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DEVELOPMENT OF CONFORMITY CRITERIA FOR DURABILITY AND ITS INFLUENCE ON SERVICE LIFE PREDICTIONS

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Abstract. To ensure the quality of produced concrete batches, it is often verified whether a specified concrete compressive strength is reached by the application of conformity control. The conformity criteria used for this purpose are related to the probability of accepting a batch, in relation to a specified quality. Batches fulfilling the conformity criteria are accepted, whereas others are rejected. In this way, the outgoing quality of the accepted concrete is higher than without the application of conformity control. This is the result of the filtering effect of conformity control and affects the probability of failure of concrete structures. Instead of only applying conformity control to the concrete compressive strength, a similar procedure could be applied to durability related variables. One example hereof is the diffusion coefficient of the concrete. When conformity criteria are defined and applied in relation to the diffusion coefficient, the result will be a filtering effect on the distribution of the diffusion coefficient. The outgoing distribution will have a lower mean value and standard deviation compared to the incoming distribution. This will influence the time-dependent reliability of reinforced concrete structures. This paper investigates the effect of conformity criteria for diffusion coefficients on the service life and failure probabilities of reinforced concrete elements. The filtering effect is investigated by a numerical study applying analytical methods and numerical integration.

Keywords: Concrete, conformity control, durability, service life.

1. Introduction

By requiring quality inspection on concrete properties, producers are stimulated to obtain higher performance. One example of a method for quality inspection is the application of conformity control to the concrete compressive strength [1, 2], based on operating characteristic curves (OC-curves) [2, 3]. These OC-curves relate the probability of accepting a concrete batch to its quality. As such, some concrete batches will be rejected whereas others will be accepted. As a result, a filtering effect is induced on the distribution of the investigated property. In case of concrete compressive strength, this leads to a higher mean value and a lower standard deviation of the outgoing distribution (after conformity control) compared to the incoming concrete offered for conformity control [4, 5]. When the outgoing strength distribution is used in structural reliability calculations, the probability of failure decreases, which illustrates the beneficial effect of quality control [6].

In this article, conformity criteria are applied to the diffusion coefficient, and the effect on the parameters of the probabilistic model is investigated together with the effect on the service life of reinforced concrete structures. The principles of conformity control are summarized in Section 2, and the resulting filter effect is explained in Section 3, which provides the applied analytical models and methods for numerical integration. The quantification approach is applied to the diffusion coefficient in Section 4. In this section, it is also investigated how sampling from a concrete batch influences the probability of accepting the batch. In Section 5, the influence of conformity control on the distribution of the initiation period is investigated, together with the influence on the service life.

2. Quality control by conformity criteria

Conformity control verifies whether produced concrete batches comply with specified properties. For this purpose, a sample of limited size is used and from this sample inferences are made with regard to the whole population. As stated in [7], for the diffusion coefficient, the mean value D_m, corresponding to the 50%-fractile of the theoretical distribution can be considered as the specified value, or the characteristic value D_k corresponding to the 90% fractile [7, 8]. In practice, the fraction above the specified value (corresponding to an undesired situation of a high diffusion coefficient) will be smaller or higher than 50% or 10% respectively. When θ is the fraction of test results higher than D_m or D_k in the offered distribution, equations (1) and (2) are valid [7] (where X is the diffusion coefficient, considered as a random variable). This value θ will be further denoted as the fraction defectiveness.

$$P\left[X \geq D_m\right] = \theta_1 \tag{1}$$

$$P\left[X \geq D_k\right] = \theta_2 \tag{2}$$

When a conformity criterion in specified, for each fraction defectiveness θ, the corresponding probability that a concrete batch will be accepted can be calculated, under the assumption of a theoretical distribution of the diffusion coefficient. This probability of acceptance is denoted as $P_a(\theta)$ and is called the operating characteristic (OC-curve).

3. Conformity criteria and their filter effect

In [9], an analytical method is provided that can be used to evaluate the filter effect, but is only applicable to some common (basic) conformity criteria. In practice, more complex criteria are used [10]. In such situations, a numerical algorithm can be applied, such as the one developed in [11], which has its basis in Bayesian statistics and applies numerical integration. The method applied in this work is also described in [7]. Similar as in [7], in the following, the batches offered for conformity control, i.e. the incoming concrete batches, are represented by the index 'i'. The accepted batches, i.e. the outgoing concrete batches, are represented with the index 'o' The mean and standard deviation of the incoming concrete batches are given by Equations (3) and (4) respectively (assuming normal distributions).

$$\mu_i = \mu_m \tag{3}$$

$$\sigma_i = \sqrt{\sigma_m^2 + \sigma_l^2} \tag{4}$$

Given the OC-curve of a conformity criterion, the posterior distribution of the diffusion coefficient can be quantified by numerical integration, and the mean and standard deviation can be calculated. The latter can then be compared with the prior (incoming) values to quantify the filter effect of the conformity control.

4. Conformity control for the diffusion coefficient of concrete

In this section, conformity control is considered for the diffusion coefficient and the filter effect on its distribution is investigated. Since there are no standards yet providing conformity criteria for the diffusion coefficient, in this work, some assumptions are made in relation to the format of the conformity criteria, which are similar to those in [7].

4.1. OC-curves

If a value for the diffusion coefficient has to be specified, often the mean value D_m (50% fractile) or the characteristic value D_k (90% fractile) are used (as also indicated in Section 2). To define a conformity criterion, either the sample standard deviation s_n could be used, leading to Equations (5) and (6) [7], or the criterion could be based on the standard deviation of the incoming batches σ_i, according to Equations (7) and (8) [7]. The latter can be applied when sufficient information is available to have a reasonable estimate of the standard deviation σ_i.

$$\overline{x}_n \leq D_m + \lambda\, s_n \tag{5}$$

$$\overline{x}_n \leq D_k + \lambda\, s_n \tag{6}$$

$$\overline{x}_n \leq D_m + \lambda\, \sigma_i \tag{7}$$

$$\overline{x}_n \leq D_k + \lambda\, \sigma_i \tag{8}$$

In these Equations, n is the number of samples used for conformity control and $\overline{x}_n$ is the sample mean.

The parameter λ corresponding to a certain value of n can be derived based on the AOQL (average outgoing quality limit) concept, as described in [3, 12, 13]. The AOQ (average outgoing quality) is defined according to Equation (9).

$$AOQ = \theta \cdot P_a \tag{9}$$

A boundary for the unsafe region in the $\theta - P_a$ diagram could be defined, which is represented by the AOQL. This AOQL equals 50% for conformity criteria (5) and (7), when on average the specified value should be a 50% fractile. Similarly, the AOQL equals 10% for conformity criteria (6) and (8), where a specified value equal to the 90% percentile is desired [7]. Also an uneconomic region in the $\theta - P_a$ diagram can be defined, for which the boundary is given by Equations (10) and (11) according to [14] (for $\theta_1 \leq 50\%$ or $\theta_2 \leq 10\%$).

$$\frac{\theta_1}{1 - P_a^1} = 50\,\% \tag{10}$$

$$\frac{\theta_2}{1 - P_a^2} = 10\,\% \tag{11}$$

In these Equations, θ_1 are the fraction defectives according to Equation (1) and P_a^1 the corresponding probability of acceptance. Accordingly, θ_1 and P_a^2 are related to Equation (2). It should be pointed out that in Equations (10) and (11) other values of the AOQL can also be assumed, depending on the acceptability requirements.

The resulting values of λ to be used for different values of n are summarized in Table 1 for the conformity criteria given by Equations (5) and (7) (AOQL= 50%) and Equations (6) and (8) (AOQL= 10%), assuming that each time n different samples are taken from the incoming concrete batches. The sample mean $\overline{x}_n$ and sample standard deviation s_n are then evaluated based on these n different and independent samples. The corresponding OC-curves for the conformity criterion given by Equations (5) and (6) are visualized

n	λ			
	AOQL= 50%		AOQL= 10%	
	$\overline{x}_n \leq D_m + \lambda\, s_n$	$\overline{x}_n \leq D_m + \lambda\, \sigma_i$	$\overline{x}_n \leq D_k + \lambda\, s_n$	$\overline{x}_n \leq D_k + \lambda\, \sigma_i$
3	1.32	0.57	− 1.24	− 0.59
4	1.04	0.51	− 1.07	− 0.60
5	0.90	0.49	− 1.01	− 0.60
6	0.81	0.45	− 0.98	− 0.62
7	0.76	0.44	− 0.96	− 0.62
8	0.70	0.42	− 0.95	− 0.63
9	0.66	0.40	− 0.95	− 0.64
10	0.64	0.39	− 0.96	− 0.64
11	0.61	0.38	− 0.94	− 0.65
12	0.59	0.37	− 0.96	− 0.66
13	0.57	0.37	− 0.96	− 0.66
14	0.55	0.35	− 0.96	− 0.66
15	0.54	0.35	− 0.96	− 0.66

TABLE 1. OC curves for conformity control on the diffusion coefficient.

in Figure 1. Also the boundaries of the uneconomic and unsafe region are indicated.

4.2. Influence of sampling on the probability of accepting a concrete batch

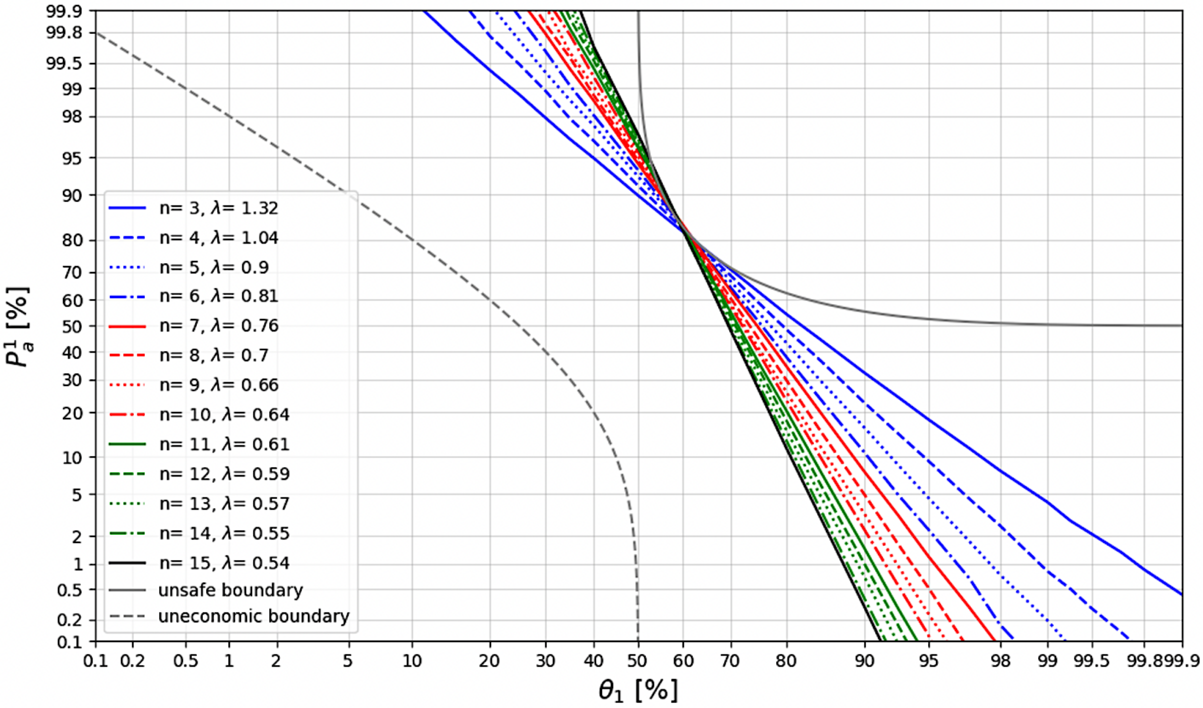
For derivation of the OC-curves in the previous section, it has been assumed that n different samples are taken from the concrete batch. $\overline{x}_n$ and s_n are then evaluated based on these n different samples. However, $\overline{x}_n$ could also represent a moving average. Consider for example the case where $n = 3$ and where six samples are available. In the first situation, conformity control could be applied two times, i.e. once with $\overline{x}_n$ and s_n evaluated based on the first three samples, and once with $\overline{x}_n$ and s_n evaluated based on the next three samples. If $\overline{x}_n$ is replaced by a moving average, the conformity control can be applied $n + 1$, i.e. 4 times, i.e. once $\overline{x}_n$ and s_n are evaluated based on samples 1 to 3, once samples 2 to 4 are used, once samples 3 to 5 are used, etc. Hence, each time a new sample is added to the set and the first sample is thrown out. Since in the second situation more tests for conformity control are performed, this will have an influence on the probability of accepting a concrete batch.

In this section, this influence will be investigated. The probability of accepting a lot P_a will be derived for both situations. Each time, the total set of samples is equal to $2n$. Hence, in the first situation, conformity will be checked 2 times, and in the second situation, with the moving average, conformity will be checked $n + 1$ times. The influence on the probability of accepting a lot is visualized in Figure 2 for the two types of conformity criteria as given by Equations (8) and (9) and for n equal to 3, 5 and 15, for the different values of the fraction defectives. Here it can be seen that working with the moving average leads to a lower probability of accepting a concrete batch. This because more tests are performed, leading to a more strict criterion. However, moving averages might be sensible to consider if for example from an economic point of view only a limited number of samples can be obtained.

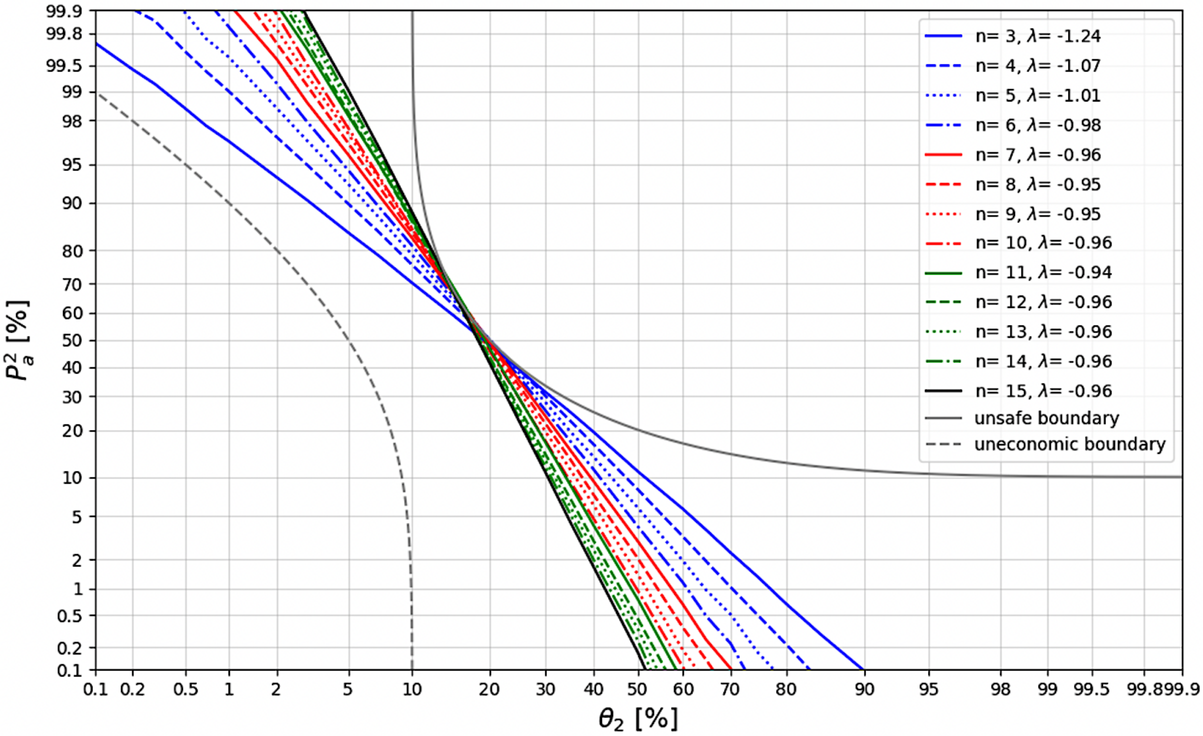
4.3. Filter effect of the application of conformity control on the diffusion coefficient

In this section, the filter effect on the mean and standard deviation of the diffusion coefficient is quantified. For this purpose, the ratios μ_o/μ_i and σ_o/σ_i, i.e. the outgoing mean or standard deviation of the diffusion coefficient relative to the incoming values, are evaluated based on the numerical algorithm described in [15]. For AOQL= 50% and $\overline{x}_n \leq D_m + \lambda\, s_n$, the influence of the filter effect is visualized in Figure 3 (i). Similarly, for AOQL= 10% and $\overline{x}_n \leq D_k + \lambda\, s_n$the results are presented in Figure 3 (ii) [7]. To derive these results, a set of n samples is assumed together with the values for λ as given in Table 1. In Figure 3, it can be observed that both the mean value and standard deviation of the diffusion coefficient decrease when conformity control is applied. The magnitude of this reduction depends on the applied conformity criterion, where a lower outgoing mean and standard deviation (i.e. a larger filter effect) are observed for a higher number of samples n. Moreover, the filter effect becomes more pronounced if the fraction defectives increases (i.e. lower quality in regard to durability).

If the conformity criteria from Equations (7) and (8) are applied, the filter effect is influenced by the assumptions on σ_i. In the following, the filter effect after application of conformity control on the diffusion coefficient is evaluated for equal to $0.1D_m$. For the ratio σ_l/σ_m values of 0.5, 1 and 2 are assumed. The results are summarized in Figure 4. All these results are given for the conformity criteria based on AOQL = 50 % ($\overline{x}_n \leq D_m + \lambda\, \sigma_i$) and AOQL = 10% ($\overline{x}_n \leq D_k + \lambda\, \sigma_i$). In Figure 4, it can be observed that a



(i) AOQL = 50% and $\bar{x}_n \leq D_m + \lambda s_n$



(ii) AOQL = 10% and $\bar{x}_n \leq D_k + \lambda s_n$

FIGURE 1. OC curves for conformity control on the diffusion coefficient.

higher ratio of the outgoing vs. incoming mean and standard deviation is found for increasing values of σ_l/σ_m, and that this effect on the standard deviation is the strongest. If the value of σ_i would be increase, a stronger reduction in outgoing versus incoming mean would be found. The influence of σ_i on the ratio of the outgoing vs. incoming standard deviation is rather limited.

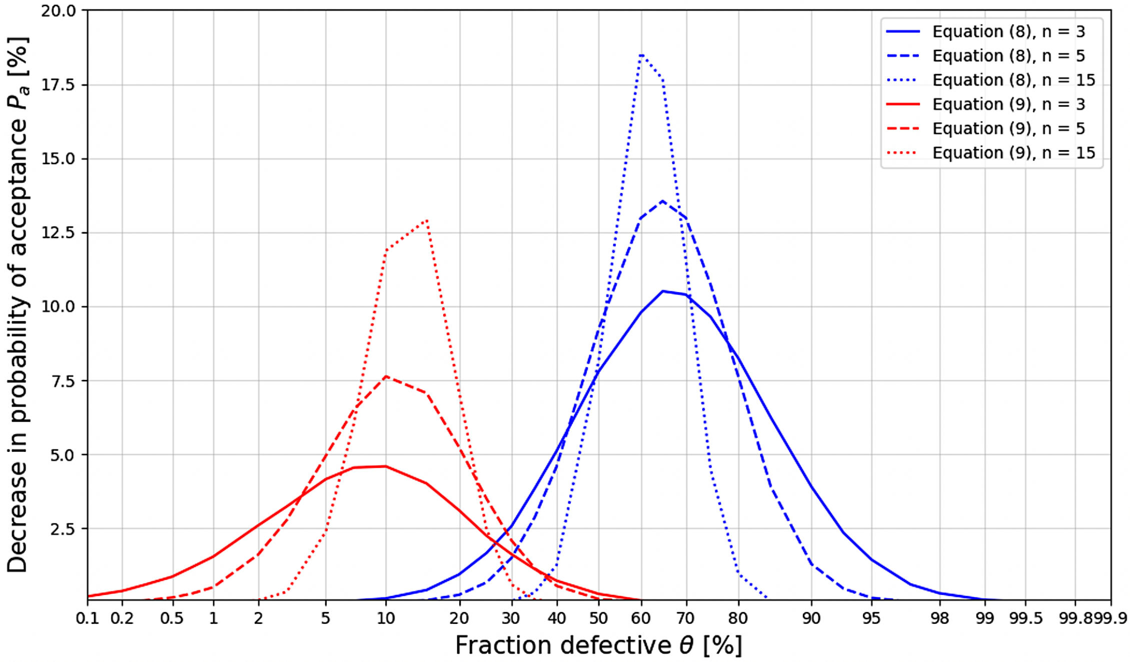
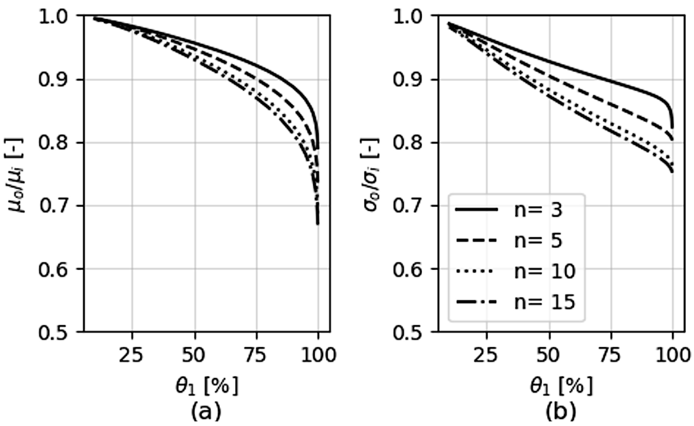
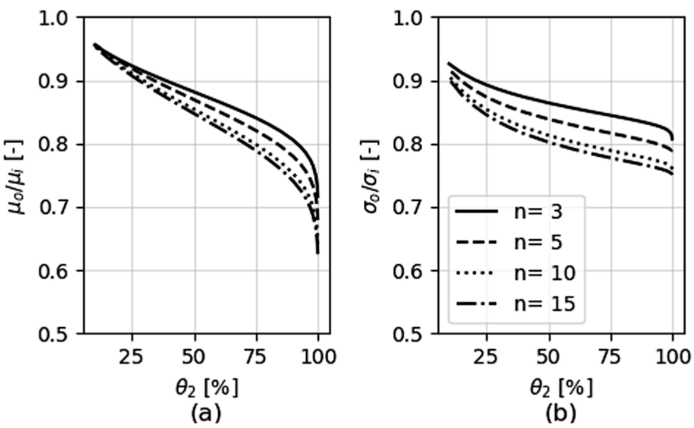


FIGURE 2. Decrease in probability of accepting a concrete batch when going from 2 tests with n different samples to $n+1$ tests with a moving average (AOQL= 50% and $\overline{x}_n \le D_m + \lambda\, s_n$).

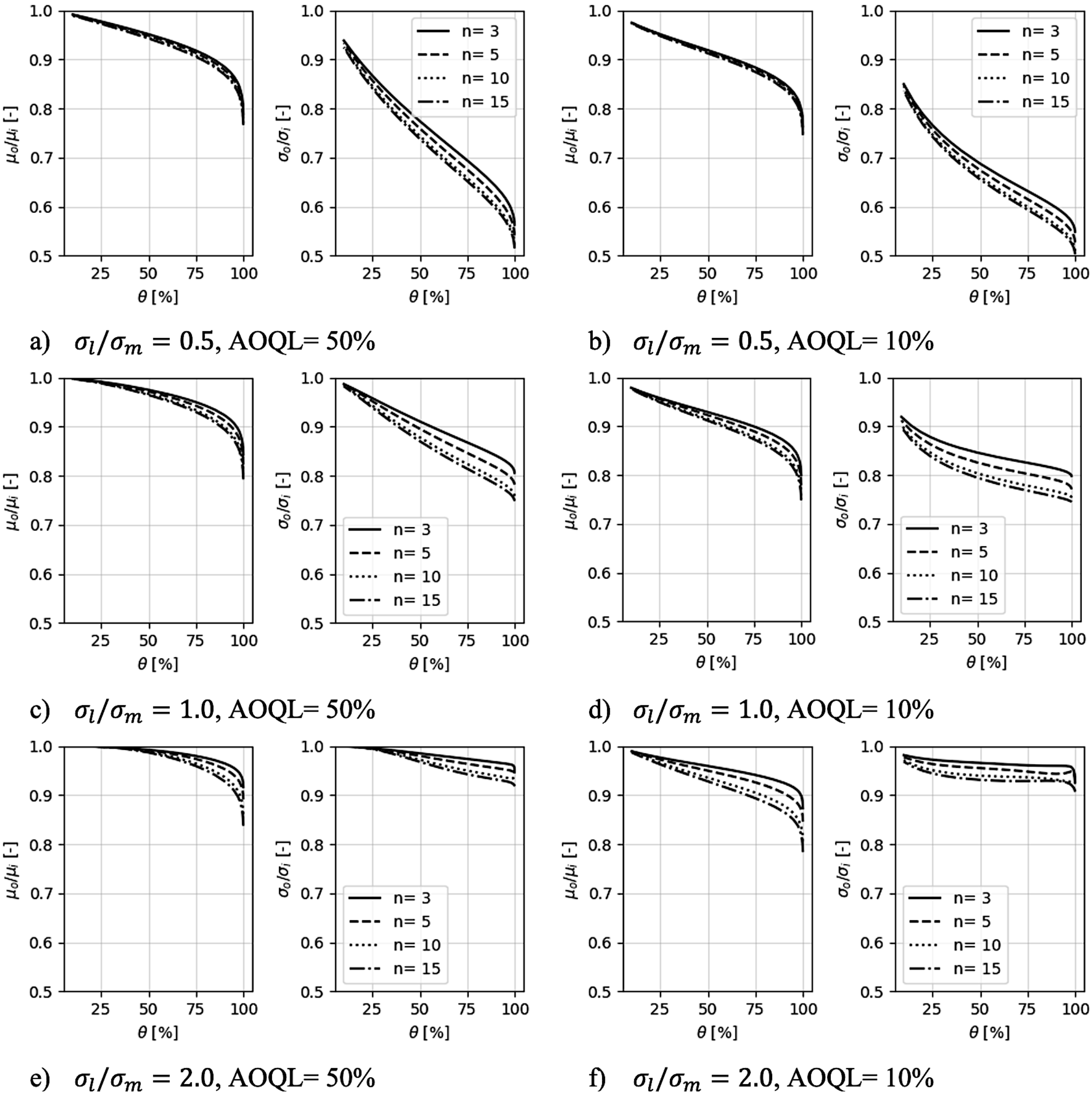


(i) AOQL = 50% and $\bar{x}_n \le D_m + \lambda s_n$



(ii) AOQL = 10% and $\bar{x}_n \le D_k + \lambda s_n$

FIGURE 3. Filter effect on the parameters of the diffusion coefficient.



a) $\sigma_l/\sigma_m = 0.5$, AOQL= 50%
b) $\sigma_l/\sigma_m = 0.5$, AOQL= 10%
c) $\sigma_l/\sigma_m = 1.0$, AOQL= 50%
d) $\sigma_l/\sigma_m = 1.0$, AOQL= 10%
e) $\sigma_l/\sigma_m = 2.0$, AOQL= 50%
f) $\sigma_l/\sigma_m = 2.0$, AOQL= 10%

Figure 4. Filter effect based on $\overline{x}_n \leq D_m + \lambda\,\sigma_i$ (AOQL= 50%) or $\overline{x}_n \leq D_k + \lambda\,\sigma_i$ (AOQL= 10%) with $\sigma_i = 0.1 D_m$.

Parameter	Distr.	Unit	μ	σ	a	b
c	Beta	mm	35	5	0	150
C_s	LN	wt.-%/c	0.7	0.21 –	–	
C_{cr}	Beta	wt.-%/c	0.6	0.15	0.2	2
D	N	mm^2/year	50	10	–	–

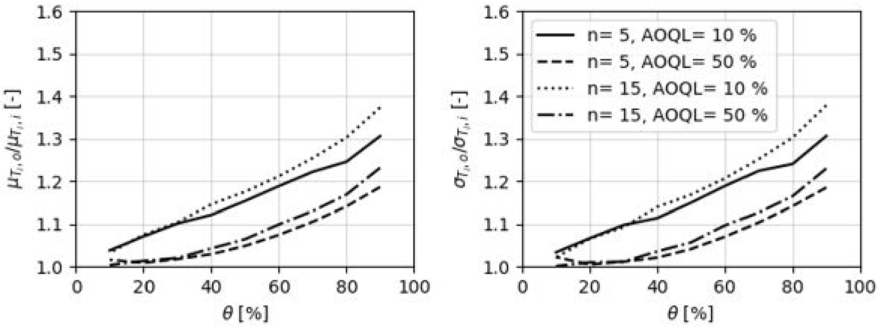
*a indicates the lower bound of the distribution and b the upper bound

Table 2. Distributions used in the estimation of the service life.

5. Influence of conformity control on the diffusion coefficient on the service life of reinforced concrete structures

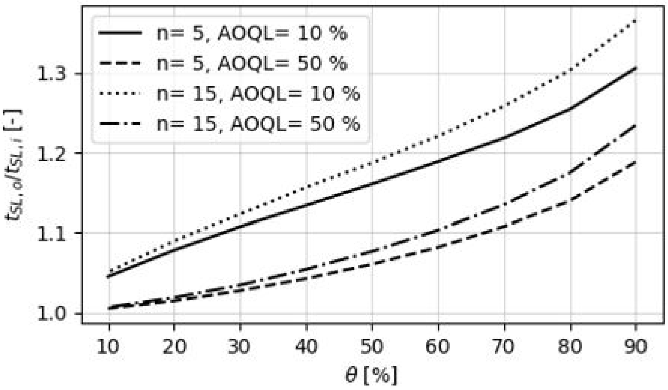
When considering durability of a reinforced concrete structure, corrosion is an important mechanism affecting the durability of the structure. When considering chloride-induced corrosion, the resistance against penetration of the chlorides in the concrete is governed by the diffusion coefficient of the concrete. Hence, the initiation period (T_i) of corrosion is determined by this diffusion coefficient D, together with the concrete cover c, the surface chloride concentration C_s and the critical chloride concentration C_{cr} according to Equation (12) [16, 17].

$$T_i = \frac{1}{4\,D_{app,C}}\,\frac{c^2}{erf^{-1}\left(1-\dfrac{C_{cr}}{C_s}\right)} \tag{12}$$



(a) (b)

(i) Influence of conformity control on the diffusion coefficient on the mean value and standard deviation of the initiation period



(ii) Influence of conformity control for the diffusion coefficient on the service life

Figure 5. Influence of conformity control on the initiation period and on the service life.

Here, erf^{-1} is the inverse error function.

It has been illustrated in Section 4.3 that due to conformity control, the mean value of the diffusion coefficient decreases. When looking at Equation (12), a decrease in mean value of the diffusion coefficient will lead to an increase in the mean value of the initiation period, i.e. it takes more time for the chlorides to reach the reinforcement steel, which is beneficial for the durability of the reinforced concrete structure. When assuming the distributions given in Table 2 [7, 16], this increase in mean value of the initiation period is illustrated in Figure 5 (i).

In Figure 5 (i), it can be observed that besides the mean value of the initiation period, also its standard deviation increases after application of conformity control on the diffusion coefficient. This effect is caused by the appearance of the diffusion coefficient in the denominator of Equation (12). Despite this increase in standard deviation of the initiation period, the influence of conformity control on the diffusion coefficient is still beneficial when considering the effect on the service life (t_{SL}). The latter can be evaluated as the time at which there is a 10% probability of exceeding the condition limit state of depassivation [16]. To evaluate the influence of conformity control of the diffusion coefficient on this service life, the latter is estimated both for the incoming and outgoing distribution of the diffusion coefficient (as quantified above). The results are visualized in Figure 5 (ii), where a significant increase of the service life is observed after application of conformity control. Hence, it can be concluded that an adequate quality control in terms of durability is enabled.

6. Conclusions

In this work, conformity criteria have been derived for application of conformity control to the diffusion coefficient. It has been assumed that the specified value is characterized either by the mean value (50% fractile) or by the characteristic value (90% fractile) of the distribution. The probability of acceptance has been evaluated for different values of the fraction defectiveness, and based on a limit on the average outgoing quality, conformity criteria have been derived. These investigations are based on analytical methods and numerical integration. Moreover, it has also been illustrated that the way samples are taken from the batches influences the probability of accepting a batch. If moving averages are applied, the probability of accepting a batch decreases compared to ordinary averages.

The derived conformity criteria have then been applied to quantify the filter effect of conformity control on the distribution of the diffusion coefficient. It has been illustrated that the mean value of the outgoing batches of concrete is lower than the mean value of the batches delivered for conformity control. The same effect has been observed for the standard deviation. These effects will also influence the service life of a reinforced concrete structure. It has been illustrated how the initiation period and the service life both increase due to the beneficial effects of conformity control applied to the diffusion coefficient.

As a final note, the authors would like to point out that similar procedures could also be applied to other durability related parameters such as the carbonation rate. For the latter, a lower mean value and standard deviation will be found due to the filtering effect of conformity control, which is again beneficial for the durability of a reinforced concrete structure. When rapid chloride migration tests are applied for the diffusion coefficient, similar procedures can be applied to the obtained D_{RCM} values [16] if the relevant statistical information (i.e. the coefficient of variation (COV)) is inserted.

List of symbols

AOQ Average outgoing quality

AOQL Average outgoing quality limit

OC Operating characteristic

c Concrete cover

C_{cr} Critical chloride concentration

C_s Surface chloride concentration

D_m Specified mean value of the diffusion coefficient

D_k Specified characteristic value of the diffusion coefficient

f Probability density function

n Number of samples used for conformity control

P_a Probability of acceptance

s_n Sample standard deviation

T_i Initiation period

t_{SL} Service life

$\overline{x}_n$ Sample mean

θ Fraction defectiveness

μ Mean value

σ Standard deviation

ϕ Probability density function of a standard normal distribution

m Variation of the diffusion coefficient of different concrete batches

l Variation within a concrete batch

o Outgoing

i Incoming

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