EFFECTS OF COVER PROPERTIES AND REPAIR METHODS ON LCC ESTIMATION OF REINFORCED CONCRETE STRUCTURE

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ABSTRACT:

Most decision makers face problem in the management of concrete infrastructure like bridge due to existence of uncertainties. Uncertainties may change the physical and mechanical properties of concrete deviates from designed value due to workmanship error, environmental conditions and by others. Deteriorated concrete structures due to uncertain parameters need maintenance and rehabilitation that causes huge financial involvement of the owner. Usually least cost option from life cycle analysis is taken as a measure for repair and rehabilitation. But most critical issue is to predict the actual performance condition of the structure at the study time. Durability parameters are to be considered as probabilistic distribution to take the effect of uncertainties caused by errors mentioned above. In this framework, for the prediction of deterioration, cover depth, permeability of cover and degree of saturation of cover concrete are taken as parameters with log-normal distributions and the probability of failures for each is compared along with the life time. It is found that the concrete with smaller cover-low permeability and high permeability-larger cover have almost similar effects on the service life of structure. It reveals that emphasis should be given on permeability to predict the service life of concrete infrastructure. Life cycle computation was done based on some assumption. 5 types of repair includes in the LCC calculation. Comparison is shown among different repair methods to help the owner to choose best option of repairing method. And effect of cover properties on LCC is also realized in this study.

KEYWORDS: cover concrete, permeability, LCC

1. INTRODUCTION

It is very difficult to control the performance of real structure in severe aggressive environmental attack. Chloride induced steel corrosion is one of the major deterioration problem for steel reinforced concrete caused by salty environment.

Since 1960's chloride deicing salts used on roadways in United States have been increased greatly; about 10 millions tons of salts are used annually [1]. The cost of highway bridge repair in US is estimated $70 billion. However cost effective maintenance plan and proper decision making can efficiently reduce the life cycle cost of infrastructure like bridges. To assist the decision makers for initiating better maintenance strategy, it is necessary to predict service life correctly.

JSCE concrete committee TC335 found that air permeability does not give indications similar to strength characteristic indicates [2]. It suggests that durability of concrete is not best indicated by strength only. Most of the popular models gave preferences on cover size, diffusion coefficient and surface chloride. But it is very important to take consideration about cover quality such as permeability characteristics to design service life of structure.

Life cycle cost of the infrastructure is included here with the costs incorporate by aging of structure and repair when needs as direct cost and delay cost, occurred by traffic, at the time of repair is considered as indirect cost. Moreover 5 types of repair methods are compared to help the owner to choose the best.

The prediction framework stated here will be useful to the engineers to design considering durability parameter and will help the owner to choose the required repair methods that cost least.

2. DETERIORATION MODEL

2.1 Corrosion initiation

The flow of chloride ion through pores in concrete is modeled here under both diffusion and convection same as solute transport shown as follows.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} \qquad [1]$$

where V is average linear rate of flow (cm/s) and follows Darcy's law when concrete pores are saturated.

$$V = \frac{k}{n}\frac{\partial h}{\partial x} \qquad [2]$$

where k is the hydraulic permeability (cm/s), n is porosity and $\frac{\partial h}{\partial x}$ is hydraulic gradient. The solution of equation [1] for semi infinite column of porous media is given by [3][4] as follows.

$$\frac{C(x,t)}{C_o} = 0.5\left[erfc\left(\frac{x - Vt}{2\sqrt{Dt}}\right) + \exp\left(\frac{Vx}{D}\right) erfc\left(\frac{x + Vt}{2\sqrt{Dt}}\right)\right] \qquad [3]$$

where $C(x,t)$ is chloride ion concentration at depth x (cm) after time t sec. (kg/m^3). C_o is the surface chloride concentration (kg/m^3), D is the apparent diffusion coefficient (cm^2/sec). Time dependency of surface chloride (C_o) and apparent diffusion coefficient (D) are considered according to ref [5][6].

2.2 Crack formation

Corrosion product is formed and internal pressure is gradually increased after corrosion initiates. As internal pressure reaches to the tensile strength of concrete cracks are generated.

Based on the concept of fracture mechanics and thick-wall cylinder Li et al. (2003) [7] formulated the crack width generation model.

$$w_c = \frac{4\pi d_s(t)}{(1 - v_c)\left(\frac{a}{b}\right)^{\sqrt{\alpha}} + (1 + v_c)\left(\frac{b}{a}\right)^{\sqrt{\alpha}}} - \frac{2\pi b f_t}{E_{ef}} \qquad [4]$$

where w_c is the crack width (mm), v_c is the poisson's ratio of concrete, α is the stiffness reduction factor which can be determined from Li et al (2006)[8], f_t is the tensile strength of concrete (MPa), E_{ef} is effective modulus of concrete, a is equal to $\frac{D + 2d_o}{2}$, b is equal to $x + \frac{D + 2d_o}{2}$, D is the steel diameter (mm), d_o is thickness of pore band of steel-concrete interface (mm) which is dependent on thickness of corrosion product ring $d_s(t)$ and can be determined based on Liu and Weyers (1998) [9]. Thickness of corrosion product is related to mass generation of rust product $W_{rust}(t)$ (mg/mm) and is stated in literature of Liu and Weyers (1998).

3. RELIABILITY BASED FAILURE

Bridge performance is defined in terms of reliability index (β) and the profile of reliability is the variation of reliability index with time β(t). Similar bridges designed and constructed to the same requirements, for various reasons, end up with different reliability levels [10]. This variation is influenced by different loading and degrading resistance conditions that can be usefully presented by random variables of durability parameters.

The performance limit state for corrosion initiation of reinforcing steel and crack width are shown below.

$$z = C_{\lim} - C(x,t) \qquad [5]$$

$$z = w_d - w_c \qquad [6]$$

Equations [5] and [6] can be generalized as load –capacity model shown in equation [7].

$$Performance = Strength - Load = A - B \qquad [7]$$

where C_{lim} and w_d are the threshold chloride concentration and maximum allowable crack width. Reliability index can be determined using load-capacity model.

$$\beta = \frac{1}{V_z} = \frac{\mu_z}{\sigma_z} = \frac{\mu_{\ln A} - \mu_{\ln B}}{\sqrt{\sigma_{\ln A}{}^2 + \sigma_{\ln B}{}^2}} \qquad [8]$$

V_z is the coefficient of variation of performance function z. All random variables are taken as log-normal distribution. Thus μ_{lnA}, μ_{lnB}, σ_{lnA} and σ_{lnB} are the mean of strength, load and standard deviation of strength, load respectively.

It is assumed that corrosion will initiate when β(t)<0.8 using equations [3] and [5] and similarly crack will exceed its allowable width when β(t)<0.8 using equations [4] and [5]. The time to initiation of corrosion is referred as t_i and t_{cr} is named as time to reach allowable crack. Thus, the study reports the failure time as the summation of both the times indicated above.

$$t_f = t_i + t_{cr} \qquad [9]$$

where t_f is the time to failure. The performance of deteriorating structure is characterized by probability of failure or damage over the interval [0, T] as shown in equation [10].

$$P_f(t) = \phi(-\beta) \qquad [10]$$

where $P_f(t)$ is the probability of failure of structure which is fixed at 21.2% corresponds to β(t) value and ϕ is the standard normal cumulative distribution function.

4. RANDOM PROCESS AND VARIABLES

Commercially available The Decision Tools software @Risk is used to generate random variables and to perform the simulation. Minimum number of iterations has to be fixed to get reliable and reproducible results. The numbers of iterations increase the variation of results decrease. Most suitable number for further analysis is taken as 1500.

Table [1] presents the cases used in this study. Cover depth, hydraulic permeability and degree of saturation are considered as the main durability parameters varied according to table [1]. Variation of permeability is maintained according to fig [1] stated in previous literature [11]. The importance of curing time can be understood by varying the hydraulic permeability of cover concrete.

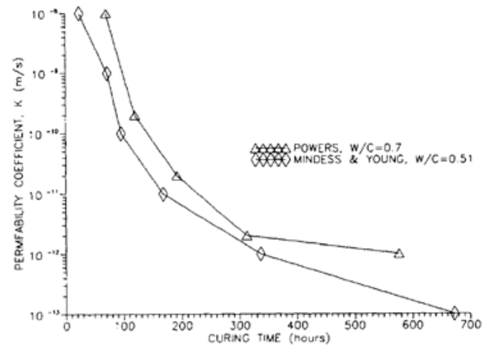

FIG. 1
Decrease in permeability with curing time

Fig. 1: Effect of curing on permeability

Table 1: Case Definition

Case	Mean	COV
Cover depth, *x* (cm)	4, 5, 6	0.1
Hydraulic Permeability, *k* (m/s)	$1e^{-9}$, $1e^{-11}$, $1e^{-12}$	0.1
Saturation Degree, *S* (%)	80, 90, 100	0.1

Table 2: Random Variables

Variables	Mean	COV	References
C_o (kg/m^3)	9	0.1	
C_{lim} (kg/m^3)	1.2	0.1	Enright and Frangopol, 1999
w_d (mm)	0.2	0.1	
$f_c^{'}$ (MPa)	35	0.2	Nowak et al. 1994
ϕ_{cr}	1.1	--	JSCE (2005-3)
v_c	0.18	--	Liu & Weyers, 1998

All the following calculations are based on the input random variables shown in table [2].

5. EFFECT OF BARRIER FUNCTION OF COVER CONCRETE ON SERVICE LIFE PREDICTION

Probability of failure was calculated for total ($parameter^{variables} = 3^3$) 27 cases.

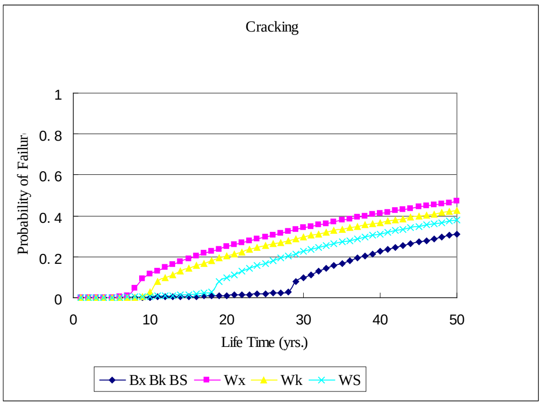

Fig. 2: Failure probability for different parameters

"Bx, Bk, BS" indicates *"Best"* i.e. largest cover, lowest permeability and lowest saturation respectively, similarly *"Wx, Wk, WS"* refers to *"Worst"* i.e. opposite properties in barrier function. Failure probability is compared in fig.[2] for best and worst cases for different parameters. Probability of failure increases for different durability parameters as the structure becomes old and older. Cover depth plays most significant role in failure. Permeability has also very close effect.

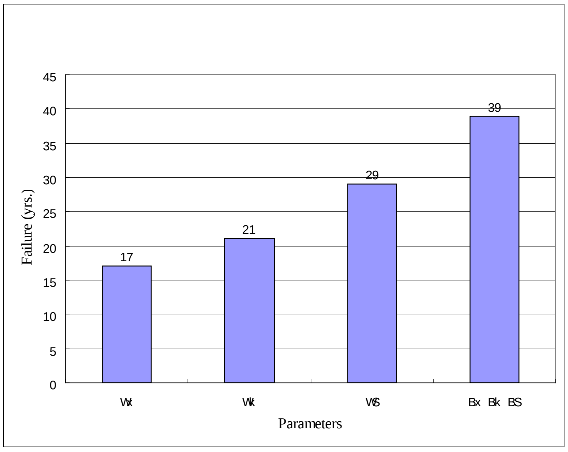

Fig. 3: Time to failure for different parameters

Fig. [3] shows the comparison of time to failure among different types of parameters. To predict the service life not only cover depth but also other qualitative parameters are to be considered.

6. LIFE CYCLE COST ESTIMATION

LCC plays key role in maintaining the infrastructure and provides necessary information to the manager or owner. In this study LCC is computed in the following way.

$$LCC = \sum_{t=0}^{T} (AgingCost + DelayCost + RepairCost)$$

The three terms in the right hand side were assumed as explained by the following sections.

6.1 Aging cost

This is the cost carried by the owner due to regular maintenance operation. Aging cost is assumed to be proportional to the failure probability, shown in fig.

[4], as both of them increase with the increase of age of the infrastructure.

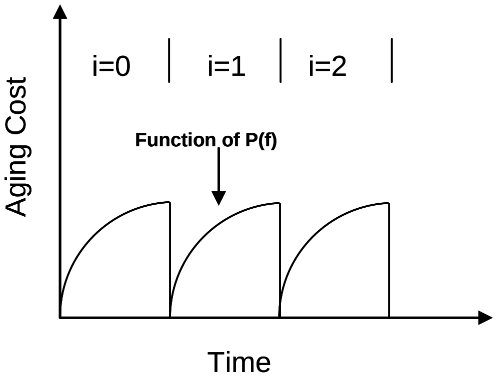

Fig. 4: Concept of aging cost

$$Aging\ Cost = Initial\ Cost \times 0.05 \times P(f)_{t_i} \quad ....u = 0 \qquad [11]$$

$$Aging\ Cost = Initial\ Cost \times 0.05 \times P(f)_{t-t} \quad ....u = 1 \qquad [12]$$

It is assumed that 5% of initial construction cost will be expended for maintenance. $P(f)_t$ is the probability of failure at yrs. *t*, number of repair is subscript *i*, *u* is the decision for repair, *u=0* means no repair and *u=1* represents do repair.

6.2 Delay cost

This is the part of expenditure carried by the road user for extra fuel consumption and delay due to congestion at the time of repair for partial or full closure of traffic way. It is assumed to be proportional of age as traffic volume is increased with the age and capacity of the road if remains constant. The schematic nature is shown below in fig [5].

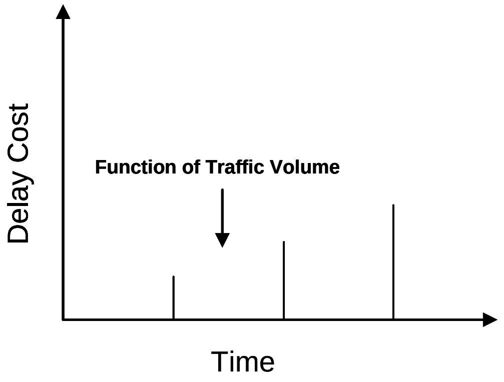

Fig. 5: Concept of delay cost

$$Delay\ Cost = 0 \qquad ....u = 0 \qquad [13]$$

$$Delay\ Cost = \%traffic\ delay \times (traffic\ volume)_t \times repair\ time \times average\ delay \times unit\ Cost \quad ....u = 1 \qquad [14]$$

where *% traffic delay* is the number of vehicle delayed at the repair time and is kept assumed here 10%, *traffic volume* is the function of time, *repair time* is the time taken by the repair in days, *average delay* is the % time delay due to repair by car or truck, *unit cost* is the time value of delay. Delay cost is calculated from literature stated in reference [12].

6.3 Repair cost

This is cost provided by the owner due to repair when the performance goes below the required. In this study the repair is taken to be happened at reliability or state of structure goes below 80% of initial. The schematic nature is shown below in fig [6].

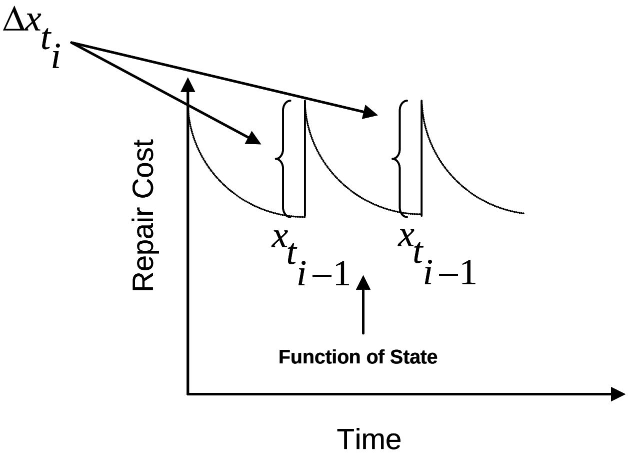

Fig. 6: Concept of repair cost

$$Repair\ Cost = 0 \qquad ....u = 0 \qquad [15]$$

$$Repair\ Cost = \left[Fixed\ Cost + \left(unit\ Cost \times area \times P(f)_{t_{i-1}} \times \Delta x_{t_i} \right) \right] \times \frac{t_{RSL}}{t_{Repair}} \quad ....u = 1 \qquad [16]$$

where *unit cost* is the cost of repair for unit area, $P(f)_{t_{i-1}}$ is the failure probability just before repair, Δx_{t_i} is the change of state done by repair i at time t, t_{RSL} is the residual service life in years, t_{Repair} is the life time of repair material.

6.4 Repair methods

To investigate the effect of different repair methods on LCC, 5 types of repair methods from references [13] and [14] are included in the calculation as below.

Table 3: Cost of Repairing

Category	Types	Fixed Cost ($)	Variable Cost ($/m^2)	Life time (yrs.)
RM1	Cathodic Protection (Mounted Conductive Polymer w/ concrete overlay)	6870	97	20
RM2	Cathodic Protection (Titanium mesh w/ shotcrete)	6870	150	35
RM3	Patching	1450	277	8
RM4	Overlay (Low slump dense concrete)	6000	43	24
RM5	Overlay (Hot mix asphaltic concrete with a membrane)	6000	11	12

7. EFFECT OF REPAIR METHODS ON LCC

Life cycle cost is estimated based on equations [11] to [16]. Different cost of repair methods are taken according to table [3]. Cost is calculated based on two assumptions. First one is that the repair is done when state is below 80% of initial and the second one is the state is improved always up to the initial level by repairing.

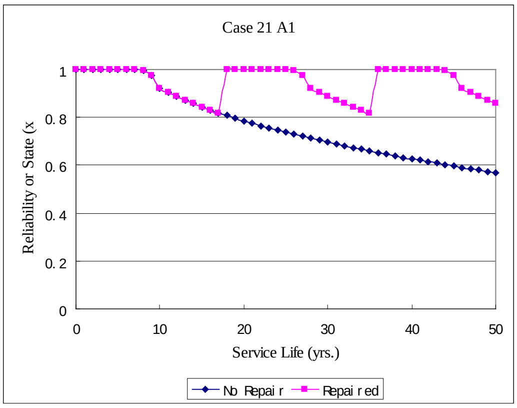

Fig. 7: State improvement by repairing

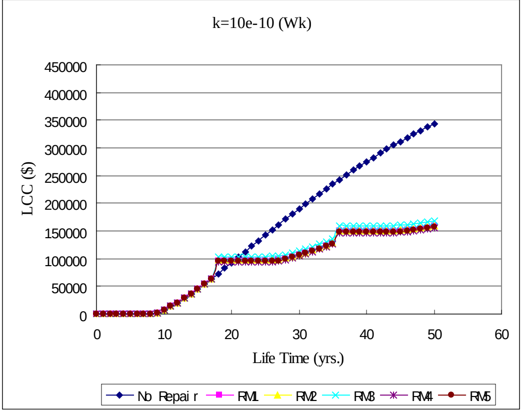

Fig. 8: Effect of repair methods on LCC

Example state improvement is shown in fig. [7] and corresponding LCC is given in fig. [8]. The cumulative cost is given with the lifetime goes on. The cost is compared between the options that if the structure is not maintained and the structure is maintained with different types of repair methods. It shows that the cost for aging of structure is compensated by the repair actions.

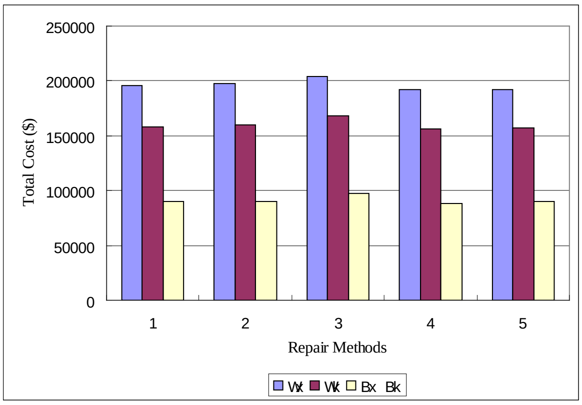

Fig. 9: Effect of repair methods and cover properties on total cost

Total cost is compared in fig. [9] for extreme cases of cover depth and permeability. It can clearly be seen that highest cost is to be carried if repair method 3 is taken as variable cost is maximum. The cost is lowest when repair method 4 is undertaken. Although the lowest variable cost is owned by repair method 5 but the lifetime is one half compared to method 4.

8. EFFECT OF COVER PROPERTIES ON LCC

Reduction of LCC consists of the change of total cost if the durability performance is improved by improving the property from worst to best. It is calculated as below.

$$LCC \;\; Reduction = \left(\frac{Cost_{Worst} - Cost_{Best}}{Cost_{Worst}} \right) \times 100$$

[17]

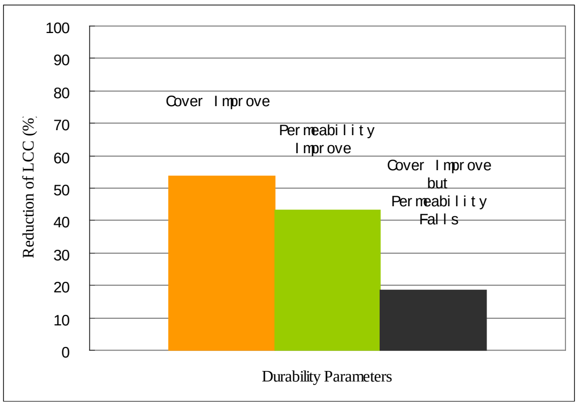

Fig. 10: Effect of cover properties on LCC reduction

Fig. [10] shows the effect of cover properties on LCC reduction. Improvement of cover depth reduces LCC by 54% whereas permeability improvement reduces LCC by 43%. But if we improve only cover depth neglecting the permeability which is falling down to worst, we are actually reducing LCC by 19%.

9. CONCLUSIONS

This computational frame for LCC generates the following conclusions.

- RM3 costs highest to the owner due to maximum variable cost of repairing.
- RM4 costs lowest due to low variable cost and greater life time of repairing as well.
- Cover properties have significant influence on service life prediction and the computation shows quality of cover such as permeability can not be ignored as life time predictor.
- LCC can be reduced as much as 54% if not only cover depth but also permeability is taken into consideration.

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