth
- n** - The number of years from the present until maintenance is to be carried out
- i** - Interest rate of deposit account

Below is an example (*Ref. Example 3*) to illustrate how the value of 'D' is derived. The value of 'g' (the rate of increase in annual payments into the deposit account) is 10% and the value of 'i' (the rate of interest earned in the deposit account) is 5%.

Example 3 - Budgeting for future repair costs

Step 1

$$w = \frac{[1+g]}{[1+i]} - 1 ; \quad w = \frac{[1+0.10]}{[1+0.05]} - 1$$

$$w = 0.0476$$

Step 2

$$R = S [1+g] \left[\frac{1}{1+w} \right] \left[\frac{w}{(1+w)^n - 1} \right] \left[\frac{1}{(1+i)^n} \right]$$

$$R = 3146.39 [1+0.10] \left[\frac{1}{1+0.0476} \right] \left[\frac{0.0476}{(1+0.0476)^{24} - 1} \right] \left[\frac{1}{(1+0.05)^{24}} \right]$$

$$R = R 23.75$$

Thus, R23,75 represents the first payment amount 'D' (which is to be increased by 10% per annum) in the annuity series to be invested in a deposit account earning 5% which will generate the required R 3146.39 at the end of 24 years.

If the above approach is used by maintenance managers of privately owned structures for budgeting purposes of future maintenance expenditure it can give owners of structures a good indication of the sums of money that should be saved monthly/annually for repair work to reinforced concrete. This figure will never be precise because one cannot forecast the area or amount of square metres that will have deteriorated on a particular structure after a given amount of time. It is also impossible to forecast an exact escalation index nor an exact rate of increase of renovation indices for the repair costs involved.

Public authorities, e.g. municipalities, however work according to a different system of budgeting. They simply put aside budget amounts for repairs to pre-selected structures on a yearly basis. To incorporate the above mentioned system of budgeting they will have to determine how many years from the present they want to repair which structures. This will mean a change from the current system of budgeting to one where fixed amounts are still put aside annually but these amounts are for future maintenance of all the structures they own and not only for specific ones.

The guidelines given in the previous chapters, combined with the information in this chapter can be used effectively if it is known when is the most economical point in time to carry out maintenance and repair work in order to minimise total lifetime costs while maximising the life-span. This issue is addressed in the following chapter with the aid of decision models together with life cycle costing so that maintenance managers can provide economic justification for the amount of money needed for future preventative maintenance.

CHAPTER 5

Decision Models and Life Cycle Costing for reinforced concrete structures

Decision Models

Decision models are a useful aid for arriving at correct decisions and in demonstrating the basis of those decisions to others. Green and James⁽²⁷⁾ define decision models in the following manner: " The fundamental principle of decision models is to allow the various relevant factors to be identified, quantified and then combined with the objective of achieving a rational analysis of the problem." When these models are used by a designer of a structure or the owner of an existing structure to define a maintenance strategy they help to structure their thought processes and help to ensure that all the variables that could have an effect, have been considered.

Maintenance management can be divided into technical decisions which will decide a maintenance programme and operational decisions which will affect the methods of carrying out the work and the efficiency of its output⁽²⁷⁾.

Broadly speaking the technical decisions will cover considerations such as the break-even point between acceptable deterioration and maintenance, when to stop maintaining and replace parts of the concrete structure or the complete structure, and the establishment of economic cycles for recurring inspection and maintenance work. All these decisions will contribute to the development of long-term plans with annual maintenance programs and budget allocations. Operational decisions will include assistance in the choice between directly employed labour and the use of sub-contractors for executing the work, the permissible time between the occurrence of a defect and its repair, and how the resources should best be deployed.

There are various types of decisions where the use of models can make a contribution and help management to make the most economic choice. An example of a decision model that has been available for many years for maintenance work is one for systemised light replacement or a re-lamping model⁽²⁸⁾. This model enabled managers to determine whether it was more economic to replace electric light bulbs individually as they fail or to carry out a bulk replacement at one time irrespective of the fact that a number of the bulbs will still have some active life left. The model takes into account the varied 'time to failure' of the bulbs under consideration to determine the correct re-lamping frequency which maximises the difference between the cost of bulk replacement which does not use the total life of every bulb and the cost of individual re-lamping as failure occurs.

Important data that is necessary to calculate the cost of individual replacement will be travelling costs incurred each time an electrician has to be called and the ease of accessibility of the bulb. Difficult access, such as in theatre buildings, will mean special equipment like scaffolding will be needed and will add to the cost; easily accessible areas will mean that an electrician is not necessary because cleaning staff, for example, can replace the bulbs. A bulk replacement in this situation would be totally uneconomic, but in a theatre a decision model will have to be used to decide which option is the most economic.

A decision model that will be relevant to making economic decisions with regards to concrete structures is a Repair/Replace model.

There will always come a time when it is economically advantageous to replace/rebuild parts of a structure or the entire structure, rather than continue repairing. Problems arise when one attempts to determine when that time has come or, better still, to be able to forecast when it is likely to come. A professional judgement can be made which often will be the correct one but it may be necessary to justify this so that it can be included in a maintenance management programme before being proved on site.

For small and uncomplicated concrete structures this may be relatively simple, provided the cost data are available. It may only be necessary to have data of the

expenditure on maintaining the structure, e.g. maintaining a concrete roof slab, over the past years and the cost of replacement, (assuming no other costs are involved when replacing the roof e.g. loss of profits if this were a factory building roof.) The use of discounted cash flow techniques will then give the capital cost of replacement as a yearly revenue cost against which may be compared the cost of continued repair. If the result doesn't justify immediate replacement, then it could be possible to predict future repair costs and a forecast can be made as to the date replacement is likely to be justified. However a problem that normally crops up in practice is that not sufficient data is available to make these predictions, thus setting up of models is not quite so easy.

Normally factors that have an effect on the decision are not so easily quantified and are more numerous than the direct maintenance cost described above. If for example the concrete roof slab were leaking this will give rise to consequential maintenance costs, such as staining of the walls and floors below. It may also affect certain activities taking place in the building or even spoil stock if the building were a warehouse.

Another decision model that is referred to in the literature ^(29,30) as being an obvious first target for those interested in developing decision models is one pertaining to the frequency of redecorating/repairing the external facade of a structure. Green and James⁽²⁷⁾ state that a number of decision models have been developed in this field, but have not always been successful due to the lack of, or the subjective nature of, the available data.

Where the results are affected by the external environment, as is the case in the Western Cape, problems start cropping up. Only with sufficient historical data can one estimate how an aggressive external environment affects the concrete. The orientation, degree of exposure and the height of a structure are only a few of the factors that affect the rate at which the concrete deteriorates. Different parts of a structure may weather at different rates and will therefore have to be repaired at different times. Whether it is economic to repair only one part or the entire structure at once will depend on the amount of work involved and on the need for scaffolding if the structure is high and difficult to access. According to Christer⁽²⁹⁾

a problem with so many variables involved is best solved by means of algebraic formulas rather than having fixed rules. The person using the model will then decide the relevant input values and apply the general model to his particular situation.

Tools used in setting up decision models

The basic tools most commonly employed in constructing decision models can be categorised as being orientated towards statistics, economics and management, although these are all interrelated⁽²⁷⁾.

(1) *Probabilities and Statistics*

There are many factors that have an influence on concrete deterioration that are uncertain in nature. An example of this is the 'bulb life' information required in the re-lamping decision model discussed earlier. Bulbs do not have a set life, yet an estimation of this is required as an input to the model; statistical data can be used for this purpose from which a probability distribution of bulb life can be determined.

For a model assessing the consequences of concrete deterioration, a large extent of the input data will have to be deterministic, otherwise the usefulness of the model will decline gradually as more of the input variables become probabilistic variables.

(2) *Economic Tools*

There are a number of economic tools and techniques that can be employed when defining a decision model, such as discounting, cost benefit and cost effective techniques, etc. Discounting means bringing future benefits and costs back to 'present worth' values. This is the amount of money which would have to be invested now to give at the appropriate time or times the money required for future maintenance and other expenses (*Ref. Chapter 4*).

Once all the data for a particular concrete structure have been collected and all the benefits and disbenefits associated with the deterioration problem have been quantified, a technique is needed to deduce the economically most optimum solution. In most cases, the optimising criterion is to minimise the cost for a given benefit or to maximise the benefit for a given cost, i.e. to adopt a '*cost effective*' approach. Life cycle costing is the technique which is most used in industry to deduce this economically most optimum solution.

(3) *Management tools*

In this field there are once again numerous tools that can be employed and thus only a selection of these will be discussed.

(i) **Decision trees:**

When a decision cannot be viewed as an isolated, single occurrence, but rather as the first of a sequence of several interrelated decisions over several future time periods, it has to be presented in such a way that the decision maker can consider a whole series of decisions simultaneously. Such a situation is called a sequential or multi-period decision process and is presented in the form of a decision tree⁽³¹⁾ (*Ref. Figure 14*). These decision trees can become fairly complicated when there are lots of probabilistic or uncertain factors involved as is the case in maintenance of deteriorating concrete structures. The tree allows all these factors such as failure rates, future maintenance or running costs, the expected life of repair work, or the life of a r.c. structure to be combined in a rational manner. Each of the probabilistic variables is described and then linked together in a diagrammatic form according to their precise relationship.

An example of a short decision model for maintenance and repair has already been given in Chapter 3 i.e. the bottom half of the degradation diagnosis flowchart, *Ref. Figure 13*, where one has three alternatives for repair after a classification has been made.

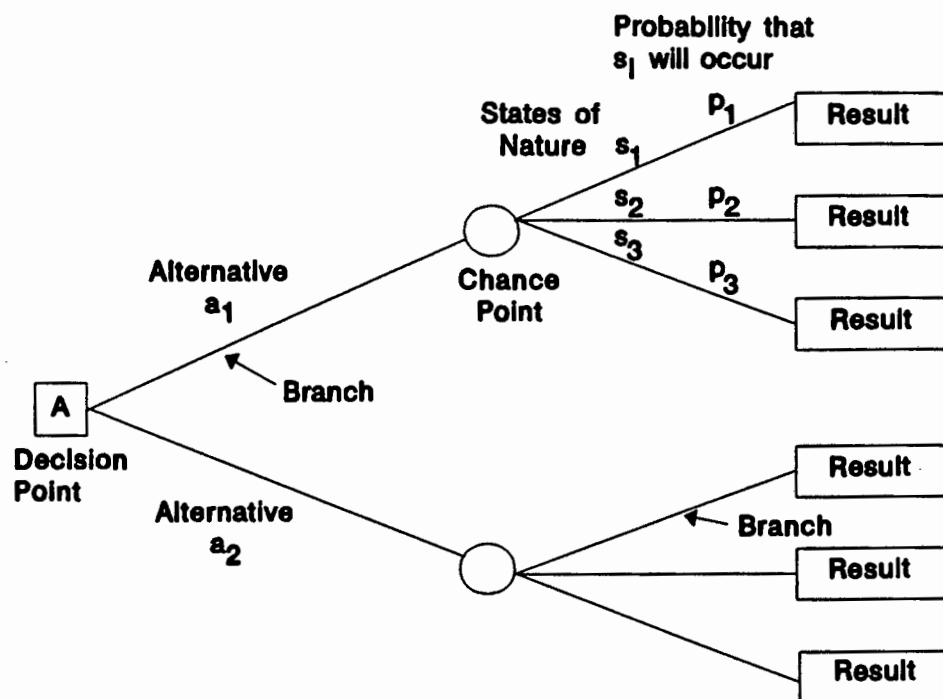


Figure 5 - The general structure of a decision tree⁽³¹⁾

(ii) **Mathematical programming:**

Mathematical programming is defined by Turban⁽³¹⁾ as the name for a family of tools designed to help solve managerial problems in which the decision maker must allocate scarce (or limited) resources i.e. labour, materials and capital, among various activities to optimise a measurable goal. A few of the more commonly used techniques in this field are:

(1) *Linear programming*

Because the resources employed when initiating maintenance are limited compared to the demand, they have to be allocated properly in order to maximise the life of the structure at minimum cost. Linear programming can be used to find the

optimal solution to this type of allocation problem as long as the objective function as well as the constraining functions remain linear. The objective function for repair work could be minimising costs and maximising the life-span whereas the constraining function could be the limited life of repair materials.

(2) *Dynamic programming*⁽³²⁾

This technique is particularly relevant when the optimisation problem involves a large number of decision variables and conditional constraints. This is the case when for example attempting to deduce the best overall maintenance policy for a particular maintenance problem such as a roof. In this circumstance performance is measured in terms of the total maintenance cost over the remaining life of the structure, and dynamic programming can be used to produce a 'ready reckoner' decision matrix. Given the existing condition of the roof, the remaining life of the structure and the minimum acceptable condition, the maintenance manager can use this matrix to decide whether to initiate repair work or allow the roof to further deteriorate.

(iii) **Expert Systems:**

An expert system, the newest addition to the maintenance manager's arsenal, "employs human knowledge captured in a computer to solve problems that ordinarily require human expertise"⁽³³⁾. When used for maintenance work, an 'expert' in the field introduces expert knowledge into the knowledge base, called the development environment (**Ref. Figure 15**). This means that all the possible choices a maintenance manager can make are already stored with their possible outcomes. A user, or in this case a maintenance manager, will then enter the so-called consultation environment to obtain the expert knowledge and advice.

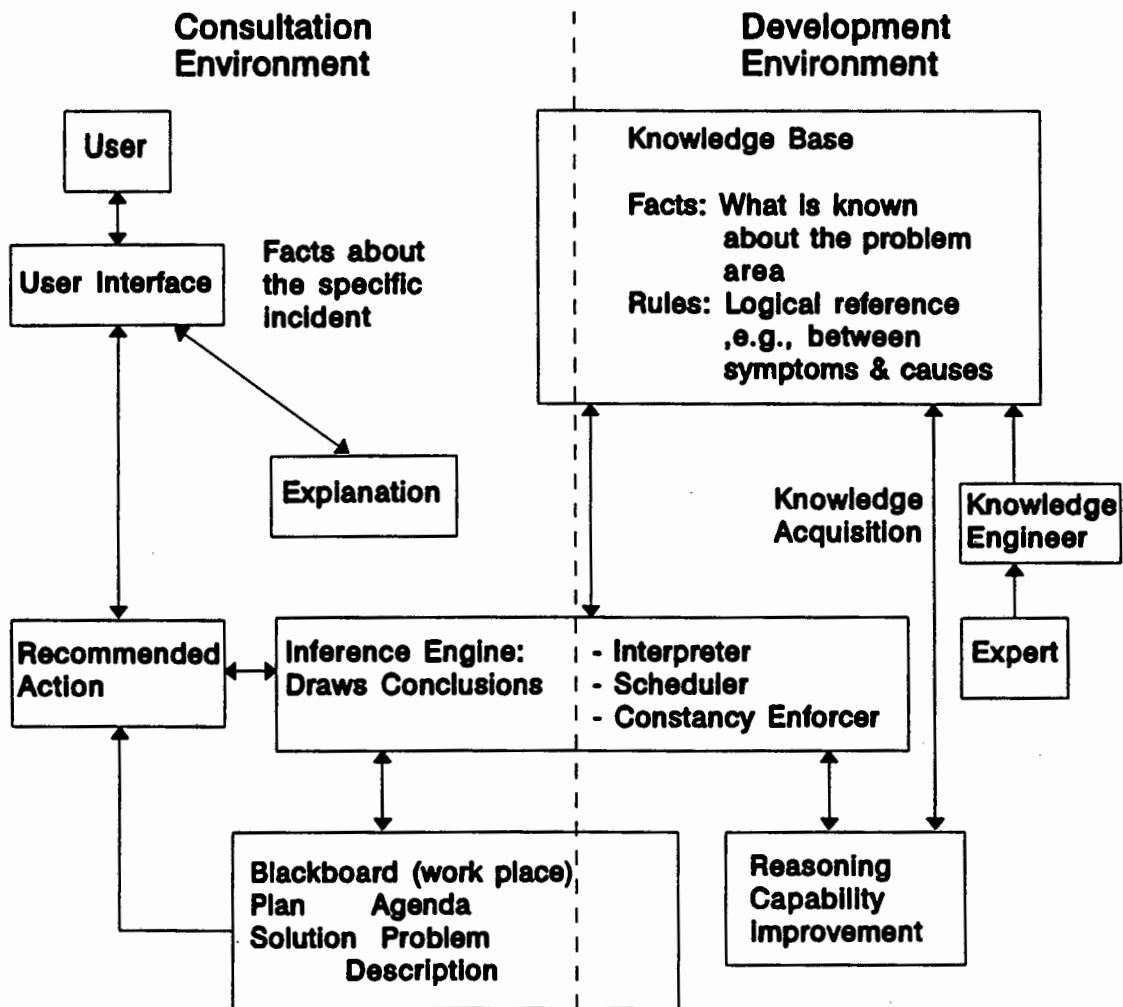


Figure 6 - The structure of an expert system⁽³¹⁾

Now that decision models have been introduced and the tools used to set up these models discussed, one needs an effective method of incorporating the above mentioned tools.

Life Cycle Costing (LCC) is a method which can incorporate the economic decision model tools. A discussion of LCC follows in the next section and with an example it is illustrated how this approach could be used to determine the most economic point in the deterioration cycle to initiate periodic preventative maintenance.

Life cycle costing of concrete structures

The construction industry is becoming increasingly aware of the need to adopt a holistic approach to the design, construction and disposal of concrete structures. In most developed countries 60% of the total construction budget is being spent on repair and maintenance⁽³⁴⁾ so one can see the need to design for durability and reliability, with carefully planned finance, maintenance and repair scheduling. It is important to consider how all costs are allocated and distributed during the lifetime of a structure. This approach, known as life cycle costing, has the aim of minimizing total lifetime expenditure.

Life cycle costing is defined by Dale⁽³⁴⁾ as a "mathematical method used to form or support a decision and is usually employed when deliberating on a selection of options. It is an auditable financial ranking system for mutually exclusive alternatives which can be used to promote the desirable and eliminate the undesirable in a financial environment."

Life cycle costing is best explained by means of an example. In **Table 10** below, construction costs for five different designs of the same kind of concrete structure as well as their maintenance costs, the life-span, demolition costs and simple lifetime costs, have been tabulated. Option (2) has the lowest capital cost, thus in a developer's mind this is the best financial solution and will thus be selected. This "lowest cost" method of decision making is, without question, the current major method of building option selection and works on the assumption that the cheapest solution is the best financial option⁽³⁴⁾.

Only fairly recently has the South African construction industry realised that the running costs of any structure are impacting heavily on the owners' financial resources⁽³⁵⁾. They have found that the 'lowest-cost' system of selection is not always the cheapest solution over the lifetime of a structure. It has become obvious that some other method of financial analysis which takes into account the running costs of the structure must be used to give credence to the decisions when a number of options are under consideration.

Table 10 - Life cycle costing example
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Option	Capital Cost	Maintenance cost/annum	Life-span (years)	Demolition costs	Simple lifetime costs
(1)	R 10 mil	R 400 000	30	R 100 000	R 22.1 mil
(2)	R 8 mil	R 500 000	30	R 100 000	R 23.1 mil
(3)	R 15 mil	R 300 000	30	R 100 000	R 24.1 mil
(4)	R 9.5 mil	R 500 000	30	R 100 000	R 24.6 mil
(5)	R 11 mil	R 425 000	30	R 100 000	R 23.85 mil

In **Table 10** above, the first option, (1), seems to be the cheapest option over the life of the structure. However, the basis of this decision does not stand up to close inspection. It is a well known fact that if maintenance costs are R 400 000 in the first year they won't stay the same for the next ten years but will rise due to inflation, replacements, etc. Other factors that could influence the maintenance expenditure are for example use of different materials to the original, some items may require periodic change over a number of years, resulting in variable annual maintenance costs. Thus, to be able to express all the costs as one single figure would be very beneficial to designers and owners of structures but due to the many variables that influence this figure, this is not always easy.

Methods of Financial Evaluation

There are several methods for solving the problem of finding the cheapest and most economic option. The three most commonly used in the construction industry are the following⁽³⁴⁾:

- (1) *Simple payback* is defined as the time taken for the return on an investment to repay the investment⁽³⁴⁾.

- (2) *Net present value (discounting)* is defined as the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of the investment⁽³⁴⁾.
- (3) *Internal rate of return* is defined as the percentage earned on the amount of capital invested in each year of the life of the project after allowing for the repayment of the sum originally invested⁽³⁴⁾.

These three methods were originally designed to be used in the manufacturing industry to evaluate the financial worth of an investment. These methods were then gradually phased into the building industry where there is no known return being generated but rather money paid out. In the construction industry we want to know whether additional money spent on the construction of a building is worth the savings that will be made by a subsequent reduction in running (including maintenance) costs. For example, the specification of leaving scaffolding and formwork in place for a longer period of time while curing may be more expensive but the saving in maintenance costs over the alternative less durable concrete if stripping takes place too soon, may prove worthwhile.

Reasons why life cycle costing is used as an aid in the decision making process

One reason why it is believed that life cycle costing (LCC) is the method to use for the determination of the most optimal maintenance strategy is because the figures produced by the method provide a more substantive case for certain choices than merely a description. There is some empirical evidence to show that humans are more likely to believe in figures than words because the former imply measurement⁽³⁶⁾. Consequently an argument containing figures is supposed to provide the stronger case. Most research involving cost involves numerical information but if we are to use this information for forecasting then a number of issues need to be addressed.

The first problem is that of obtaining all the data. Without structured data there is little information but in LCC, historic information in terms of costs and performance

is dependent on the constraints imposed on the maintenance manager in terms of budgets allocated towards maintenance. This data gives reasonable information as to how money was spent in the past but doesn't say much as to what will happen in the future.

Decision making is not always entirely logical or rational and many psychological factors come into play. For most people numerical information is a useful starting point but decisions are very often based on other criteria.

A major problem that one has to keep in mind when forecasting on figures based on LCC, is that these costs reflect assumptions about the future behaviour of the environment, of the materials the structure was constructed of, and the people that have an influence on the structure. Much of this information will relate to non-economic issues and will be difficult to measure. Schumacher⁽³⁶⁾ in an attack on cost benefit analysis stated "... to undertake to measure the immeasurable is absurd and constitutes but an elaborate method of moving from preconceived notions to foregone conclusions". However the objective of LCC is to obtain one all embracing figure which represents the investment position of the client.

The reason why all the above issues have been raised is to establish whether LCC really is a suitable tool for the decision model. Brandon⁽³⁷⁾ states: "At best the technique needs to be seen as a reference point, at worst we should recognise the possibility of undermining other values. The weight given to one all embracing figure is dependent on the level of expertise which interprets that figure within the overall decision making process."

Data necessary for the LCC calculation & the establishment of the most economical point in the deterioration cycle to initiate maintenance

(1) *Component Performance:*

A great number of variables have an effect on the performance of a structure e.g. design detailing, workmanship, use of the structure, client's attitude to maintenance, exposure, climatic conditions, etc. It also has to be known how long repair materials last and by how long they extend the life of a repaired r.c. structure. Because component performance is so dependent on all these widely variable factors, one needs a very comprehensive collection of data when attempting to predict the future.

(2) *Life of the structure:*

This is also referred to as the economic life of the structure. Factors like location, population trends, economic climate and planning initiatives are just a few which can have a great impact on the economic life of a structure and with the political and economic situation in this country at present these become even more difficult to predict.

(3) *Inflation:*

Inflation has a very big effect on the costs-in use of a structure. With the relatively high inflation rate in South Africa, that is for ever fluctuating, it is very difficult to make predictions. The next fifty years are likely to be very erratic because of the political uncertainty in this country and because the scarce non-renewable resources of the world will be subjected to differential demand patterns.

(4) *Technology changes & fashion:*

These two factors are forever changing and it is absolutely impossible to predict what is going to happen in the long-term. It is possible that there will

be a substitution for concrete in twenty years time and it is well known fact that new and more advanced repair materials enter the market every year. Fashion changes will also have an influence on the design of structures i.e. whether the superstructures of more and more buildings may be constructed of steel members rather than reinforced concrete, although this trend is not apparent in South Africa.

(5) ***Taxation:***

This has a dramatic effect on future expenditure and in recent times has resulted in a 50% reduction on many future costs for those paying corporation tax. Any changes in taxation and tax relief will have a substantial effect on LCC and the importance of considering future costs.

All the above factors create uncertainty in predicting the future and contribute to the risk involved in decision making. A distinction between risk and uncertainty is sometimes helpful but as Hertz and Thomas⁽³⁸⁾ point out, while the distinction is useful, in conceptual terms it has little value in the practical process of risk assessment and analysis. They go on to say that "... concepts of strategic risk must reflect the realities of strategic decision situations. That is, they must recognise such issues as the quality of information available to decision-makers and the importance of outcomes and organisational goals. Therefore, our concept of strategic risk recognises that strategic decision-making situations involve 'structural uncertainty'. In other words there is considerable uncertainty about the formulation of the problem in terms of its structure and underlying assumptions".

This just highlights the fact that LCC has to be modelled as close to reality as possible to render the data obtained useful in any way.

Due to the fact that it is difficult to obtain data to estimate by how much the life of a structure is extended by initiating maintenance on a more regular basis as opposed to for example only initiating maintenance once rust staining has become visible, it is almost impossible to show in monetary terms that more frequent maintenance is the more economic option. This means that to be able to calculate what the cheapest repair strategy is, one needs to have data available which

outlines by how long specific repair strategies extend the structure's life i.e. time it takes to reach a maximum acceptable deterioration level (*Ref. Figures 6, 7 & 8*).

This is the main reason why no optimal maintenance strategy is proposed in this dissertation, but with further research in the field of the life of repair materials and their effect on the life-extension of repaired structures, it will become possible to demonstrate, in monetary terms, the most economical stages in the deterioration cycle to carry out periodic maintenance and repairs.

An example, outlining the costs involved with four different repair strategies is given below. It is important to realise that the results are mere guidelines because all the data necessary for the LCC calculation have not yet been quantified. Once all this data has been quantified and added to the data already collected in the course of this study, can a more accurate guideline be given as to when the most economic point in the deterioration cycle to initiate planned preventative maintenance comes about (*See also Recommendations for further research*).

Example 4 - Repair options

All the costs used in the below example are based on average costs from **Table 9**. The escalation index value used is extracted from *ref. (25)*.

Four maintenance options are costed / m² of reinforced concrete (i.e. same as the options listed in the degradation flowchart, **Figure 13**). The member to be costed is situated in a severe coastal exposure climate. For comparative purposes the intended life of the member is arbitrarily fixed at 60 years (design life of structures in a marine environment) i.e. it has to remain serviceable for 60 years before a state of maximum acceptable deterioration is reached.

Option 1: Periodic application of a protective coating every time deterioration category 8 is reached (*Ref. Table 2*)(chlorides only penetrated the surface layer).

- This involves smoothing of the surface, filling of hairline cracks and application of a protective surface coating

- Option 2:** Periodic repair work every time deterioration category 6 is reached (*Ref. Table 2*)(chlorides penetrated to 50 - 70% of coverconcrete thickness).
- This involves sealing of cracks with a crack injection resin, application of a bonding coat to isolated spalled surfaces where chlorides have reached the steel, patching of the spalled surfaces and application of a protective surface coating.
- Option 3:** Periodic repair work every time category 3 is reached (*Ref. Table 2*)(chlorides have reached the steel, depassivated it and corrosion has been progressing for some time).
- This involves breaking out of the chloride contaminated areas to behind the reinforcing steel, grit blasting the steel and cleaning of the spalled areas, application of an anti-corrosive coating on the steel, application of a bonding agent on the spalled concrete surface, patching, and application of a protective surface coating.
- Option 4:** Installation of cathodic protection once deterioration category 4 is reached (chlorides have reached the steel, depassivated it and corrosion has only recently commenced).

Many assumptions have to be made in this example, for example the amount of time after repairs until a structure will fall in the same category again. It is assumed after first-time repairs that the structure/member will return to an excellent condition for option 1 but option 2 and 4 only to a very good condition. Option 3 will return to a satisfactory condition because so much deterioration has already taken place i.e. after each repair the structure/member in each of the options will not return to the original condition but will drop by one, two or even three categories. The discount rate to be used to discount future repair costs back to the present is assumed in this example to be equal to the renovation index for building work. A further assumption that was made is the amount of spalling to be repaired (Taken from **Table 9**).

The solution to the above example, i.e. at what point in the deterioration cycle is the most economical point to initiate maintenance, is best illustrated in a hypothetical example given in a table (*Ref. Table 11*).

**Table 11 - Repair option example
(Repair costs expressed in Rands/m²)**

Description	Option 1	Option 2	Option 3	Option 4
Starting category	9	9	9	9
Years from present to time of first repair (years) (<i>Ref. Figure 5</i>)	8	16	34	26
Category at first repairs	8	6	3	4
Present value of first repair cost at given percentage spalling (<i>Ref. Table 9</i>)	R 79.05 0%	R 147.30 15%	R 230.23 45%	R 500.00 35%
Category after first repairs	9	8	6	8
Time to second repair (years) (Assumption - see discussion below)	20	15	10	---
Years from present to time of second repair (years)	28	31	44	---
It is assumed that at the time of the second repair each repair option will have dropped by one category. Because the structure never returns to its original condition after repairs, the time taken to reach the planned deterioration amount will increase gradually and every time repair work is carried out the structure will find itself in a category lower than the originally intended deterioration category when repairs are supposed to have been carried out (lowest allowable deterioration category is 2).				
Category at second repairs	7	5	2	8
Present value of second repair cost at given percentage spalling (<i>Ref. Table 9</i>)	R 85.25 10%	R 162.86 25%	R 431.64 60%	---
Category after second repairs	8	7	5	---
Time to third repair (years) (Assumption - see discussion below)	16	12	8	---
Years from present to time of third repair (years)	44	43	52	---
Category at third repairs	6	4	2	8
Present value of third repair cost at given percentage spalling (<i>Ref. Table 9</i>)	R 147.30 15%	R 196.55 35%	R 431.64 60%	---
Category after third repairs	7	6	4	---

Description	Option 1	Option 2	Option 3	Option 4
Time to fourth repair (years) (Assumption - see discussion below)	12	10	8	---
Years from present to time of fourth repair (years)	56	53	60	---
After the third repairs option 3 should last the intended service life.				
Category at fourth repairs	5	3	---	7
Present value of fourth repair cost at given percentage spalling (Ref. Table 9)	R 162.86 25%	R 230.23 45%	---	---
Category after fourth repairs	6	5	---	---
After the fourth repairs, options 1 and 2 should last the intended service life.				
Total present day cost over the 60 year service life of the structure/member	R 474.46	R 736.94	R 1093.51	R 500.00 + running costs & minor repair costs (25%), Total = R 625.00

Although assumptions were made in the above example especially with regards to the extent to which protective coatings decrease the deterioration rate, the trend that is exhibited is quite clear i.e. protecting a structure from any ingress of chlorides or carbonation is the cheapest repair/protection solution in the long-run. Once the chlorides have penetrated the structure, cathodic protection is the cheapest repair option.

This conclusion, although based on no proven data in this example, ties up with the Federal Highway Administration's policy statement⁽¹⁶⁾ (Ref. Chapter 3) and it should be seen from the example that, although it will still take a great amount of research to quantify all the information necessary for a proper life cycle costing exercise, protection will usually always be cheaper than repair.

In this study life cycle costing concepts will not be discussed in any more detail. From the above short introduction and the example it is clear how important they are to the formulation of any planned preventative maintenance strategy. Because there are so many variables and factors that have an effect on a decision model which is all encompassing, the best way to solve such problems logically and in a consistent manner is with the aid of computers (Ref. Chapter 6).

CHAPTER 6

The use of computer systems to assist in maintenance planning

The world is moving towards being run with the help of computers. This too is the case in the construction maintenance industry. As part of this study, it was investigated how these computer programs came about and the thinking that went into developing them. From personal interviews and the available literature it was attempted to establish what computer programs are available locally, written specifically for South African conditions, as well as what is available abroad.

Introduction

That field of the construction business that deals with the repair of concrete buildings and structures is expanding quite rapidly, especially in the Peninsula area with its severe environment^(2,17,39), and already demands a considerable financial effort from the owners of these structures and the nation's economy as a whole. The large amount of defects on newly repaired concrete structures indicate that the diagnosis of the original defect was incorrectly carried out and that repair products are not used correctly. Companies like FOSROC, SIKA, ABE and PROSTRUCT have progressed far in developing products for repair but from this study it became clear that not all people involved with repair of concrete structures are sufficiently trained to diagnose the various stages in the deterioration process correctly.

At Darmstadt University in Germany the need that this field be taught thoroughly at undergraduate level was recognised and a rule-based expert system for diagnosis and repair of concrete structures was developed called **REPCON**⁽⁴⁰⁾. This expert system was designed as an aid tool for engineers and currently has a knowledge base consisting of about 400 rules implemented in an expert system

shell. The concept of the shell is quite similar to that of **MYCIN** (a rule-based medical expert system that assists in diagnosing infectious diseases and gives advice in antibiotic therapy). **REPCON** has an extensive knowledge base including many facts and relations^(41,42). The user does not only have access to this knowledge base to ask for a diagnosis and a way of repair but also learns about its process of reasoning. The user may therefore ask the program "why" information he is asked for by **REPCON** is needed and the computer will tell which rule it is trying.

However the **REPCON** package only deals with the diagnosis and repair of damaged or deteriorated concrete and still is far from a maintenance management package. In order to come up with a proper maintenance management package one has to integrate Expert Systems with Decision Support Systems (DSS). There is no universally agreed definition for DSS. However Sprague *et al.*⁽⁴³⁾ advanced a useful definition. They define DSS as:

- computer-based systems
- that help decision makers
- confront badly structured problems
- through direct interaction
- with data and analysis models.

Expert or knowledge based systems, on the other hand, use computer programs that incorporate (human) knowledge representations and structuring techniques⁽⁴⁴⁾. These systems are knowledge bases of information which can perform as an expert. Given sufficient data, they can make valid reasoned deductions that can aid the user in making decisions. Expert systems contain three basic components⁽⁴⁴⁾. These are:

- A knowledge base which represents knowledge of facts, general

information, judgements, intuition and experience about a particular problem area.

- An inference mechanism which interprets the knowledge in the data base and performs logical deductions.
- A control mechanism which organises and controls the strategies taken to apply the inference process.

The resulting system of integrating the expert system and the DSS is referred to in most publications as an 'intelligent' DSS which is essentially a DSS as defined above but has the additional capabilities to "suggest", "learn" and "understand" in dealing with managerial tasks and problems⁽⁴³⁾.

The main functional features to be expected of an intelligent DSS for maintenance management of buildings and structures are as follows⁽⁴⁵⁾:

- (1) To access the pre-entered history data from the database for a component of the structure or the entire structure.
- (2) To recognise data patterns i.e. understand the data.
- (3) To be able to query the user for information, judgement, criteria, etc.
- (4) To select a suitable model for the analysis.
- (5) To estimate model parameters.
- (6) To present results to the user in a flexible format, including evaluation of the current maintenance policy and proposed optimal or superior policy.
- (7) To respond to user enquiries and perform a specified analysis (What If? modelling)

- (8) Self-learning and enhancement of the data (knowledge) base subject to constraints e.g. user permission.

Figure 16 shows the outline of a knowledge-based maintenance management system⁽⁴⁵⁾. The system comprises five main sections. i.e.:

- (i) **Database interface** - its main function is to capture the maintenance data from the database and sort it into a usable format.
- (ii) **Model base** - this contains the mathematical formulae and statistical analysis tools which are necessary for data analysis.
- (iii) **Knowledge system** which plays the role of the expert mathematical modeller. This means that it should be able to query the user (maintenance manager) for further information regarding criteria, judgement, data, etc.
- (iv) **User interface** - provides easy communication between the user and the system.

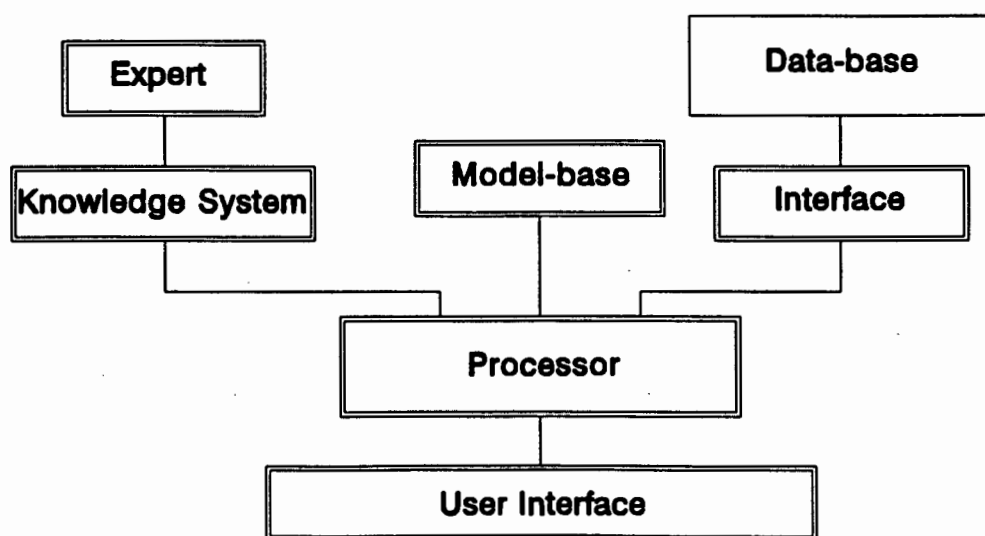


Figure 7 - An outline of a knowledge based maintenance management system⁽⁴⁵⁾

- (v) **Processor** - which is the at the heart of the system and communicates with all other modules. The processor would call other modules to perform certain functions e.g. the knowledge base to advise on model selection. The processor would be responsible for production of results and carrying out "What If?" modelling.

The development of a system which has the above attributes requires a great deal of effort ranging from research in maintenance policies and modelling, to complex software development.

The objective of this study was not to develop a DSS system from scratch but to find out what is available in the field, always keeping the most important aspect in mind - minimising costs. The optimal maintenance management system addresses this aspect and makes adherence to this aspect its prime objective. The package should also be user friendly - i.e. even an inexperienced person should be able to use the package without any problems.

Maintenance Management in the Cape Town area

As a small part of the overall research project, the author interviewed a dozen civil engineering as well as repair and renovation consultants in the Cape Town area. This investigation did not bear much fruit in the field of computerised systems for maintenance of concrete structures because most maintenance plans are based on a qualitative basis rather than a quantitative one. Most consultants were of the opinion that one can't generalize when looking at concrete structures. Each structure has to be assessed on its own which would mean that a computer package which addresses all concrete deterioration problems would have to have a very large database.

Another reason why computers are not used to do planned preventative maintenance is because the availability of money is very limited. Normally "crisis management" i.e. last minute patch repair work is applied to deteriorating structures because of this lack of funding. On reinforced concrete framed buildings

there are many services interacting all the time, and money is rather spent on the essentials like the HVAC (Heating Ventilating & Air-conditioning) system or maintenance of internal fittings and fixtures rather than on the external facade. The majority of consultants that had been involved with maintenance of concrete framed buildings were of the opinion that it is difficult to convince the owners of the particular structures that they should spend, say, R 20 000 on testing what the extent of deterioration is and to work out a preventative maintenance program rather than for, say, repainting the interior walls.

Buildings are all different from each other, with their own design, position, orientation and problems. Some might have dampness and leakage problems, others spalling. A misperception amongst consultants is that one can't have a computer programme which addresses all these problems i.e each structure has to be assessed separately.

Bridges on the other hand are a different matter altogether. Bridges in South Africa are designed to a 120 year design life⁽⁴⁶⁾. Because these consist mainly of reinforced concrete, consultants that have been involved with the design informed the author that the work and expense involved when repairing a bridge is totally out of proportion to new construction so they rather over-design⁽⁴⁷⁾ i.e. use a lower w/c ratio or 20 mm of extra cover to ensure durability.

Concrete roads are also different from the two above. They are far simpler i.e. flat and at ground level, and have fewer components to them. Maintenance of roads is also a fairly simple process - thus the reason that most computer work has been done in this specific field.

Most computer packages that are used address the fields of pavements, bridges or buildings. They are mainly used by semi-government organisations because currently they are the only ones that can afford the initial capital outlay for such systems and own enough structures to use the packages to their full potential^(10,35,48). The reason why they are not used by private organisations yet is because of the costs involved in purchasing such a system and the great amount of work involved to learn the system and to enter all relevant data into the data

base⁽³⁵⁾. Another reason is because consultants do not really believe that computer packages are powerful enough to address all maintenance problems and come up with cost-efficient solutions^(49,50). From interviews with the developers of maintenance software in South Africa, the author believes that the available packages are not too difficult to use and the cost and time savings one makes once a system is up and running far outweigh the initial purchase cost i.e. with a planned maintenance scheme reinforced concrete will last much longer than originally planned⁽⁵¹⁾. Now it is up to consultants to find out what is available and to inform clients and try to promote the use of computers in maintenance planning.

Once an owner of a structure has decided to use computers for maintenance planning he is faced with the following question:

Buy Standard Software or develop In-House?

Much research has been done in the field of deciding whether it is better to use the standard software packages (SSWPs) available on the market for maintenance planning or whether one should rather develop one's own in-house packages (by members of IFRIM - International Foundation for Research in Maintenance)⁽⁵²⁾. With the ever decreasing price of computer equipment as a result of technological advancements during recent years, the computer is becoming more and more feasible for smaller firms and organisations that only own a limited number of structures.

Comparisons between the advantages and the disadvantages of buying standard software have been discussed by several authors of papers in international journals (i.e., Martin⁽⁵²⁾, Wortmann⁽⁵³⁾, and Stahlknecht & Nordhaus⁽⁵⁴⁾). In general the authors agree that buying a suitable SSWP is cheaper compared to in-house development. However SSWPs are seldom found to "fit" without modification, requiring a considerable additional effort in cost and time. In order to personally judge whether SSWPs meet the requirements of a client a measurable instrument is needed, which measures the deviation between predefined required properties, in terms of information requirements, functions, etc, and the properties of the available SSWPs considered. Martin⁽⁵²⁾ has done research in this field and has

developed a framework which can be used when a client is faced with the decision discussed above. However, the author of this thesis does not entirely agree with the learned authors referred to in this section because the better computer packages available need almost no modification. If modification is really necessary the developers of the package are normally willing to do so at a minimal charge⁽³⁵⁾.

Maintenance management systems available in South Africa

In the following section are brief discussions on various computer systems which were inspected while in the Witwatersrand and Pretoria areas.

(1) *Pavement maintenance management systems*

There are a number of maintenance planning packages available that provide road authorities with information management and decision support tools which facilitate cost effective management and maintenance of road networks (concrete as well as asphalt).

The most versatile of these systems, from the results of this study, is one developed by Paul Olivier of the consulting engineering firm, *Jeffares & Green*.

One of the major advantages of this pavement management system, called **JEFFPAVE**, is that it has an automatic and transparent link to a geographical information system (GIS).

In a personal interview with Mr Olivier at *Jeffares & Green* headquarters in Johannesburg it was attempted to establish his basic reasoning and thinking in developing his system. In short the development of the system entailed the following:

- The first aspect that was tackled by the development team was the identification of various defects that can occur on roads, which were then separated into different categories. [These are different for each element of a road network and some are less severe than others e.g.

discolouration is less severe than cracking or spalling.]

- Each defect is then assigned a rating. This is where the system is unique in that the rating consists of two variables, namely degree and extent.
 - The degree variable assigns a percentage to the size of a particular defect.
 - The extent variable expresses the extent to which the defect occurs over the entire structure.
- An algorithm was also formulated which multiplies the **degree** by **extent** times a certain weighting factor. This weighting factor is different for each type of distress so that the computer package recognises that a structural problem requires higher priority for attention than an aesthetic problem.
- When all the data has been entered for a particular road network all the roads in that area have ratings assigned to them which represent their current state in comparison with the other roads of the same network. Costs are calculated for each type of repair multiplied by the length of road and then added in a cumulative manner. See example below (*Ref. Table 12*):

Table 12 - Road maintenance example
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Road	Rating	Costs to Repair	Cumulative Costs
A	26	R 100 000	R 100 000
B	32	R 250 000	R 350 000
C	46	R 170 000	R 520 000
D	55	R 30 000	R 550 000
E	73	R 110 000	R 660 000
F	81	R 80 000	R 740 000
G	84	R 130 000	R 870 000

If, for example, there was a limited budget of say R 600 000 to initiate repairs for the current financial year then roads A,B,C & D would be repaired. Once repairs have been done the road is again inspected according to the same criteria as before and given a new rating which will normally lie between 90 and 100 (where 100 is the rating given to a new road). This means that the road is once again in an excellent condition. Road E would then move into the first priority position when the budget for the following year is prepared and money is again available for maintenance.

The system also makes use of a five year budgeting module using the *Markov Probabilistic Theory*. This theory, in brief, is a procedure that can be used to describe the behaviour of a system in a dynamic situation. "Specifically, it describes and predicts the movement of a system, among different system states, as time passes. This movement is done in a probabilistic (stochastic) environment."⁽⁵⁵⁾ This theory makes predictions in the maintenance and deterioration field with regard to:

- The probability of finding a system in a particular state at a given time, and
- The long-term probabilities of being in such a state.

[This dynamic stochastic system has been used extensively in the field of mathematical deterioration models e.g. by Grandori *et al.*⁽⁵⁶⁾ for durability analysis of buildings in seismic areas, by Binda⁽⁵⁷⁾ for materials-durability analysis and by Binda and Molina⁽⁵⁸⁾ for defining a mathematical model using the semi-Markov process to interpret the decay of building materials subjected to the action of aggressive environments.]

A short explanatory example of this theory is illustrated below (*Ref. Table 13*):

Table 13 - Markov probabilistic theory example

Condition\Year of road\	Now	1	2	3	4	5
Excellent	50%	90% 45%	85% 38%	80% 31%	75% 23%	70% 16%
Good	25%	90% 23%	85% 19%	80% 15%	75% 11%	70% 8%
Fair	15%	90% 14%	85% 11%	80% 9%	75% 7%	70% 5%
Poor	10%	19%	31%	45%	59%	71%

- The above example is for a road network upon which no maintenance is carried out for a period of 5 years.

Brief explanation of the example:

After a routine inspection of all the roads in a certain road network, it is found that 50% of the roads are in an excellent condition, 25% in a good condition, 15% in a fair condition and 10% in a poor condition. For explanatory purposes it is assumed that 90% of the roads in the network will move to a lower category at the end of the first year without maintenance, 85% at the end of the second year, 80% at the end of the third, etc. (These probabilities are updated every year when the package is actually used as real data is received but to do the initial model one has to assume values for the probabilities.) If probabilities remain unchanged from the initially used values then at the end of year 5 only 16% of the roads will still be in an excellent condition and 71% will now be in a poor state.

This example indicates how expensive maintenance could become if it is not carried out in a yearly and planned manner. By budgeting a certain amount of money every year for maintenance and repair of the road network, the figures will not reduce every year i.e. roads in a poor state will actually move to the excellent category once repaired. With **JEFFPAVE** one can assess the effect that various budgets will have on the network.

Other interesting & innovative functions of **JEFFPAVE** include:

- It can handle multiple data base files and offers a facility which enables the user to optimise the assessment algorithm⁽⁴⁸⁾.
- An expert system allows tracking of the logic of the process in order to determine why certain rehabilitation recommendations have been made⁽⁴⁸⁾.
- For the link to a GIS, *Jeffares & Green* has developed a customised menu system which is simple to follow and offers

a host of facilities, such as graphical information filtering features to highlight errors and inconsistencies in the input data (i.e. if a person incorrectly fills in an assessment sheet for a particular road the computer will pick up a mistake in the logic e.g. where a road is classified as good but exhibits cracking as well)⁽⁴⁸⁾.

- Colour coding of the road network according to different calculated indices and maintenance requirements⁽⁴⁸⁾.

Overall, it was found that **JEFFPAVE** is an extremely powerful tool once full maintenance and rehabilitation histories for every road in a particular network has been entered, compared to setting up maintenance strategies without the use of a computer.

(2) ***Bridge maintenance management systems***

All the consultants that were interviewed while attempting to establish what bridge maintenance systems are available informed the author about a package developed fairly recently in Pretoria. This is a system which was developed by ***Van Wyk & Louw Consulting Engineers*** for the Department of Transport (DoT). It is based on a similar system developed by the North Carolina Department of Roads in the United States. Although the basic structure and thinking that went into the development of this system is the same as the American system, ***Van Wyk & Louw*** encountered problems because the climatic conditions and the materials used in the United States were different to those applicable in South Africa. The basic framework remained the same, only the data and input parameters varied.

About 1050 bridges were inspected for the DoT⁽¹⁰⁾. Consulting engineering firms all over the country were each given about 20 bridges to inspect and assess according to a standard assessment sheet. Regular meetings were held so that the assessment criteria were the same for all firms and to be able to keep the data as standard as possible. Each bridge was given a rating between 1 - 9 and comments were added on the assessment sheet to describe the extent of the deterioration.

In this package *Markov Probability Chains* are also used (as in **JEFFPAVE**) where probabilities are assigned to the various conditions/categories within which the individual structures/bridges fall. This is a matrix based system and is based on many assumptions especially with regard to deterioration rates but becomes more accurate as it is updated every year with actual deterioration rates.

Once the maintenance history and current condition of each bridge has been entered into the database (which was the case at the end of 1993⁽¹⁰⁾), the client (i.e. the DoT) will be able to determine on which bridges there should be maintenance expenditure. If the maintenance budget is limited the computer indicates which bridge needs maintenance most urgently and makes recommendations as to how the repairs should be initiated. Once repairs have been completed the bridge will once again move up in categories e.g. to category 9 which is excellent (same classification system as used earlier in this thesis) and will not require maintenance for the next few years.

When the budget is limited and the computer indicates that there are two bridges that need repair equally the computer decides which one should be repaired first by dividing the change in class that would result from the repairs (i.e. a major resurface might move a class 5 bridge to class 8 or 9, thus the Δ class = 3 or 4) by the amount of capital (Rands) that would be spent on the particular repair. The computer package then compares the resultant figure with the resultant figure for the other bridge under consideration and the larger one will be the one chosen for repair.

The package also takes into account the different climatic conditions in the country, and the computer system "knows" that bridges in the Western Cape deteriorate faster than those on the highveld⁽¹⁰⁾. When cracking, for example, occurs on a bridge in the Western Cape the time before serious corrosion starts is much less than for a similar crack on a bridge on the highveld.

The DoT has already started using the package to do preventative maintenance of bridges i.e. bridges on the N1 north between Pretoria and Pietersburg. These bridges are all still fairly young and some of them are being coated with an epoxy-

based transparent resin⁽¹⁰⁾. These bridges exhibit almost no signs of distress (only a few isolated minor cracks) but the computer programme recommended that the most economical maintenance strategy was to carry out preventative maintenance now rather than carrying out major repairs a few years later.

By drawing on the knowledge and experience of others, it is believed that we can avoid the problems by using planned preventative maintenance. [An illustration of how severe the problem could become if it is not addressed timeously is outlined in an article in *Scientific American*⁽⁵⁹⁾ - ***Why America's Bridges Are Crumbling*** - *Inadequate maintenance has piled up a repair bill that will take decades to pay off. Indeed, the scope of the problem is only now becoming clear.*]

(3) ***Building & real estate maintenance management systems***

The system that was inspected for the purpose of building maintenance planning is called **PREMIS** (**P**rofessional **R**eal **E**state **M**anagement **I**nformation **S**ystem). It is a computer system, designed by the *CSIR's Division of Building Technology* in Pretoria, specifically for managers of estates consisting of buildings and equipment, as well as associated land, roads and engineering services infrastructure.

Some of the features of **PREMIS** include:

- Once entered, the package keeps a record of when the building was built and who the design team, contractors, subcontractors and suppliers were. It keeps track of expected life-spans of the various construction and engineering services elements and equipment items, as well as their recommended maintenance procedures and guarantee periods. The system also keeps record of the types of spaces available within each building, e.g. office, laboratory or retail space, and whether these are owned, or leased to or from another organisation. It can also track lease periods and the efficiency with which space is utilised.
- In the database the system stores a computer drawing of each building (drawn in **AutoCAD**). Answers to questions can be displayed on a drawing

of an individual room, of a building, on a map of a town, region, country or even a continent⁽³⁵⁾. One can also ask the computer very complex questions, such as: *"Show me all buildings in the city bowl area with more than five storeys, that are within three kilometres of the coastline, have roofs with a remaining life of less than four years, where the annual maintenance budget exceeds R 50 000 a year and the lift cable inspection is overdue by more than six weeks."*

- At a meeting in Pretoria the system was inspected and demonstrated by Mr Graham Lockly, the computer programmer on the design and development team of **PREMIS**. He indicated that the package bases its maintenance planning on preventative maintenance rather than "crisis management" as is currently the situation in the industry⁽⁶⁰⁾. The user of the system can select one of three options of how often he wants to carry out inspections i.e.

- Fixed date inspection
- Percentage of remaining life
- Work hours

For the fixed date inspection one merely specifies a date for inspections e.g. on the 1st of every alternative month. The second option is the best in the author's opinion because if a door has an estimated life of 10 years it might be inspected when 50% of its life remains i.e. in year five. The door's remaining life then gets re-evaluated and then inspected again once 50% of that period has elapsed. This means that inspections will become more frequent as the full life of an element is approached. The work hours option is intended for elements like lights, HVAC systems, computer monitors, etc. which can be assigned an estimated service life measured in hours of service.

- With the above information the system can handle forward maintenance budgeting and can track both routine inspection and maintenance schedules. The system gives information on what will need repair/replacement during the next month.

- The core of the system, a Geographical Information System (GIS), is linked to **Oracle**, one of the world's most widely used Relational Database Management Systems (RDBMS)⁽³⁵⁾. This combination allows the creation of endless sets of graphic and non-graphic data of virtually unlimited size. **AutoCAD** has also been incorporated into the system as well as **SQL**, an international standard database query language.

- The major advantage of this system is that it can be used as an accommodation management system, a rental administration system or as a maintenance management system or a combination of all three. The implementation can be phased gradually to eventually cover all aspects or it can remain partial, depending on one's organisational needs⁽³⁵⁾.

Overall, it is believed that this system can be used very effectively for the maintenance of one's buildings once all the data has been entered and one adheres to the computer's recommendations.

Maintenance management computer systems abroad

The available literature refers to a number of computer packages and expert systems that have been developed in the fields of diagnosis & repair of deteriorating concrete structures (e.g. **REPCON**⁽⁴²⁾) as well as in the fields of preventative maintenance planning and management taking into account the economics side of maintenance. This section is a brief summary of computer systems that are referred to in the local available literature (University of Cape Town library, PCI library & the Cape Town public library).

From the investigation, it was found that most of the research on maintenance had been done at the Eindhoven University of Technology in the Netherlands, at the University of Strathclyde in the UK as well as at Kyoto University in Japan.

At Eindhoven University C.W. Gits & W.M.J. Geraerds, with their students, have developed a computer based package called **The EUT maintenance model**, which is a package which evolved over a number of years⁽⁶¹⁾. At the University maintenance was introduced as an elective in the late sixties in the MSc curriculum in Industrial Engineering and Management Science. According to Geraerds⁽⁶¹⁾ students chose this elective course with the specific intention to concentrate their final MSc research project on this area. Over a hundred have up to now made use of this option. Geraerds⁽⁶¹⁾ also states that the research started off in an explorative nature and that it appeared impossible to evaluate the abundance of publications as for the relevance of their specific contributions to maintenance science.

Most publications state that preventative maintenance "is good for you" but they don't specify how this maintenance should be carried out. The majority of publications on the economic aspect (mostly in the *International Journal of Production Economics*) suggest that maintenance costs are too high and that all that needs to be done is realize maintenance at optimal costs, again not specifying in what way this should be achieved.

Geraerds and his students had similar problems⁽⁶¹⁾ and that is why they developed this computer programme.

(1) *Maintenance management of pavements & highways*

In the specific field of roads and highways there are many computer packages available. The first real computer based package was one developed by the Massachusetts Institute of Technology (MIT)⁽⁶²⁾. This was updated in order to address its deficiencies by the Transport and Road Research Laboratory (TRRL), in collaboration with the World Bank and a model called **RTIM**⁽⁶³⁾ was developed. The World Bank however soon required a more complex model and in 1976 contracted MIT to produce the Highway Design and Maintenance standards model, **HDM**⁽⁶⁴⁾.

In the UK the Department of Transport (DoT) developed a cost benefit analysis computer program in the '70s called **COBA** which evaluates costs and benefits over a 30-year period and bases results on the net present value⁽⁶²⁾. The current version of the program is **COBA9**⁽⁶⁵⁾. Recently, the Department has introduced another new program, **URECA**, for the assessment of urban road networks⁽⁶⁶⁾.

Other models that have been developed around the world to assist in the evaluation of life cycle costs for roads and maintenance planning are **EAROMAR**⁽⁶⁷⁾, **LIFE2**⁽⁶⁸⁾, **NIMPAC**⁽⁶⁹⁾, **RENU**⁽⁷⁰⁾ to name but a few.

(2) *Maintenance management of buildings*

Not much reference is made to this specific field in the available literature. The literature does make some reference to names of people or companies that have developed models but it is not always clear whether they are computerized or not.

A firm in Canada, **COPLANAM Ltd**, has done some work in the computerization of maintenance systems for buildings and advertise a wide variety of applications⁽⁷¹⁾.

Dr S. Gustafsson of the Institute of technology in Sweden developed a computer model for optimal energy retrofits in multi-family residences (The **OPERA** model) which reduces life-cycle costs and maintenance requirements. He also incorporates the preventative maintenance side of HVAC systems in his model⁽⁷²⁾.

A computer program that is used throughout the United States on army owned housing is one developed by the U.S. Army Construction Engineering research Laboratory (USA-CERL). This maintenance and repair prediction model (**MRPM model**) serves as a system of record and maintains a list of all available computer tools (**PAVER, ROOFER**). The main function of this computer program is to set up a preventative maintenance program and then to predict the labour, material, equipment and capital resources required for maintenance over a 10-year planning period⁽⁷³⁾.

Another model is one developed in Japan at Kyoto University by three professors Furusaka, Furukawa and Tohiguchi. In this planning model for maintenance the user can select whether to either carry out (1) preventative maintenance (repair regularly) or (2) replace (replace without repair) or (3) do corrective maintenance (when deterioration amount exceeds a prescribed value then maintenance is carried out)⁽⁶¹⁾.

[For further information with regards to computerized maintenance management systems See Ref. (74)]

Conclusion and Recommendations

Conclusion

From the data collected and presented on deteriorating structures in the two exposure climates in the Cape Peninsula, it appears that there is a problem to be faced. Younger reinforced concrete structures in a severe coastal exposure climate are taking an average of 38 years to reach a stage of maximum acceptable deterioration (*Ref. Figure 5*). From *Figure 5* it can be seen that younger structures (about 30 years of age) are very close to a maximum acceptable deterioration limit, whereas older structures have shown good durability and are still standing after 70 years. With the high costs of repairs, as illustrated in costed examples and quoted costs in tables and figures, it is also clear that something has to be done to ensure that these fairly young r.c. structures last longer. What has to happen is that the lives of structures have to be extended at a lowest possible cost.

Formulas are given to enable the calculation of future maintenance costs as well as formulas to calculate how much should be saved in order to have sufficient funds to carry out maintenance at some specified date in future. These formulas can be used for short-term budgeting of future maintenance expenditure if one uses the deterioration trend curves in conjunction with the repair cost data (*Ref. Figure 4 & 5 and Table 9*).

After the evaluation of some of the major decision model tools available, life cycle costing was chosen to be used for the determination of the most economical point in the deterioration cycle to initiate periodic maintenance. An example is given in which the author attempts to illustrate how life cycle costing can be used to establish the most economic point in the deterioration cycle. Due to the vast amount of data that has not yet been quantified, can the example only be used as a guide of how one would go about determining the most economical point to initiate maintenance. Guidelines are given of how a decision model should be

developed. (The data that still has to be quantified is listed (*Ref. Chapter 5 & Recommendations for future study*)).

The recommendations and conclusions of this study can be summed up in the following way:

Due to the ever increasing costs of maintenance, costs of repair work have to be kept to a minimum; not by using cheap repair materials or by extending the time between periodic maintenance, or by saving on site supervision, but by following a planned **preventative** maintenance strategy.

The best way this can be done is by educating owners of structures as to the advantages of preventative maintenance and encouraging consultants to advocate the collection of historical data on all elements of a structure and then with the use of computer aided maintenance management systems formulate a preventative maintenance strategy.

Recommendations for future study

There is a great deal of data that has to still be collected before a useable model can be developed which optimises maintenance cycles and methods of repair, namely:

- Data needs to be collected on r.c. structures that have been repaired in the past to see how long the various repair materials last, at what time intervals those structures have to be repaired again and by how long the life of the specific structures is extended.
- Rates of chloride diffusion and carbonation penetration through repair materials need to be quantified.
- The compatibility of repair materials to 'old' concrete needs to be assessed i.e. the possibility of patched sections diverting the corrosion process into adjacent areas, thus developing incipient anodes.
- Discount rates and escalation rates of repair work indices need to be quantified.

With the above data in hand, combined with the data quantified in this dissertation, proper life cycle costing can be carried out on reinforced concrete structures and a model can be developed which can be used to establish the most economical maintenance management strategy.

Another study that can be carried out, once a model has been developed, is a comparative costing between repetitive repairs, electro-osmosis (re-alkalisation of concrete⁽⁷⁵⁾) in conjunction with repairs and cathodic protection to see what really is the most cost effective repair method over the life of a r.c. structure. Such costings should also be compared with the costs of designing and building a structure specifically with extra durability in mind. It may well prove that this strategy is more economical over the life of a structure than repetitive repairs.

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APPENDIX 1

Cost build-up for items (1) - (5) in Example 1

- (1) High pressure water-sand jet cleaning of the surface to remove all paint, organic matter, loose concrete and dust

Cost: Taken from Table 6, Item no. 2 i.e. High pressure water-sand jet cleaning

R 13.73/m²

- (2) Fill non-structural cracks and blowholes with Sikaguard 75 Epo Cem

Cost: Materials -

Sikaguard 75 Epo Cem

Quoted purchase price (Feb. 94) for a 23 kg kit = R 173.00

Average contractor's discount = 20%

Price = R 173.00 + 14% VAT - 20% Discount
R 157.78

After mixing all components get a yield of 10.5 litres per 23 kg kit.

At an application thickness of 0.5 mm get a coverage of:

$$1.05\text{m}^2 @ 10 \text{ mm thick} * 10/0.5 = 21\text{m}^2$$

$$\begin{aligned} \text{Cost/m}^2 &= \text{R } 157.78/21 \\ &= \text{R } 7.51/\text{m}^2 \text{ (Ref. Table 7)} \end{aligned}$$

Labour -

Taken from Table 6, Item no. 11 i.e. Application of skimming layer on surface of concrete to fill blowholes and smooth surface

R 20.52/m²

Total cost: R 7.51 + R 20.52 = R 28.03/m²

But only apply this 90% of the surface area

Total cost = R 25.23/m²

- (3) Apply a bonding agent, **Sikacem 810**, on spalled areas to ensure strong bond between old concrete and repair mortar.

Cost: Materials -

Sikacem 810

Quoted purchase price (Feb. 94) for 5 litre (5.2 kg) container = R 52.00

Average contractor's discount - 20%

Price = R 52.00 + 14% VAT - 20% Discount
R 47.42

Require 200 kg **Sikacem 810** /m³ for bonding slurries

Thus require 2 kg/m² per 10 mm coat

Cost/kg = R 47.42 / 5.2kg = R 9.12/kg

Cost/m² = R 9.12 * 2 = R 18.24/m² @ 10 mm thick

Portland cement

Quoted purchase prices (Feb. 94) from PPC:

Supplied from -

De Hoek - R 10.95 + VAT = R 12.48

Riebeeck West - R 11.25 + VAT = R 12.83

Montagu Gardens -R 11.85 + VAT = R 13.51

R 38.82

Ave price/ 50kg bag = R 12.94

Price/kg = R 12.94 / 50 = R 0.26

Require 625 kg **Portland Cement** /m³ for bonding slurries

Thus require 6.25 kg/m² per 10 mm coat

Cost/m² = R 0.26 * 6.25 = R 1.63/m² @ 10 mm thick

Phillipi Dune Sand

Quoted purchase price (Feb. 94) from Ready Mix Materials, delivered to Rondebosch

$$\text{Price} = \text{R } 28.05 / \text{m}^3$$

Require 1:1 - 1:1.5 parts of sand by weight of cement for bonding slurries

Thus require $625 * 1.25 = 781.25 \text{ kg sand/m}^3$ of slurry

$$\rho = m/v, \text{ thus } v = m/\rho$$

$$\text{where } \begin{array}{l} \text{loose bulk density of sand } (\rho) \\ = 1745 \text{ kg/m}^3 \end{array}$$

Thus $v = 781.25 / 1745 = 0.4477 \text{ m}^3 / \text{m}^3$ of bonding slurry

$$\text{Cost} = \text{R } 28.05 * 0.4477 = \text{R } 12.56 / \text{m}^3 \text{ mortar}$$

$$\text{Cost/m}^2 = \text{R } 0.13/\text{m}^2 @ 10 \text{ mm thickness}$$

$$\begin{aligned} \text{Total Cost/m}^2 &= \text{R } 18.24 + \text{R } 1.63 + \text{R } 0.13 \\ &= \text{R } 20.00 / \text{m}^2 @ 10 \text{ mm thick} \end{aligned}$$

When using as bonding slurry only apply to a thickness of 1.5 mm

$$\text{Total Cost/m}^2 = \text{R } 3.00/\text{m}^2 \text{ (Ref. Table 7)}$$

Labour -

Taken from Table 6, Item no. 6, i.e. Apply bonding coat to raked out concrete surface

$$\text{R } 1.14/\text{m}^2$$

$$\text{Total Cost/m}^2 = \text{R } 3.00 + \text{R } 1.14 = \text{R } 4.14/\text{m}^2$$

But only apply this to 10% of surface

$$\text{Total Cost/m}^2 = \text{R } 0.41$$

- (4) Patching of light spalling with **Sikarep** on horizontal and vertical surfaces and **Sikarep LW** on vertical and overhead surfaces.

Cost: Materials -**Sikarep**

Quoted purchase price (Feb. 94) for a 25 kg bag = R
45.00

Average contractor's discount = 20%

Price = R 45.00 + 14% VAT - 20% Discount
R 41.04

After mixing with water get a yield of 12 litres per 25 kg
bag.

Thickness of repair varies from 0 - 20 mm in this
category thus take an average of 10 mm.

At a patching thickness of 10 mm get a coverage of:

1.2 m² @ 10 mm thick @ R 41.04

Cost/m² = R 34.20 (*Ref. Table 7*)

Labour -

Taken from **Table 6**, Item no. 7 i.e. Concrete repairs with a
cementitious repair mortar within the following height ranges
above existing ground level: (i) 0 m up to 1.5 m

R 10.11 /l = R 10.11 /m² @ 10 mm thickness

Total cost: R 34.20 + R 10.11 = R 44.31 /m²

But only apply this to 10% of surface

Total Cost/m² = R 4.43

- (5) Application of a protective surface coating i.e. **Sikaguard 550 Elastic Top**.

Cost: Materials -**Sikaguard 550 Elastic Top**

Quoted purchase price (Feb. 94) for a 5 l container = R
120.00

Average contractor's discount = 20%

Price = R 120.00 + 14% VAT - 20% Discount

R 109.44

After mixing all components get a coverage of 4 m²/l/coat * 2 coats.

Cost/l = R 109.44 / 5 = R 21.89 /l

Cost/m² = R 21.89 / 4 * 2 coats

= R 10.94/m² (*Ref. Table 7*)

Labour -

Taken from **Table 6**, Item no. 12 i.e. Application of barrier coating to concrete surface: (iii) 2 coats Polymer modified cementitious coating or elastic coating

R 14.39/m²

Total cost: R 10.94 + R 14.39 = R 25.33/m²

APPENDIX 2

Cost build-up for items (1) - (8) in Example 2

- (1) Removal of defective r.c. up to 20 mm behind the reinforcing bar

Cost: Taken from Table 6, Item no. 4, i.e. Removal of defective Reinforced concrete within the following height ranges above existing ground level: (i) 0 m up to 2.5 m

R 3.06/l

Assuming that the reinforcing steel is at an average depth of 50 mm from the surface, raking out has to occur to a depth of 70 mm. The sides of the raked out fillet are sloped so one can assume for estimating purposes that the raking out occurs to a depth of 50 mm with straight sides.

Cost = R 3.06/l = R 3.06/m² @ 10 mm deep

Cost/m² = R 3.06 * 5 = R 15.30 /m² @ 50 mm deep

But only rake out 35% of the surface area

Cost = R 5.36/m²

- (2) High pressure water-sand jet cleaning of the surface to remove all paint, organic matter, loose concrete and dust

Cost: Taken from Table 6, Item no. 2 i.e. High pressure water-sand jet cleaning

R 13.73/m²

- (3) High pressure grit blasting to remove all iron oxide (rust products) from reinforcing steel

Cost: Taken from **Table 6**, Item no. 3 i.e. High pressure grit blasting
R 23.55/m²

Assuming an average diameter of 12 mm for the steel rebar.

$$\begin{aligned} \text{Circumference of 12 mm diam. bar} &= 2 * \text{pie} * r \\ &= 2 * \text{pie} * 0.006 = 0.0377 \text{ m} \end{aligned}$$

In 1m² have on average 10 m of steel⁽²⁰⁾

$$10 \text{ m} * 0.0377 \text{ m} = 0.377 \text{ m}^2/\text{m}^2 \text{ on concrete}$$

$$\text{Cost} = 0.377 * \text{R } 23.55 = \text{R } 8.88/\text{m}^2$$

But this only applies to 35% of area

$$\text{Cost} = \text{R } 3.11/\text{m}^2$$

- (4) Apply anti-corrosive coating on the steel rebar, **Nitoprime Zincrich**

Cost: Materials -

Nitoprime Zincrich

Quoted purchase price (Feb. 94) for a 0.5 l container =
R 29.18

$$\begin{aligned} \text{Price} &= \text{R } 29.18 + 14\% \text{ VAT} * 2 \\ &\text{R } 66.53 / \text{l} \end{aligned}$$

Coverage rate = 7.4 m² /l

Assuming an average diameter of 12 mm for the steel rebar.

$$\begin{aligned} \text{Circumference of 12 mm diam. bar} &= 2 * \text{pie} * r \\ &= 2 * \text{pie} * 0.006 = 0.0377 \text{ m} \end{aligned}$$

Thus have 26.53 linear metres of steel /m²

$$\begin{aligned} \text{Cost} &= \text{R } 66.53 / [26.53 * 7.4] \\ &= \text{R } 0.34 / \text{m} \text{ (Ref. Table 7)} \end{aligned}$$

In 1m² have on average 10 m of steel⁽²⁰⁾

$$\text{Cost} = \text{R } 0.34 * 10 = \text{R } 3.40/\text{m}^2$$

Labour -

Taken from **Table 6**, Item no. 5 i.e. Prime Reinforcing Bars with

an approved coating

R 3.26/m

$$\text{Cost} = \text{R } 3.26 * 10 = \text{R } 32.60 /\text{m}^2$$

$$\text{Total cost: R } 3.40 + \text{R } 32.60 = \text{R } 36.00/\text{m}^2$$

But this only applies to 35% of area

$$\text{Total cost} = \text{R } 12.60/\text{m}^2$$

- (5) Apply a bonding agent, **Nitobond HAR**, on spalled areas to ensure strong bond between old concrete and repair mortar (35% of area)

Cost: Materials -

Nitobond HAR

Quoted purchase price (Feb. 94) for a 20 litre container

$$= \text{R } 220.40$$

$$\text{Price} = \text{R } 220.40 + 14\% \text{ VAT}$$

$$= \text{R } 251.26$$

$$\text{Price/l} = \text{R } 251.26 / 20 = \text{R } 12.56 /\text{l}$$

Applied at a given application rate/coverage of 3.5 m²/l

for bonding purposes

$$\text{Cost/m}^2 = \text{R } 12.56 / 3.5$$

$$= \text{R } 3.59 /\text{m}^2 \text{ (Ref. Table 7)}$$

Labour -

Taken from Table 6, Item no. 6, i.e. Apply bonding coat to raked out concrete surface

$$\text{R } 1.14/\text{m}^2$$

$$\text{Total Cost/m}^2 = \text{R } 3.59 + \text{R } 1.14 = \text{R } 4.73/\text{m}^2$$

But only apply this to 35% of surface

$$\text{Total Cost/m}^2 = \text{R } 1.66$$

- (6) Patching of advanced spalling and raked out areas with **Renderoc HB** (35% of area)

Cost: Materials -

Renderoc HB

Quoted purchase price (Feb. 94) for a 18 kg bag = R 70.38

$$\begin{aligned} \text{Price} &= \text{R } 70.38 + 14\% \text{ VAT} \\ &= \text{R } 80.23 \end{aligned}$$

After mixing with water get a yield of 14.5 litres per 18 kg bag.

Thickness of repair in this category averages to 50 mm with perpendicular raked out sides (Ref. Item 1 above).

At a patching thickness of 10 mm get a coverage of:

$$1.45 \text{ m}^2 @ 10 \text{ mm thick @ R } 80.23$$

$$\text{Cost/m}^2 = \text{R } 80.23 / 1.45 = \text{R } 55.33/\text{m}^2 @ 10 \text{ mm}$$

$$\text{Cost/m}^2 = \text{R } 276.65/\text{m}^2 @ 50 \text{ mm thick}$$

(Ref. Table 7)

Labour -

Taken from **Table 6**, Item no. 7 i.e. Concrete repairs with a cementitious repair mortar within the following height ranges above existing ground level: (i) 0 m up to 1.5 m

$$\text{R } 10.11 / \text{l} = \text{R } 10.11 / \text{m}^2 @ 10 \text{ mm thickness}$$

$$\text{Cost} = \text{R } 10.11 * 5 = \text{R } 50.55$$

$$\text{Total cost: R } 276.65 + \text{R } 50.55 = \text{R } 327.20 / \text{m}^2$$

But only apply this to 35% of surface

$$\text{Total Cost/m}^2 = \text{R } 114.52$$

- (7) Application of a thin surface coat to fill blowholes and little cracks to provide a smooth surface for a protective surface coating i.e. **Renderoc FC**

Cost: Materials -

Renderoc FC

Quoted purchase price (Feb. 94) for a 25 kg bag = R 63.50

$$\begin{aligned} \text{Price} &= \text{R } 63.50 + 14\% \text{ VAT} \\ &= \text{R } 72.39 \end{aligned}$$

After mixing with water get a yield of approximately 15 litres per 25 kg bag.

At an application thickness of 1.5 mm get a coverage of:

$$1.5\text{m}^2 @ 10 \text{ mm thick} * 10/1.5 = 10\text{m}^2$$

$$\begin{aligned} \text{Cost/m}^2 &= \text{R } 72.39 / 10 \\ &= \text{R } 7.24 / \text{m}^2 \text{ (Ref. Table 7)} \end{aligned}$$

Labour -

Taken from **Table 6**, Item no. 11 i.e. Application of skimming layer on surface of concrete to fill blowholes and smooth surface

$$\text{R } 20.52/\text{m}^2$$

$$\text{Total cost: R } 7.24 + \text{R } 20.52 = \text{R } 27.76/\text{m}^2$$

But only applies to 65% of the total surface area

$$\text{Total cost} = \text{R } 18.04/\text{m}^2$$

(8) Application of a protective surface coating, **Nitocote Dekguard 'S'**

Cost: Materials -

Nitocote Dekguard 'S'

Quoted purchase price (Feb. 94) for:

$$\text{Dekguard Primer} = \text{R } 11.84 / \text{l}$$

$$\begin{aligned} \text{Price} &= \text{R } 11.84 / \text{l} + 14\% \text{ VAT} \\ &= \text{R } 13.50 / \text{l} \end{aligned}$$

$$\text{Dekguard 'S' Topcoat} = \text{R } 23.10 / \text{l}$$

$$\text{Price} = \text{R } 23.10 / \text{l} + 14\% \text{ VAT}$$

$$= \text{R } 26.33 / \text{l}$$

Coverage rate of primer - 2.5 m²/l

$$\text{Cost/m}^2 = \text{R } 13.50 / 2.5 = \text{R } 5.40$$

Coverage rate of topcoat - 7 m²/l/coat

$$\text{Cost/m}^2 = \text{R } 26.33 / 7 * 2 \text{ coats} = \text{R } 7.52$$

$$\text{Cost/m}^2 = \text{R } 5.40 + \text{R } 7.52$$

$$= \text{R } 12.92/\text{m}^2 \text{ (Ref. Table 7)}$$

Labour -

Taken from **Table 6**, Item no. 12 i.e. Application of barrier coating to concrete surface: (ii) Primer & 2 coats Topcoat

R 17.86/m²

$$\text{Total cost: R } 12.92 + \text{R } 17.86 = \text{R } 30.78/\text{m}^2$$