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ABSTRACT:

Part 2 of the paper concentrates on the issue of life cycle costing (LCC) for deteriorating reinforced concrete structures. A simple example is given, and data necessary for applying the LCC approach are discussed

A series of repair options related to various deterioration categories are discussed, and the options costed on an LCC basis. It is shown, subject to the assumptions, that protecting a structure from ingress of chlorides in the marine environment is the cheapest repair/protection solution in the long-run. Once chlorides have significantly penetrated the structure, cathodic protection becomes a favourable repair option economically

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TECHNICAL PAPER

DETERIORATION, REPAIR AND MAINTENANCE OF REINFORCED CONCRETE STRUCTURES IN THE CAPE PENINSULA – PART 2

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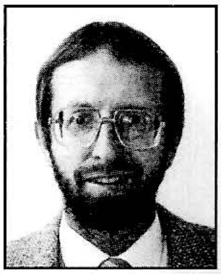

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ABSTRACT

Part 2 of the paper concentrates on the issue of life cycle costing (LCC) for deteriorating reinforced concrete structures. A simple example is given, and data necessary for applying the LCC approach are discussed. A series of repair options related to various deterioration categories are discussed, and the options costed on an LCC basis. It is shown, subject to the assumptions, that protecting a structure from ingress of chlorides in the marine environment is the cheapest repair/protection solution in the long-run. Once chlorides have significantly penetrated the structure, cathodic protection becomes a favourable repair option economically.

1. INTRODUCTION

Part 1 of this paper provided data indicating the rate at which reinforced concrete structures deteriorate in the Cape Peninsula due to environmental degradation. It also covered maintenance and repair options and repair costs, and the minimising of short-term costs.

Part 2 deals with aspects of decision models and life cycle costing, to assist in determining the most economic point in the deterioration cycle for preventative maintenance. It is not intended to be definitive or exhaustive, but rather to raise important issues in the ongoing debate on concrete durability and its implications.

Various repair and maintenance options were discussed in Part 1, for example, patch repairs, cathodic protection, demolition and replacement. The choice of repair option 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 should be to discover the cause of the distress or deterioration. What follows is a short introduction of the options available for arriving at correct decisions for repair and maintenance.

2. DECISION MODELS FOR MAINTENANCE OF REINFORCED CONCRETE STRUCTURES

Decision models are a useful aid for arriving at correct decisions. Green and James[1] define decision models as follows: "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 to define a maintenance strategy they help to structure the thought processes and to ensure that all the significant variables have been considered.

Maintenance management can be divided into

- technical decisions which will govern a maintenance programme, and
- operational decisions which will affect the methods of carrying out the work and the efficiency of its output[1].

The technical decisions will cover considerations such as the break-even point between acceptable deterioration and maintenance, when to replace the concrete structure or parts of it, and the establishment of economic cycles for recurring inspection and maintenance work. These decisions will contribute to the development of long-term plans with annual maintenance programmes and budget allocations.

Operational decisions will include considerations such as 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.

A decision model can 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 systematic light replacement or a re-lamping model[2]. This model enables managers to determine whether it is 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 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.

A decision model relevant to making economic decisions with regard 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. The problem is 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.

For small and uncomplicated concrete structures this may be relatively simple, provided cost data are available. It may only be necessary to have expenditure data on maintaining the structure over the past years, and the cost of replacement, (assuming no other costs are involved when replacing, such as loss of profits if operations are disrupted). 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 does not justify immediate replacement, then it could be possible to predict future repair costs and a forecast could be made as to the date replacement is likely to be justified. However a practical problem is that sufficient data is usually not available to make these predictions. Furthermore, many more factors than the direct maintenance cost described above will affect the decision, and may not be easily quantified. For example, the influence of the external environment, together with the orientation, degree of exposure and the height of a structure are a few of the factors that affect the rate at which concrete deteriorates.

2.1 Tools used in setting up decision models

The basic tools most commonly employed in constructing decision models are connected with statistics, economics and management, although these are all interrelated[1].

(1) Probabilities and Statistics

Concrete deterioration and the factors affecting it 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 as more of the input variables become probabilistic.

(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. Discounting involves 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.

Once the data for a particular concrete structure have been collected and the benefits and disbenefits associated with the deterioration problem quantified, a technique is needed to deduce the most economical 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.

(3) Management tools

In this field there are once again numerous tools that can be employed, such as "Decision Trees", Mathematical programming, and Expert Systems. It is beyond the scope of this paper to discuss this, and the interested reader should consult references 3-5 for further details.

3. LIFE CYCLE COSTING OF CONCRETE STRUCTURES

Life cycle costing (LCC) is a method which can incorporate the economic decision models and tools briefly introduced above. This section discusses LCC, primarily with an example to illustrate how this approach could be used to determine the most economic point in the deterioration cycle to initiate periodic preventative maintenance.

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, hence 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[6] 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 a hypothetical example. In **Table 1** 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, making it the best financial solution for most developers. This "lowest cost" method of decision making is, without question, the current major method of building option selection.

Only fairly recently has it been realised that the running costs of a structure are impacting heavily on the owners' financial resources[7]. The 'lowest-cost' system of selection is thus not always the most economical 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.

In **Table 1** below, the first option, (1), seems to be the most economical option over the life of the structure. However, the basis of this decision does not stand up to close inspection. It is well known that if maintenance costs are R 400 000 in the first year, they will rise due to inflation, replacements, etc. Other factors that could influence the maintenance expenditure are, for example, use of materials different from the original, items which may require periodic change over a number of years, all resulting in variable annual maintenance costs. Thus, to be able to express all the costs as one single figure would be beneficial to designers and owners of structures, but due to the many influencing variables, this is never easy and often practically impossible.

Data necessary for applying the LCC approach would include:

- **Component Performance:** this depends on variables such as 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 reinforced concrete structure. Much of this data is not yet available.
- **Life of the structure:** factors influencing this would include location, population trends, economic climate and planning initiatives.
- **Inflation:** this has a large 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.
- **Technology changes and fashion:** these are very difficult to predict, since technology is constantly changing. Concrete in the future may have very different properties; new and more advanced repair materials enter the market every year, and so on.
- **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.

Clearly, the use of any decision model such as LCC will be subject to uncertainty. Nevertheless, Brandon[8] 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."

Considerable further research in the field of the life of repair materials and their effect on the life-extension of repaired structures is necessary before it will become possible to demonstrate, in monetary terms, the most economical stage in the deterioration cycle to carry out periodic maintenance and repairs, using LCC.

Table 1 – Life cycle costing example

OPTION	CAPITAL COST ($X 10^6$)	MAINTENANCE COST/ANNUM	LIFE-SPAN (YEARS)	DEMOLITION COSTS	SIMPLE LIFETIME COSTS ($X 10^6$)
(1)	R 10	R 400 000	30	R 100 000	R 22.1
(2)	R 8	R 500 000	30	R 100 000	R 23.1
(3)	R 15	R 300 000	30	R 100 000	R 24.1
(4)	R 9.5	R 500 000	30	R 100 000	R 24.6
(5)	R 11	R 425 000	30	R 100 000	R 23.85

An example, outlining the costs involved with four different repair strategies is given below. It is important to realise that the results are guidelines only because the data necessary for the LCC calculation have not yet been fully quantified.

Example – Repair options

The costs used in the example are based on average costs from Table 2 in Part 1, related to the various deterioration categories listed in Table 1 of Part 1. The escalation index value used is extracted from ref. 9.
Four maintenance options are costed / m^2 of reinforced concrete. The member to be costed is assumed to be situated in a severe coastal exposure climate. For comparative purposes the life of the member is arbitrarily fixed at 60 years (assumed 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 (chlorides only minimally 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 (chlorides penetrated covercrete thickness).
-This involves sealing of cracks with a crack injection resin, patching of the spalled surfaces and application of a protective surface coating.

Option 3: Periodic repair work every time category 3 is reached (major chloride depassivation has occurred and corrosion has been progressing for some time).
-This involves breaking out 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, e.g. the amount of time after repairs until a structure returns to 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 for options 2 and 4 only to a "very good" condition. Option 3 will return to a satisfactory condition because extensive deterioration has already taken place. Thus, after each repair the structure/member in each of the options will not return to the original condition but will reduce 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 is made is the amount of spalling to be repaired (see Table 2, Part 1).

The example is illustrated in Table 2.

Assumptions have been made in the above example, especially with regard to the rate at which protective coatings decrease the deterioration rate. However, despite this shortcoming, the trend that is exhibited is quite clear i.e. protecting a structure from ingress of chlorides is the cheapest repair/protection solution in the long-run. Once chlorides have penetrated the structure, cathodic protection is the cheapest repair option.

This conclusion, although based on no proven data in this example, accords with the Federal Highway Administration's (FHWA) policy statement[10] i.e.

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

It should be seen from the example that, although it will take a great amount of research to quantify all the information necessary for a proper life cycle

Table 2 – Repair option example
(Repair costs expressed in Rands/m^2)

Description	Option 1	Option 2	Option 3	Option 4
Starting category	9	9	9	9
Time from present to time of first repair (years) (Ref. Figure 4, Part 1)	8	16	34	26
Category at first repairs	8	6	3	4
Present value of first repair cost at given percentage spalling (Ref. Table 2, Part 1)	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 (year) (Assumption – see note below)	20	15	10	–
Time from present to time of second repair (years)	28	31	44	–
Category at second repair	7	5	2	8
Present value of second repair cost at given percentage spalling (Ref.Table 2, Part 1)	R 85.25 (10%)	R 162.86 (25%)	R 431.64 (60%)	–
Category after second repair	8	7	5	–
Time to third repair (years) (Assumption – see note below)	16	12	8	–
Time from present to time of third repair (years)	44	43	52	–
Category at third repair	6	4	2	8
Present value of third repair cost at given percentage spalling (Ref. Table 2, Part 1)	R 147.30 (15%)	R 196.55 (35%)	R 431.64 (60%)	–
Category after third repair	7	6	4	–
Time to fourth repair (years) (Assumption – see note below)	12	10	8	–
Time from present to time of fourth repair (years)	56	53	60	–
After the third repair Option 3 should last the intended service life.				
Category at fourth repair	5	3	–	7
Present value of fourth repair cost at given percentage spalling (Ref. Table 2, Part 1)	R 162.86 (25%)	R 230.23 (45%)	–	–
Category after fourth repair	6	5	–	–
After the fourth repair, 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 (say 25%), Total = R 625.00

Note

It is assumed that at the time of the second or subsequent repair each repair option will have reduced by one category (with the exception of Option 4). Because it is impossible to return the structure 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 be in a category lower than the originally intended deterioration category when repairs were to be carried out (lowest allowable deterioration category is 2).

costing exercise, protection may be expected to be usually cheaper than repair.

Clearly, one further option, not discussed above, is the "Durability Design" option, whereby additional durability is designed and built in to the structure by way of, for example, extra cover, particular requirements for the covercrete layer, more careful detailing, modified construction practices, etc. Further research could well indicate that this option may be overall the most economical on a life cycle basis, despite initial costs being higher.

4. Concluding Remarks

Due to the ever increasing costs of maintenance, costs of repair work have to be kept to a minimum. It would appear this would best be achieved, 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. Consultants should also be encouraged to advocate the collection of historical data on all elements of a structure, with the use of computer aided maintenance management systems so that a preventative maintenance strategy can be formulated.

5. Acknowledgements

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