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ORIGINAL ARTICLE

EUROSTRUCT

Economic assessment of corrosion prevention measures in new structures

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Abstract

Chloride-induced corrosion is a main cause of deterioration in reinforced concrete (RC). The premature deterioration of RC leads to unplanned repairs, hence elevating the direct and indirect costs of the RC infrastructure. The current prescriptive durability design approach has proven to be insufficient in assuring the durability of the RC exposed to chlorides. The objective of this study is an economical evaluation of several prevention measures for chloride-induced corrosion following the performance-based approach. A case study is inspired by a real set of RC columns, which suffered from chloride-induced corrosion damage after 14 years in service. The considered prevention measures are the use of different binder systems, variation of the water/binder ratio, and changes in the concrete cover. To compare the obtained results, a reference design is set with a concrete mix and a cover thickness according to the requirements of the prescriptive approach described in the European standards. The results show that a balance between the binder type, concrete cover and water/binder ratio is necessary in order to optimize the costs while assuring the durability of the RC element.

Keywords

corrosion, reinforced concrete, economic assessment, performance-based, case study, prescriptive rules

1 Introduction

Premature deterioration of reinforced concrete (RC) structures has become a concern worldwide due to the elevated repairs costs and negative economic impact on the overall economy [1]. Chloride-induced corrosion of the steel reinforcement has been acknowledged as the main cause of RC deterioration [2]. The current European standard for durability follows a prescriptive approach [3] in which limit values are set for the concrete cover, maximum water/binder ratio, minimum compressive strength and minimum cement content based on the qualitative evaluation of the exposure conditions (exposure classes). Nevertheless, some studies have shown that some RC structures exposed to severe chloride environments do not achieve their designed service life, despite complying with the current standards for durability design in RC [4–6].

In an ongoing German joint research project initiated by the German Committee for Reinforced Concrete (DAfStb), the goal is to ensure the durability of future concrete structures over the entire design service life using a performance-based approach for durability design. Furthermore, future changes in the binder composition and field experience are also considered. In the present paper, the goal is an economical evaluation of several prevention measures for chloride-induced corrosion following the performance-based approach. This paper uses a set of RC columns located in an underground parking garage as a case study. After 14 years of service, these elements had to be repaired due to chloride-induced corrosion. The chloride loads are obtained based on the chloride profiles of the real element. In this study, several prevention measures are considered either alone or as combinations. The prevention measures are the use of different binder systems, variation of the water/binder ratio, and changes in the concrete cover. A concrete mix design and concrete cover according to the requirements of the prescriptive approach [3] is used as reference. Finally, the evaluation considers all scenarios in terms of performance and costs.

2 Methods

2.1 Case study

The case study is a “standard” reinforced concrete column (“standard”: all columns were built equally) from an underground parking garage located in southern Germany built in 2001. After 14 years of service, the elements

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showed signs of reinforcement corrosion: cracks and spalling in several spots. Therefore, the columns did not achieve the designed service life of 50 years as recommended by the current standards [3]. A detailed condition assessment of the elements included measurement of the concrete cover and drill-dust extractions for chloride profile evaluation. The condition assessment showed that the corrosion was initiated due to chloride contamination [7]. The source of the chlorides is the salty water carried by cars, as the streets in the area are treated with de-icing salts in the winter period. The cross-section of the column as built in 2001 is shown as section A in Figure 1 . The section is 250 x 500 mm, and the nominal concrete cover is 35 mm.

Two approaches are evaluated for ensuring the durability of reinforced concrete elements subjected to chloride attack: the prescriptive approach and the performance-based approach. The prescriptive approach is described by the current European standards [3]. In this approach, the exposure class needs to be defined based on the type of attack (chloride contamination, chemical, carbonation, etc.) and the moisture condition of the element. Afterwards, the standard set values for the nominal and minimal concrete cover, maximum water/binder ratio, and minimum cement content. Table 1 summarizes the parameters for the presented case study, here referred as Business as Usual (BAU).

Table 1 Durability parameters after the prescriptive approach (BAU)

Exposure class	XD3/XS3
Min. compressive strength class	C35/45
Max. water/binder w/b ratio (-)	0.45
Min. cement content (kg/m^3)	320
Min. concrete cover (mm)	40
Nominal concrete cover (mm)	55
Consistency class	F4
Maximum aggregate size (mm)	16

In the performance-based approach, the durability of the element is evaluated employing quantifiable models contrasting the acting loads (chlorides i.e) and resistance of the materials (concrete cover, concrete permeability, etc.) [8]. For this purpose, the limit state must be defined first. Common limit states are depassivation of steel reinforcement, cracking of the concrete surface or spalling of concrete cover. Afterwards, the probability of exceeding the defined limit state is computed and expressed in terms of reliability (reliability index β). Unlike the prescriptive approach, the performance-based allows the durability assessment of the reinforced concrete element considering variations in the element geometry and material properties.

2.1.1 Prevention measures

This case study evaluates 10 binder systems with different cement types and water/binder (w/b) ratios. Table 2 resumes the mentioned binder systems along with their laboratory results of the migration coefficient at 28 days and assumed aging coefficients according to [9]. Furthermore, 7 different nominal concrete covers are evaluated ranging from 35 mm (as constructed) up to 65 mm. To achieve the same structural performance as the constructed element, both the arrangement of the steel reinforcement and the bar diameter are modified depending on the selected alternative. Figure 1 presents the different cross sections as function of the concrete cover. Figure 2 presents the results of the column interaction diagram following [3] of the reinforced concrete column with the mentioned cover variations in Figure 1. In total 70 different scenarios for preventing corrosion are evaluated using a factorial combination of the proposed concrete cover and binder systems.

Table 2 Considered binder systems*.*

Binder Type	**w/b Ratio [-]**	**$D_{RCM,28d}$ [10^{-12}m²]**	**Aging Coef. [-]**
CEM I 42.5 R	0.50	14.0	0.30
CEM I 42.5 R	0.43	9.5	0.30
CEM I 42.5 R*	0.45	14.5	0.30
CEM II/A-LL 42.5 N	0.49	16.0	0.30
CEM II/B-S 42.5 N	0.47	7.5	0.40
CEM II/B-S 42.5 R	0.40	3.2	0.40
CEM III/A 32.5 N	0.50	5.2	0.40
CEM III/A 42.5 N	0.42	2.0	0.40
CEM III/A 42.5 N	0.50	4.3	0.40
CEM III/B 42.5 L-LH/HS/NA	0.40	0.7	0.45

** Also employed for the Business as Usual (BAU)*

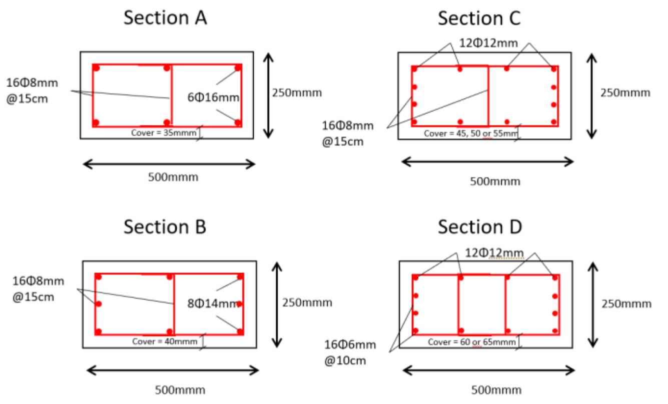

Figure 1 Cross sections of the reinforced concrete column with variation of the concrete cover.

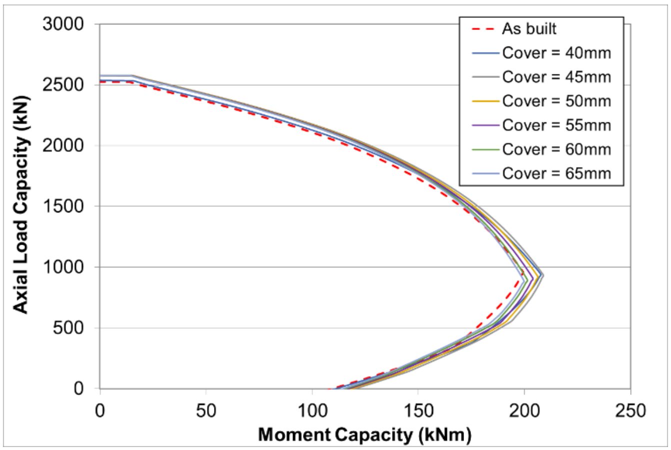

Figure 2 Column interaction diagram of the original design (as built) and the proposed nominal concrete cover.

2.2 Service life prediction

The durability assessment follows a fully probabilistic approach using the procedure in [9]. The depassivation of the steel reinforcement is selected as the serviceability limit state. Depassivation is defined as the time when the chlorides at the steel surface C(c,t) reach a critical threshold C_{crit}, and active corrosion of the steel reinforcement will start. The limit state function is represented by equation **Erro! A origem da referência não foi encontrada.**. Equation **Erro! A origem da referência não foi encontrada.** calculates the chloride content at any time on the steel surface.

$$g(c,t) = C_{crit} - C(c,t) < 0 \qquad (1)$$

$$(c,t) = C_o + \left(C_{S,\Delta x} - C_o\right) \cdot \left[1 - \mathrm{erf}\left(\frac{c-\Delta x}{2 \cdot \sqrt{D_{app}(t) \cdot t}}\right)\right] \qquad (2)$$

where: C(c,t) is time-dependent chloride concentration (wt.%/b) at the steel surface; C_0 is the initial chloride concentration (wt.%/b); $C_{s,\Delta x}$ is the chloride surface concentration (wt.%/b); Δx, depth of the convection zone (m); c, concrete cover (m); t, time (s); $D_{app}(t)$ the time dependent diffusion coefficient of concrete, which is calculated with equation **Erro! A origem da referência não foi encontrada.**.

$$D_{app}(t) = k_e \cdot D_{RCM}(t_o) \cdot \left(\frac{t_o}{t}\right)^{\alpha RCM} \qquad (3)$$

where: k_e is an environmental parameter to consider the ambient temperature [-], $D_{RCM}(t_0)$ is the chloride migration coefficient at the reference point [m²/s], α_{RCM} is the aging exponent.

Table 3 presents the input values used for the probabilistic modeling. The temperature corresponds to the mean in south Germany. The value for the chloride surface concentration ($C_{s,\Delta x}$) is estimated based in the data from the chloride profiles obtained from the condition assessment of the columns [7]. The maximum allowed variation for the concrete cover (Δc_{dev}) is 15 mm after [9]. All the other parameters are to be found in [9]. After obtaining the probability of failure (p_f) for the selected limit state in equation **Erro! A origem da referência não foi encontrada.**, the results are converted to the reliability index (β) using equation **Erro! A origem da referência não foi encontrada.**).

$$\beta = -\Phi^{-1}(pf) \qquad (4)$$

where Φ^{-} *is the inverse standard distribution*

Table 3 Input parameter for probabilistic modelling

Parameter	Unit	Distribution	Average (μ)	Standard deviation (σ)
$D_{RCM}(t_0)$	10^{12} m²/s	Normal	**Table 2**	0.2 μ
α_{RCM}	-	Beta (0,1)	**Table 2**	0.2 μ
t_0	Year	Constant	0.0767	-
T	Year	Constant	100	-
T_{ref}	°K	Constant	293	-
T_{real}	°K	Normal	283	8
b_e	°K	Normal	4800	700
Cs,Δx	wt.-%/b	Lognormal	2.6	1.2
Δx	mm	Beta (0,50)	10	5
C_{crit}	wt.-%/b	Lognormal	0.6	0.12
C_0	wt.-%/b	Constant	0	
c	mm	Normal	Nominal concrete cover	$\frac{\Delta c_{dev}}{1.64}$

2.3 Economic assessment

The economic assessment considers the costs of concrete materials required for the concrete mixes (cement, aggregates, and admixtures), steel reinforcement, and workforce. For reasons of comparability between the different binder systems, the concrete mixes are designed to have the same water content and only a variation on the admixture amount is applied to assure the flow properties shown in Table 1. Hence, the binder content is changed according to the desired water/binder ratio, and aggregate content is adapted for volume adjustment. The prices of the materials for concrete and steel can be found in detail in [10]. The workforce includes the staff for setting the formwork, reinforcing steel placement, concreting, and curing after [11]. These activities are dependent on the steel configuration shown in Figure 1. In this economic assessment, the costs related to construction job administration, taxes, and profits are not considered.

3 Results

3.1 Service life prediction

Figure 3 presents the development of the reliability index β throughout the design service life of 50 years. For the sake of space, only the results for selected alternatives are shown. In the diagram, the best performance is obtained with the binder system CEM III/B L-LH/HS/NA 42.5 N with water binder ratio (w/b) equals to 0.4. After 50 years the binder system has a reliability index β is 2.1. The CEM III/A 42.5 N with w/b = 0.42 performs as second best with a β value of 1.2, followed by CEM II/B-S 42.5 R with w/b = 0.40 with a β value 0.9. Finally, the CEM II/A-LL with w/b = 0.49 and BAU (CEM I 42.5 R with w/b = 0.45) presents the worst performances, the β values are -0.9 and -0.8, respectively.

Target values for the reliability index are set after recommendations found in [8, 12]. Here two conditions could be defined. The first is when the depassivation of steel reinforcement has just started but no visual damage is expected (cracking, spalling). For this case, the value for the reliability index β is 1.5 (depassivation probability of 7%). For the second condition, the depassivation of steel is likeable to have already started. In this case some level of visual damage such as cracking and spalling due to chloride-induced corrosion is expected. Here the value for the reliability index is set to be 0.5 (depassivation probability of 31%). After the previously defined target values for the β, only the alternative with the binder CEM III/B L-LH/HS/NA 42.5 N meets the design service life without visual damage (β > 1.5). On the other hand, the alternatives with the binders CEM III/A 42.5 N and CEM II/B-S 42.5 R meets the lower target value for the β (0.5). Finally, the BAU and CEM II/A-LL after just 5 years are below the lower target value for the reliability index, hence they do not meet the design service life.

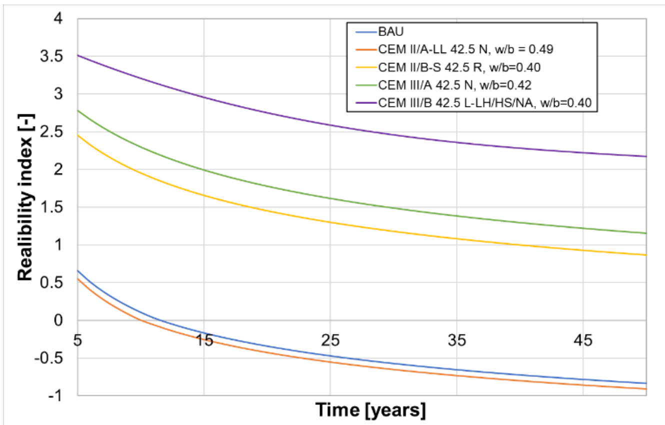

Figure 3 Development of the reliability index (β) over time for selected binder systems with a nominal concrete cover of 55 mm.

3.2 Economic assessment

Figure 4 presents the results of the reliability index (β) vs the costs in EUR per each m of column after 50 years for all variations. The graph also includes the results for the original design of the column (as built in 2001) after [7]. The first remark of this graph is that even following current standard prescriptions (BAU), the design service life of 50 years is not achievable. In comparison with the "As built 2001" scenario, the nominal concrete cover increased from 35 mm to 55 mm representing a cost increment of around 11 EUR per m. Despite this, the change in the reliability index β is from -1.6 to -0.8, below the target value (β => 0.5).

The second remark is that changing the binder system significantly enhances the durability with just a slight increase in the costs. The binder CEM III/B L-LH/HS/NA 42.5 N presented the best improvement of the β value, ranging from 1.0 up to 2.9 while the maximum costs increment VS BAU is 2.3%. For this binder option, the nominal concrete cover can even be decreased to 35 mm and still meet the lower target value for the reliability index (β = 1.0). Hence, saving the amount of steel reinforcement which is translated into potential savings in costs (-3.2% vs BAU). The CEM III/A 42.5 N offered the second-best improvement of β ranging from 0 up to 1.5 and a cost increase of 2.0%. The CEM II/B-S 42.5 R offered the third-best improvement of β, with values from 0 up to 1.24 and a maximum cost increase of 2.0%. The other binder systems also enhance the reliability index. However, the values are mostly under the lower target value of 0.5.

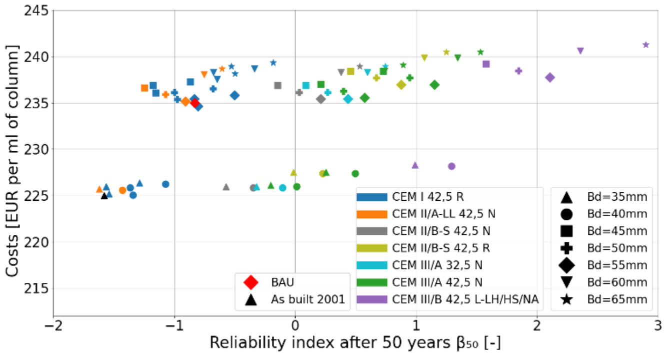

Figure 4 Results of the reliability index (β) after 50 years and the costs in EUR per m of column for all variations studied. The lines represent the trends for each binder type.

Figure 5 compares the 3 different prevention measures. Here, the relationship between the reliability index β at 50 years and the cost increase vs the BAU in EUR/m per column is presented. For the alternatives water/binder ratio and binder system the results for the same nominal concrete cover as BAU (55 mm) are shown. For the increase of the nominal concrete cover, the binder system CEM I 42.5 R with w/b = 0.45 is considered. In the graph, it can be observed that an increase in the concrete cover is the less cost-efficient path to enhance durability. Increasing the concrete cover implies an additional amount of steel reinforcement to conserve the structural performance (see Figure 1 and Figure 2). Considering that the price of steel reinforcement per ton is up to 10 times higher than cement, the cost increase is the highest among the alternatives with up to4 EUR per m of column. Nevertheless, the reliability index β after 50 years is lower than the targeted value even for 65 mm (β = -0.5).

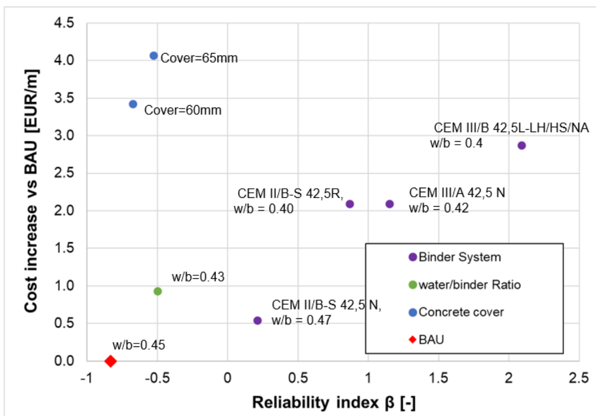

Figure 5 Increase of the costs for selected alternatives with nominal

concrete cover of 55 mm vs the BAU.

On the other hand, just the reduction of the water/binder ratio is a limited solution for preventing reinforcement corrosion. In Figure 5 the ratio was reduced to 0.43 while keeping the same binder type (CEM I). This option is the cheapest but the improvement of the β is rather limited. Here a further reduction in the water/binder ratio is still necessary. However, the high amount of binder required to further reduce the water/binder ratio would increase the probability of surface cracking [13]. The cracks are a path for a rapid intrusion of chloride ions and moisture, thus reducing the depassivation time and in this way significantly affecting the service life of the element [14]. Finally, the variation of the binder system offers the best enhancement of the reliability index with a moderate increase in costs. Being this in the range of 0.5 EUR to 2.9 EUR per m of column. Based on the results of the study, a balance between the binder system type, nominal concrete cover, and water/binder ratio must be found to optimize the costs while assuring the durability of the element.

4 Conclusions and outlook

Based on the findings of this study, the following conclusions can be drawn:

- The standardized prescriptive approach for preventing chloride-induced reinforcement corrosion does not guarantee achieving the design service life of the reinforced concrete element, especially in the case of chloride exposure. The element durability should be assessed considering the geometry and binder system employing the performance-based approach.
- The variation of the binder system is the most cost-efficient path to significantly enhance the durability of a reinforced concrete element.
- The reduction of the water/binder ratio alone is a rather limited solution for preventing reinforcement corrosion. While increasing the concrete cover is a less cost-efficient path to enhance durability.
- To find the most durable and cost-efficient alternative to prevent corrosion, a suitable balance between the binder system type, nominal concrete cover, and water/binder ratio is necessary.

This study presents the first results from an ongoing German joint research project. This paper considers just a limited number of binder systems. The next step is the expansion of the database with new and/or alternative binder systems such as limestone calcined clays cements or alkali-activated binders. Since both cement and steel reinforcement have a considerable CO_2 footprint, another task is to evaluate the influence of carbon pricing on the final costs. Furthermore, to have a broader view of sustainability is necessary to also determine the environmental impacts of the different prevention strategies. Finally, there is still a discussion in the field about what is the suitable limit state for chloride-induced corrosion in reinforced concrete. Therefore, other limit states such as cracking and spalling should as well be considered in the durability assessments. The ongoing joint research project is currently investigating these open issues.

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[1]Forschungsvereinigung der deutschen Beton- und Fertigteilindustrie e.V.

[2]Bundesministerium für Wirtschaft und Klimaschutz

[3]AiF: die Arbeitsgemeinschaft industrieller Forschungsvereinigungen

[4]IGF: Industrielle Gemeinschaftsforschung

[5]DAfStb: Deutscher Ausschuss für Stahlbeton

[6]Engineering Consultancy Schiessl-Gehlen-Sodeikat GmbH

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