OPTIMISATION OF LCC OF CONCRETE BRIDGES

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ABSTRACT

Research within concrete durability has resulted in longer and longer required service lives for bridges. However, the cost for the longer service lives has been of lower interest. This research project focuses on the possibilities the structural engineer has to make cost-effective concrete structures. In the design phase, several structural measures are available to lengthen the service life of a structure. The primary aim with this project is to connect the cost, related to these measures, with the benefit for the community.

Keywords: Concrete Bridges, Service Life, Life-Cycle Cost, Economy, Optimisation

1 INTRODUCTION

Functional infrastructure is of major importance for the nation and bridges constitute an important part of the technical infrastructure. Since concrete was introduced in bridge construction, concrete has become the dominating material. In the beginning, concrete was believed to be as durable as rock, but unfortunately that was not the case. The older bridges are quite often in bad shape and require a large amount of repair and maintenance. Projected cost for repair, rehabilitation and replacement is limited and will bear heavily on future national economies.

To prevent this for new structures, concrete durability has gained increased importance in design and maintenance. Research within concrete durability has resulted in deterioration models and better concrete quality. Nowadays, concrete durability is often a dominating factor in the design stage. The standards and recommendations have been sharpened in several ways. Among these, the most common are: better concrete quality, larger thickness of the concrete cover and more reinforcement to reduce crack width. Altogether these measures may give a structure the required service life, but the average service life will probably be yet longer.

Of tradition, research within structural engineering has been separated from economy. The economical consequences for the structure of improvements, innovations et cetera have been omitted. Very little research has been made concerning concrete durability in combination with the life-cycle cost of the structure. Especially regarding choice of parameters to lengthen the service life of structures in the design phase, the economical consequences have been neglected. However, Siemes, Vrouwenvelder and van den Beukel ought to be mentioned, who during the eighties have made research within this field, for example on carbonation of balcony plates /1/. Because of the lack of research considering economical consequences of structural design and durability, this kind of research is of great importance.

Effective methods and measurements to predict the residual service life of existing concrete structures have been developed already. However, to provide cost-effective concrete structures, it is also necessary to predict the expected service life of a concrete structure already in the design phase. When the expected service life is calculated, and the maintenance and repair costs are assumed, the annuity cost can be calculated. In this way, different durability alternatives can be economically compared.

This research project is a part of the program "The durability, management, repair and LCC of concrete structures" at the Department of Structural Engineering at the Royal Institute of Technology, Stockholm. It focuses on the possibilities the structural engineer has to make cost-effective concrete structures.

2 DURABILITY, SERVICE LIFE AND ECONOMY

2.1 Introduction

With the durability problems from the sixties, seventies and eighties in mind, concrete durability has become an interesting subject of research. Concrete quality has increased and methods to design concrete structures with longer service lives have been developed. The design codes have provided longer and longer service lives of structures. If this is economical for the nation has not been examined.

To find optimal durability it is necessary to know all about the future needs and economical situation. This is of course impossible. Therefore the nations aim should be to get as good infrastructure as possible to as low yearly cost as possible. The best possibility to influence the long-term economy of a structure is in the design phase. Optimal durability probably varies in different cases. Calculation models for these tasks are missing.

It is important to remember that a long service life is not always preferable. In the future the traffic situation will be different from today. There is a slight possibility that the traffic increases still using the existing traffic routes, but it is more likely that the future infrastructure needs will differ from those today. Over-provision of capacity to allow for future traffic increases, is in general not economical. That would result in unnecessary stiffness in the infrastructure. More preferable would be to build bridges that could be moved, dismountable bridges or bridges constructed to simplify alterations.

In cost-benefit analyses of road projects, the bridge cost is often taken into account only as a fixed sum, usually at a special rate per square metre bridge surface. If the road project has been cost-benefit analysed then the bridge shall not be cost-benefit analysed also. The bridge is a necessity for the road project and shall therefore be analysed with regard to lowest LCC.

2.2 Need of interaction formulae

Concrete research has led to increased knowledge in concrete durability and better deterioration models have been developed. To design structures with low annuity cost, it is necessary to connect these deterioration models to the life-cycle cost of the structure. The common factor in the deterioration models and the economical models is time. This enables economical design with interaction formulae, Figure 1.

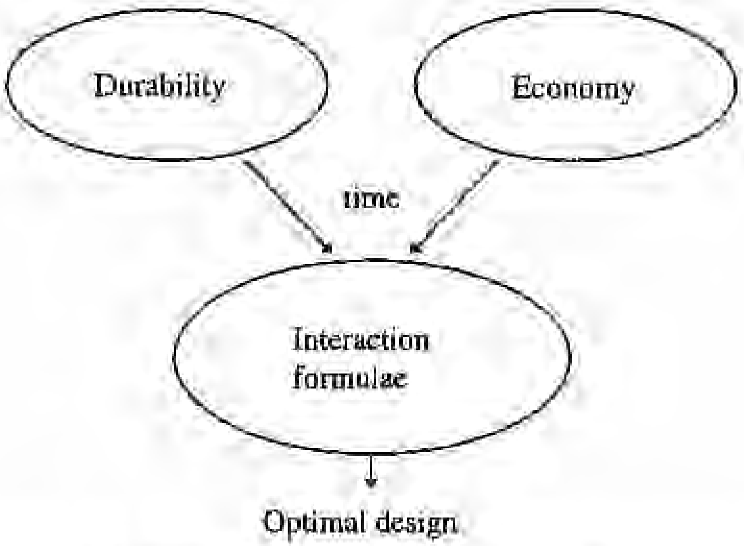

Figure 1 Durability and economy can be connected with interaction formulae /2/. The common factor is time. Optimal design with respect to durability and economy can then be calculated.

If the future benefit of a bridge considers constant and deterioration models are chosen, then it is possible to calculate the annuity cost. The design that results in the lowest annuity cost is the optimal solution and should be chosen. In this research project, interaction formulae have been used to find the most optimal solution for designing bridges with regard to economy and durability.

2.3 Present value method

The life-cycle cost of a concrete structure depends on service life, discount rate, investment cost, costs and incomes during the life time such as inspection, maintenance and repair costs, and finally disposal cost. The most common method to compare future costs and benefits with those today is the present value method.

To calculate the life-cycle cost, LCC, of a structure, all costs (and benefits) must be discounted to present value and then summarised to a single LCC number. This can be expressed as the LCC equation:

$$LCC = \sum_{n=1}^{N} \frac{B_n}{(1+r)^n} \qquad (1)$$

Where B_n is the sum of all costs and benefits in year n, r is the discount rate and N is the service life.

To be able to compare life-cycle costs of structures without future incomes and with different service lives, instead of the present value, the annuity costs can be compared. The annuity cost is the present value multiplied by the annuity factor:

$$A = LCC \cdot F_A = LCC \cdot \frac{r}{1-(1+r)^{-n}} \qquad (2)$$

The discount rate is very important when calculating costs, and may be difficult to choose in a proper way. However, it is preferable that the discount rate does not include the inflation.

3 CALCULATION EXAMPLES

3.1 Chloride diffusion

Chloride induced reinforcement corrosion is the most common problem of concrete in marine and de-icing salted environment. The humidity in outdoor concrete are relatively high, and chloride ingress is supposed to be caused by diffusion. Therefore chloride initiated reinforcement corrosion is here calculated with Fick's second law of diffusion:

$$\frac{\partial C}{\partial t} = D_{eff} \cdot \frac{\partial^2 C}{\partial x^2} \qquad (3)$$

Where C is the chloride concentration, t is time, x is distance from concrete surface and D_{eff} is the diffusion coefficient. The classic solution of this equation (if D_{eff} is considered constant) is

$$t = \frac{x_{cr}^2}{4 \cdot D_{eff} \cdot \left[\operatorname{erfc}^{-1}\left(\frac{C_{cr} - C_i}{C_s - C_i} \right) \right]^2} \qquad (4)$$

Where t is initiation time for reinforcement corrosion, x_{cr} is the distance from concrete surface and D_{eff} is the diffusion coefficient. C_{cr} is the chloride threshold value, C_i is the former chloride concentration inside the concrete and C_s is the chloride concentration at the concrete surface. In equation 4, erfc^{-1} is the inverted complementary error function.

The chloride concentrations and the diffusion coefficient depends on concrete depth, material properties and environmental impacts. Later research shows that the diffusion coefficient also depends on time /3/. Although, when the structure has revealed a certain age, the diffusion coefficient can be assumed constant. In the following examples, the effective diffusion coefficient calculated out of measured chloride profiles is used /4/.

3.2 Chloride concentrations

As an example, the chloride concentrations in Swedish bridge concrete, made of ordinary Portland cement and with water reducer, have been measured as a function of water binder ratio and the result is shown in Figure 2. For a different concrete mix, of course also the result would differ.

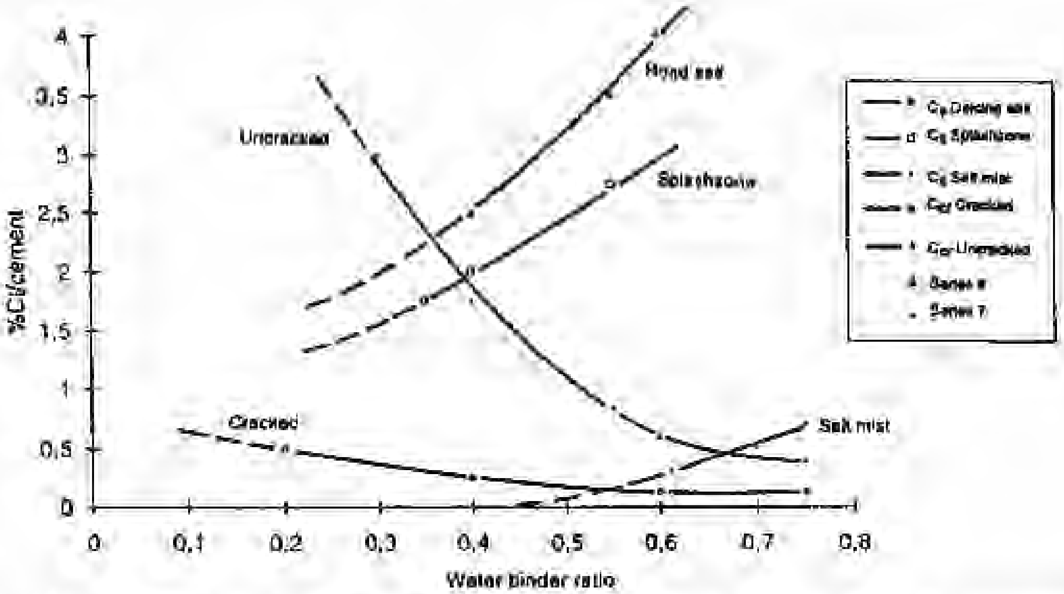

Figure 2 Measured chloride threshold values and maximum surface chloride concentrations in relation to water binder ratio /5/.

Figure 2 is a summary of the chloride threshold values and highest chloride contents on the concrete surface in relation to water binder ratio /5/. The maximum surface concentrations have been obtained from 15 to 40 years old outdoor structures which have been exposed to de-icing salts and marine environments.

Cracked concrete refers to crack width of 0,4 mm and a cover thickness of 30 mm. Uncracked structures are here structures with cracks so thin that they do not affect the durability, here with crack width less than 0,1 mm. Road salt sorts within de-icing salted environment and splash zone relates to structures in the water line, marine environment.

The chloride threshold value is the maximum chloride level where the concrete can protect the reinforcement from corrosion. The threshold value decreases when water binder ratio increases. Chloride concentration at the concrete surface increases when the water binder ratio increases. Figure 2 indicates that there is a lower limit of water binder ratio for which the chloride threshold value is higher than the surface chloride concentration. Then theoretically, the initiation time for chloride induced reinforcement corrosion, is infinite. This is of course not true, because other deterioration mechanisms, together with chloride diffusion, will reduce the durability of the structure.

3.3 Service life calculations

In service life calculations, the service life must be specified. If the technical service life is chosen equal to the initiation time of reinforcement corrosion, the further choice will be optimal; whether to repair, renovate or keep using the structure until the deterioration has an influence on safety or comfort. Therefore, the service life is here chosen equal to initiation time for reinforcement corrosion. Of course it would have been possible to choose another definition of service life.

The following calculations show examples how durability with regard to chloride induced reinforcement corrosion can be valued economically in the structural design. In the calculations, the annuity cost of a concrete slab has been compared to the annuity cost of a reference object, and the relative annuity cost is therefore dimensionless. The effective height has been kept constant in the calculations. That is, a thicker concrete cover makes the total height larger than for the reference object, and a thinner concrete cover makes the total height of the concrete slab smaller. The reason to this is to retain the bending capacity of the slab. With a better concrete quality it may be possible to make thinner structures, still with the same bending and shear capacity. However, this has not been taken into consideration. Nor have reinforcement cost been taken into account, only concrete cost.

Initiation time for chloride induced reinforcement corrosion in de-icing salted environment has been calculated by equation 4. Chloride concentrations expressed as functions of water binder ratio, out from the measured values in Figure 2, are used /2/. The calculated initiation time is shown in Figure 3.

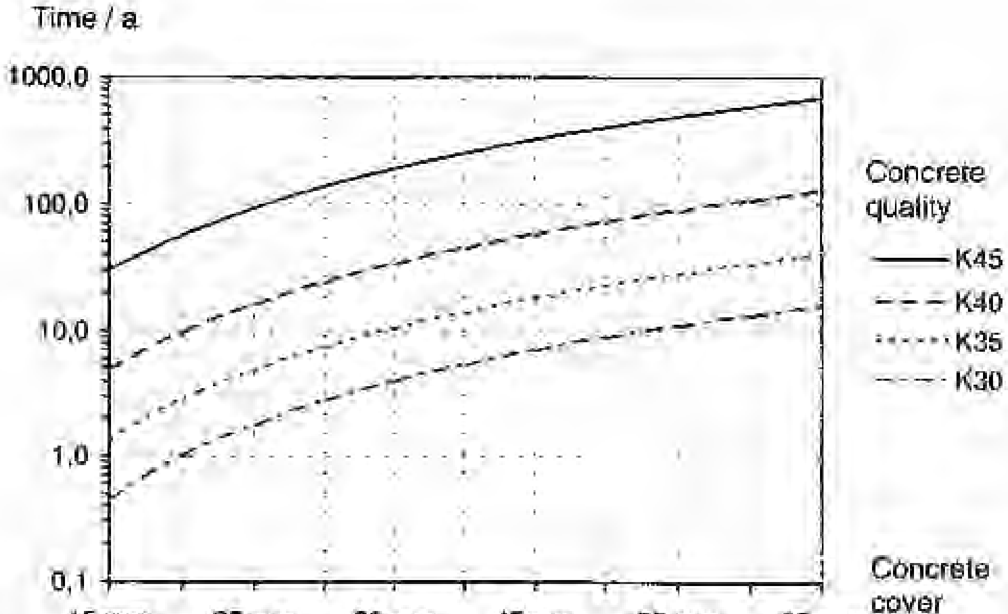

Figure 3 Initiation time in years of chloride induced reinforcement corrosion as a function of concrete cover and for different concrete qualities.

Initiation time for concrete quality K50 (required cube compressive strength $f_K = 50$ MPa) without cracks is, according to Figure 2 and de-icing salted environment, infinite. Therefore concrete quality K50 is missing in Figure 3. Though, other deterioration processes will break down the structure in the long run, as for example, carbonation.

3.4 Cost calculations

When the initiation time is calculated, the annuity cost can be calculated if the concrete cost as a function of concrete quality and concrete cover is known. The relative concrete cost is the concrete cost divided to the cost of a reference object, that is the relative price divided to relative volume. If the reference object is a concrete slab made of quality K30, with slab thickness 250 mm out of which 35 mm makes the concrete cover, then the relative cost of different durability design alternatives can be shown in Figure 4.

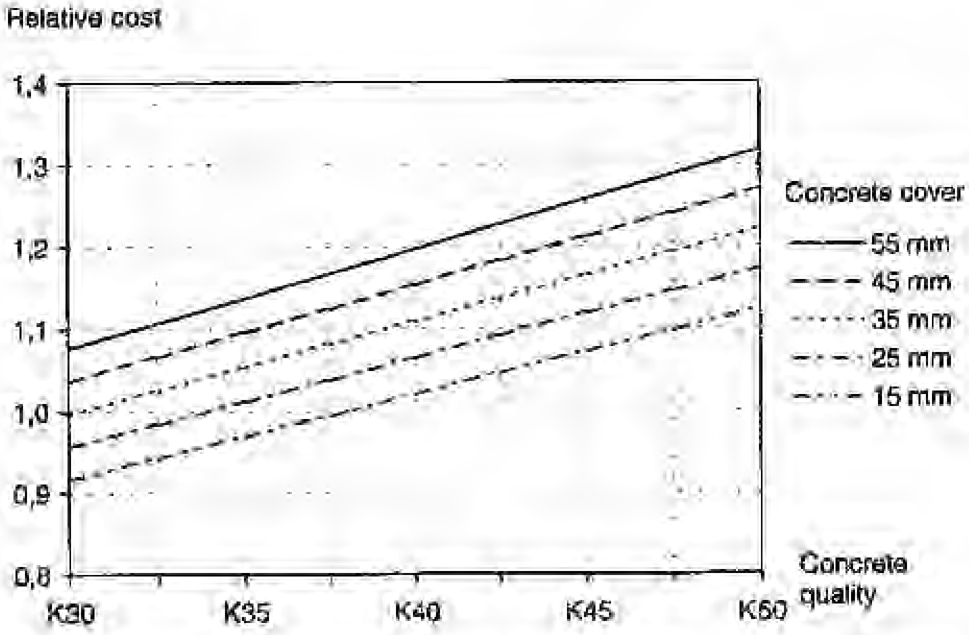

Figure 4 Relative cost as a function of concrete quality and for different thickness of the concrete cover. Reference: concrete slab 250 mm, 35 mm concrete cover. Concrete quality K30.

For thin structures, the concrete cover is relatively more expensive than for thicker structures. Therefore the relative cost for different thickness of the concrete covers differs more for thin slabs than for thicker slabs. When the initiation time and the relative cost are calculated, then they can be connected into annuity cost.

In this first example, Figure 5, the annuity cost has been calculated for different ways to solve the durability in de-icing salted environment of a reinforced concrete slab, thickness 250 mm, made of typical Swedish bridge concrete. A discount rate at 4 % is chosen.

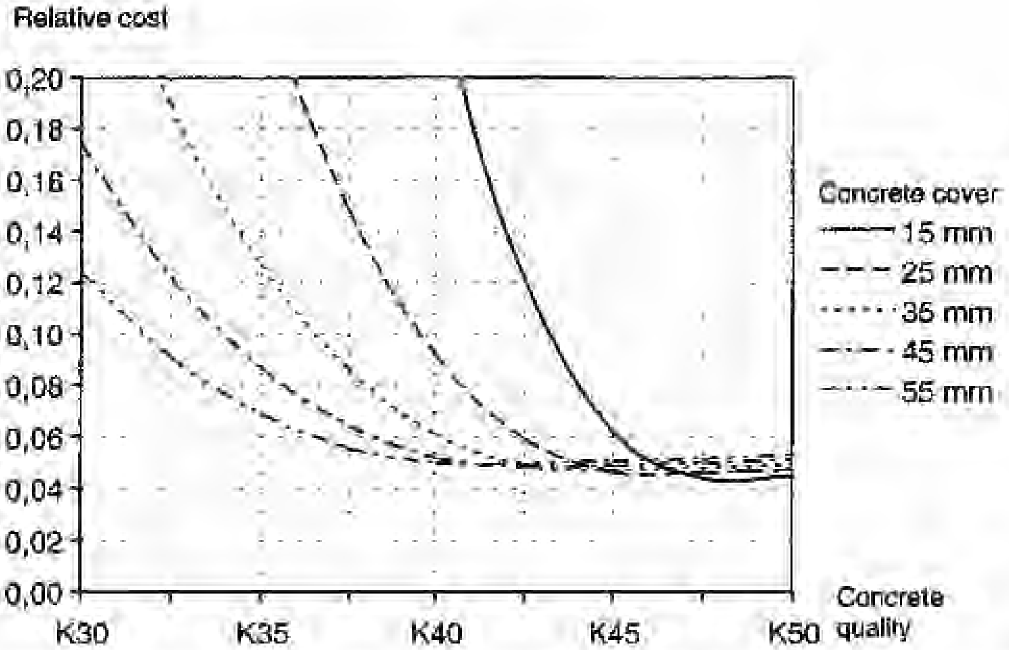

Figure 5 Annuity cost as a function of concrete quality and for different thickness of the concrete cover. Concrete slab 250 mm, de-icing salted environment, discount rate 4 %.

The lowest annuity cost in this example will be achieved with a high concrete quality and a small thickness of the concrete cover. Expected averaged service life can then be calculated.

Most economical in this example, is to choose concrete quality K50 with 15 mm concrete cover. Theoretically the service life then is infinite. Of course this is not the case, because other deterioration mechanisms, together with chloride diffusion, will make the process to continue. Almost as economical is choosing K45 with 30 mm concrete cover. The service life is then 140 years. Third alternative is K45 with 25 mm concrete cover, service life 90 years.

A thickness of the concrete cover at 15 mm may not be sufficient because of anchorage and arrangement of the reinforcement, resistance against carbonation and construction tolerances. Furthermore, the thickness of the concrete cover must be thick enough, so that the chloride ingress is mainly caused by diffusion. If 25 mm is the thinnest acceptable concrete cover, the second alternative is most economical.

In the same way, calculations of concrete slabs in different environments are made. In spite of the chloride aggressive environment, unexpectedly long[1] service lives attended to be optimal. A summary for a 250 mm concrete slab made of bridge concrete, based on Portland cement, is made in Table 1.

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[1] At a discount rate of 4 %, the present value of costs more than 60 years away are almost negligible. Though, Swedish bridge concrete are quite durable and the costs for better quality are relatively small.

Discount rate 4 %	Rank.	Concrete	cover (mm)	Optimal service life (years)
De-icing salted environment, no cracks	1	K50	15	∞
	2	K45	30	140
	3	K45	25	92
De-icing salted environment, thin cracks	1	K50	20	160
	2	K50	15	88
	3	K50	25	260
Splash zone, water-line	1	K45	15	200
	2	K45	20	390
	3	K45	25	630
Marine environment, under water-line	1	K50	15	∞
	2	K45	30	99
	3	K45	25	150

Table 1 Summary of optimal service life of concrete structures in chloride aggressive environment. Discount rate 4 %.

The calculations show that high concrete qualities and relatively thin concrete covers are most economical in chloride aggressive environment. High concrete quality has two positive effects: the chloride threshold value increases as the water binder ratio decreases and the chloride binding at the concrete surface decreases as the water binder ratio decreases. If using thin concrete covers, it is important to control these concrete covers in the construction phase.

The calculations in this paper are only intended to show examples of economical optimisation with respect to durability of concrete structures, not to present results which can be directly used in structural design. However, the methods can be used whenever the deterioration can be expressed as a function of time.

The effective height of the slab has been kept constant, and a thicker concrete layer results in a thicker slab. No consideration has been taken to higher concrete qualities ability to carry heavier loads. Neither has any consideration been taken to higher weight as a result of the thicker structure.

4 A STATISTICAL APPROACH

The service life of bridges varies a lot depending on different reasons. Even if the conditions are the same, that is design and deterioration conditions, service lives differ because of variations in variables. This is why a statistical approach is useful.

In Figure 6, the Monte-Carlo method is used to calculate the service life distribution of a concrete structure. 100 000 calculations are made. Chloride threshold value and chloride concentration at the concrete surface are calculated out of Figure 2. Water to cement ratio is 0,45 and concrete cover 45 mm. Inner chloride concentration is chosen to be deterministic and 0,01 weight-% Cl^-/cement. All the other variables are supposed to be normally distributed and all variation coefficients are chosen to 0,2. Service life is calculated by equation 4. Also the annuity factor as a function of service life and by different discount rates is shown in Figure 6.

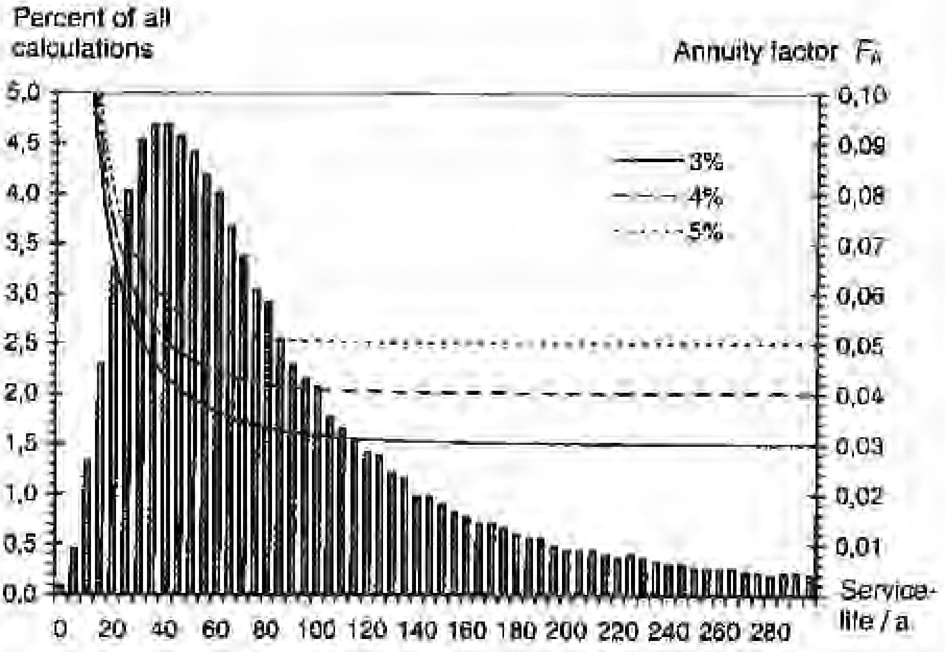

Figure 6 Statistical service life in years of a 250 mm slab made of ordinary Portland cement, water to cement ratio 0,45, concrete cover 45 mm and variation coefficient = 0,2. Results from 100 000 calculations by the Monte-Carlo method. Annuity factor as a function of service life and by discount rate.

By using results from the Monte-Carlo calculations, the average annuity cost of a certain design can be estimated. Every single service life has to be multiplied by the corresponding annuity factor. Then the average annuity cost can be calculated as the mean value of these calculated annuity costs.

The annuity cost of the average service life calculated by mean values of variables, differs from the average annuity cost of the service life distribution. That is due to the service life distribution in combination with the annuity factor. The service lives shorter than average, are multiplied with a higher annuity factor than the annuity factor of the average service life, while those service lives longer than average, are multiplied with a lower annuity factor.

In Figure 7 the annuity cost is shown as a function of different service lives and by different environments, concrete qualities and concrete covers. The average annuity cost of the service life distribution is calculated by Monte-Carlo simulation and every single dot is the mean annuity cost out of 5 000 different calculations. The line F_A is calculated out of the annuity cost of the average service life calculated by mean values of the variables. The discount rate is chosen to 4 %. The annuity cost is calculated for concrete slabs made of Swedish bridge concrete with ordinary Portland cement and with a total height of about 250 mm. Variation coefficient for all variables, except the original inner chloride concentration which here is defined to be deterministic, is chosen to 0,2.

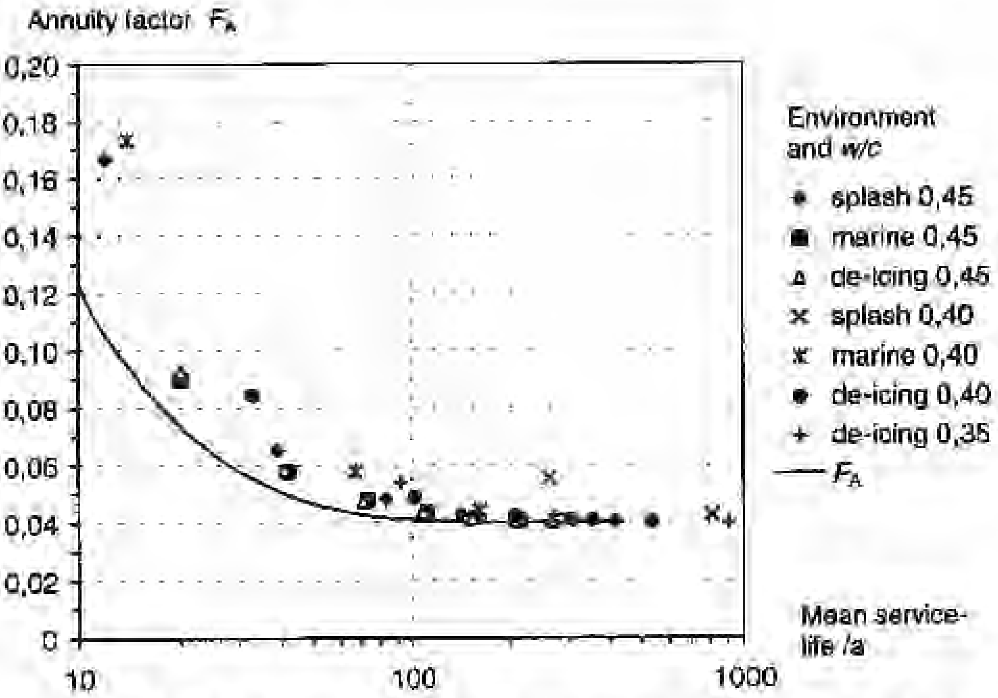

Figure 7 Annuity cost as a function of different service lives in years and for different environments, concrete qualities and concrete covers. The average annuity cost of the service life distribution is calculated by Monte-Carlo simulation and every single dot is the mean annuity cost out of 5 000 different calculations. The line F_A is the annuity cost of the average service life which is calculated by mean values of the variables. Discount rate 4 %. Concrete slabs made of ordinary Portland cement, height about 250 mm. Variation coefficient 0,2 for all variables.

The difference between the single values and the line depends on the service life distribution. Because of the rapid decrease of the annuity factor, the shorter service lives affect the annuity cost more than the longer service lives. The largest differences are with these calculation assumptions, received when small concrete covers, 10 to 20 mm, are chosen.

To calculate the annuity cost of different solutions, it is important to estimate the distributions of all variables, so that the probability of extremely short service lives will be minimized.

5 CONCLUSIONS

The calculations in this paper, show that economical optimisation of concrete structures in the design phase is possible. The research within concrete durability has led to increasing knowledge of the deterioration time for concrete structures. However, to design new cost-effective structures, more research is needed. Interaction between design parameters and deterioration is necessary to calculate expected service life of a structure already in the design phase.

The calculations in the project are only intended to show examples of economical optimisation with respect to durability of concrete structures. However, as far as possible, established theories have been used. Especially durability problems depending on carbonation and chloride diffusion have been studied, but the methods are appropriate to every durability problem where the deterioration is a function of time. Even a statistical approach for freeze-thaw problems is feasible.

Optimal service lives becomes remarkably high; 90 years and higher at 4 % real discount rate. In a chloride aggressive environment, better concrete such as K45 or K50 is most economical. Then smaller concrete covers, 15 to 30 mm, are required. An explanation to these high service lives is that Swedish bridge concrete is highly resistant towards deterioration caused by chlorides. Other concrete mixes would perform different results. However, the calculations are just intending to show examples of how durability can be connected to economy, not to present exact design values.

Because of the variation in the basic variables, it is suitable to treat the annuity cost probabilistic. The average annuity cost depends on the service life distribution and differs from the annuity cost of the average service life. Structures with lower service lives than average have higher annuity costs and the annuity factor in the durability optimisation should thus be higher.

6 REFERENCES

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