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Reliability-based conformity control method for chloride diffusivity of coastal reinforced concrete buildings

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Abstract: Chloride diffusivity significantly affects the durability of coastal reinforced concrete (RC) buildings in practice, and is one of the engineering concerns in design and execution. Durability designs of coastal RC building structures are commonly based on “deem-to-satisfy” methodology and the corresponding conformity controls for diffusivity are implicit. This may lead to the unawareness of their durability performance. In this paper, drawbacks of the existing empirical method and semi-empirical method are addressed according to the reliability assessment; and based on the statistical acceptance sampling theory and the engineering practice of Hong Kong-Zhuhai-Macau sea-link project, a reliability-based conformity control method for diffusivity is proposed, which can be applied in the construction of coastal RC buildings. Effects of local environmental conditions (e.g., temperature and humidity) on chloride diffusivity are considered in the proposed method, and the relation between diffusion coefficient for design (D_{a0}) and for conformity control (D_{nssm}) in existing engineering practice is amended accordingly for its applications in other projects. The conformity control for the concrete’s chloride diffusivity of an accessory RC building in the Shantou Harbor is taken as the example, and the schemes by empirical method, semi-empirical method and reliability-based method respectively

1 are established for this building. Their acceptable quality level (AQL) and limiting quality level (LQL),
2
3 probabilities of acceptance and outcomes in terms of durability reliability of these schemes are
4
5 evaluated and compared. It is found that the conformity control scheme by reliability-based method
6
7 can reflect the expected reliability level in design better than the empirical method and the semi-
8
9 empirical method, and can reject most of the nonconforming lots without harming the producers'
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11 benefits.
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17 **Keywords:** Conformity control; Acceptance sampling; Structural reliability; Concrete chloride
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19 diffusivity; Coastal environment
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23 **Nomenclature**

24		
25		
26	A	Acceptance constant
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28	AQL	Acceptable quality level
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31	c	concrete cover thickness
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34	C_{cr}	Critical chloride concentration for steel depassivation
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36		
37	C_s	Surface chloride concentration
38		
39		
40	D_{a0}	Reference diffusion coefficient at time t_0
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42		
43	D_{nssm}	Non-steady-state migration coefficient
44		
45		
46	k	Acceptance constant
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48		
49	LQL	Limiting quality level
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52	m_X	Mean value of the sample for X
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54		
55	n	Aging factor for diffusion coefficient
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58	N	Sample size
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61	p_A	Fraction of defectives at AQL
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1	p_k	Fraction of defectives at the design target
2		
3	p_L	Fraction of defectives at LQL
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5		
6	Rel	Reliability index
7		
8		
9	Rel_t	Target reliability index
10		
11	S_X	Sample standard deviation for X
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13		
14	X_k	Characteristic diffusivity
15		
16		
17	X_{min}	Minimum value of the sample for X
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19		
20	α	Producer's risk
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23	β	Consumer's risk
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26	$[\alpha]$	Allowed value of producer's risk
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28		
29	$[\beta]$	Allowed value of consumer's risk
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31 **1. Introduction**

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33
34 For reinforced concrete (RC) buildings and structures placed in coastal/marine environment,
35 chloride ingress may cause the corrosion of reinforcement steel bars, and as a result, the durability
36
37 insufficiency of buildings. As suggested in existing studies, diffusion is the main way of chloride
38 penetrating into the concrete (Collepari et al., 1972; Tuutti, 1982; Sarja & Vesikari, 1996); it leads to
39
40 the accumulation of chloride ion on the steel surface, and results in the steel corrosion and concrete
41 surface cracking (Akiyama et al., 2010; Li & Ye, 2018; Qu et al., 2021). Therefore, chloride diffusivity
42
43 is the vital durability property of coastal RC building structures, and limiting the diffusivity is the main
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45 task during design and execution in term of durability.
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57 Existing codes (ACI, 2014; GB/T 50476, 2019; CEN, 2004) suggest some basic requirements on
58 concrete strength or concrete mixtures for designers, based on laboratory experiments and practical
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1 experiences in the former projects. Designers can choose the proper concrete mixtures accordingly.

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3 The designs or the completed structures, which satisfy these requirements, are deemed to satisfy the
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5 durability target. It's a "deem-to-satisfy" design methodology (*fib*, 2006), which is convenient in
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7 engineering practice and widely used currently. It is noted that the chloride diffusivity is qualitatively
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9 determined and implicitly limited by the stipulations on concrete compressive strength or concrete
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11 mixtures.
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16
17 Conformity control examines the products' qualities and decides whether the products should be
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19 accepted or rejected, serving as the examination for the output of execution according to the design. In
20
21 current practice, compressive strength is the vital characteristic in grading the concrete products;
22
23 existing codes (BSI, 2013; GB/T 50107, 2010) suggested the conformity control method for concrete
24
25 compressive strength, which were checked and developed in recent studies (Pacheco et al., 2019; Tur
26
27 & Derechennik, 2020; Saleh et al., 2022; Strauss et al., 2022; Wally et al., 2022). Since the design of
28
29 chloride diffusivity is often performed implicitly in current practice, its conformity control is often
30
31 absent, and it's often regarded as "conforming" when the concrete strength or concrete mixtures
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33 achieving the design demand. Such method is widely used and served as the main way of controlling
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35 the structural durability of coastal RC buildings.
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46 These "implicit" requirements are often not enough in engineering practice. The Chinese code
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48 (GB/T 50476, 2019) suggests that for important structures, the critical value on diffusion coefficient
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50 should be designated before construction; and the code also stipulates the allowable limit of this critical
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52 value. However, there is no widely accepted instruction on how to determine the critical value; and in
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54 practice, the critical value is designated according to engineering judgement; and this method is
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56 referred as "empirical method" in this paper. Noted that an inappropriate critical value will result in
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1 either erroneous acceptance or erroneous rejection in conformity control, which will consequently
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3 result in either durability insufficiency or economic inefficiency. Currently, there is few research
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5 discussing the effects of inappropriate critical value for concrete diffusivity.
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9 In the conformity control of the Hong Kong-Zhuhai-Macau (HZM) sea-link project located in
10
11 South China Sea, additional conformity control for concrete diffusivity was performed based on
12
13 statistical acceptance sampling theory, due to the situation that the structure will service in severe
14
15 chloride-aggressive condition with a long design service life of 120 years (Li et al., 2015; Zhang et al.,
16
17 2013). Ye et al. (2021) further improved the conformity control scheme according to the project's
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19 durability reliability. The scheme was designed for HZM project; in order to use it in the other project,
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21 the effects of local environmental conditions (e.g., temperature and humidity) on chloride diffusivity
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23 of concrete should be taken into account, since these effects were investigated and widely recognized
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25 in existing study (Saetta et al., 1993; Nguyen et al., 2017; Jin et al., 2022).
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35 In this paper, the general method based on the methodology in HZM project is proposed to
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37 eliminate the confusion in designating critical levels of concrete diffusivity. For better illustration,
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39 acceptance sample theory is introduced in Section 2, and the existing conformity control method for
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41 concrete diffusivity in Chinese code and in practices are introduced in Section 3. Reliability assessment
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43 of the conformity control scheme for the concrete diffusivity of an accessory building of the Shantou
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45 Harbor, is performed as a case study to show the drawbacks of the existing empirical method and semi-
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47 empirical method in Section 4. Reliability-based method is established in Section 5, on the basis of the
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49 study on conformity control with reliability-based LQL for HZM project, and with the effects of local
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51 environmental conditions considered. Case study in Section 6 presents reliability assessment of the
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53 scheme established by the proposed reliability-based method, for the same case; and the results are
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1 compared to those in Section 4.

2. Acceptance sampling

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6 In a conformity control scheme, a lot is the basic unit and consists of the products manufactured
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8 under essentially the same conditions; if a lot was perceived as “conforming” or “nonconforming”, all
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10 the products in this lot would be accepted or rejected, respectively.
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14 Acceptance sampling is a widely-adopted method to decide whether the lot is conforming or not
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16 when the testing is destructive (Duncan, 1974). The number of samples needed for each lot is the
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18 sample size and is denoted as N . In an acceptance sampling scheme, the criteria are pre-designed
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20 according to empirical experiences or statistic theory; inspections are performed on the N samples,
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22 taken randomly from the lot; and the decision of acceptance or rejection is made according to the
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24 criteria and these inspection results.
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32 To determine the criteria based on statistic theory, the products quality levels and risks relating to
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34 statistical acceptance sampling should be quantified, which are defined based on (ISO, 2006) and used
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36 in this paper as follows.
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- 40 • Characteristic Diffusivity (X_k): Value of certain parameter X that represents the demand for
41
42 diffusivity of concrete given in structure design phase. In the reliability-based method in this paper,
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44 X is defined as the logarithm of non-steady state migration coefficient given by NT BUILD 492
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46 method.
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- 49 • Fraction of Defectives (p): The proportion of units with X larger than characteristic diffusivity X_k
50
51 in a lot. It quantifies, and is often used to represent the quality of the lot. It is unknown during
52
53 statistical acceptance sampling.
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- 56 • Probability of Acceptance: The probability of accepting the lot with a specific fraction of defective.
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It is denoted as $g(p)$.

- Acceptable Quality Level (AQL): The lot quality that is in conformity with the contract and has a high probability of acceptance for the sampling plan. The fraction of defectives for the lot at AQL is denoted as p_A .
- Limiting Quality Level (LQL): The lot quality that is deficient and the consumer is sure to reject will be limited to a low probability of acceptance for the sampling plan. The fraction of defectives for the lot at LQL is denoted as p_L .
- Producer's Risk (α): For a given sampling plan, the probability of erroneously rejecting a lot when the lot quality is acceptable (i.e. AQL) which usually refers to the contractor's and construction company's risk. This kind of risk is unavoidable due to the inherent uncertainty in sampling inspection. The risk should be no larger than $[\alpha]$. ISO (2006) suggests that the risk's limit $[\alpha]$ is 5%.

$$\alpha = P(\text{Rejection}|\text{AQL}) = 1 - g(p_A) \leq [\alpha]. \quad (1)$$

- Consumer's Risk (β): For a given sampling plan, the probability of erroneously accepting a lot when the lot quality is unsatisfactory (i.e. LQL) which usually refers to the public and agency's risk. This kind of risk is unavoidable due to the inherent uncertainty in sampling inspection. The risk should be no larger than $[\beta]$. ISO (2006) suggests that the risk's limit $[\beta]$ is 10%.

$$\beta = P(\text{Acceptance}|\text{LQL}) = g(p_L) \leq [\beta]. \quad (2)$$

3. Existing methods of conformity control for diffusivity

Conformity control for diffusivity aims at examining whether the execution quality conforms the instruction, or the completed member's concrete chloride diffusivity accords or not with the expected level in design. Chloride diffusivity of the cover concrete is the major concerns in controlling the

1 durability of coastal RC building structures; and in practice its conformity control can be divided into
2
3 (1) the conformity control of cover depth, and (2) the conformity control of the material's diffusivity.
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6 For conformity control of cover depth in practice, non-destructive detection is performed for
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8 every lot; as stipulated in Chinese code GB 50204 (2015), bias from the design value of all the detected
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10 cover depth should be no larger than +10 mm and no less than -7 mm for beams and no larger than +8
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12 mm and no less than -5 mm for slabs.
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17 The conformity control of the material's diffusivity can be performed by the empirical method in
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19 existing codes, and the semi-empirical method in practices.
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21

22 23 **3.1 The empirical method in existing codes** 24

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26 Conformity control of material's diffusivity in existing codes is performed by examining whether
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28 the concrete strength, water-to-binder ratio, binder content, and etc., accord or not with the design
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30 (CEN, 2004; ACI, 2014; GB/T 50164, 2011). These items are related to the density of the concrete
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32 product and reflect the material's diffusivity to some extent. It is assumed that the material's diffusivity
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34 is conforming, or nonconforming, when these items are conforming or nonconforming; and it's
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36 referred as the empirical method in this paper.
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43 The water-to-binder ratio and the binder content are the main properties of the concrete mixture;
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45 they are considered to be conforming if the concrete mixture accords with the design scheme. Instead
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47 of applying the acceptance sampling method, engineers usually check the incoming documents of the
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49 materials to ensure their conformity.
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53 The acceptance sampling method is typically applied in the conformity control of concrete
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55 strength (ACI, 2014; GB/T 50107, 2010); e.g., as stipulated in Chinese code (GB/T 50107, 2010), for
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57 each lot with standard deviation σ is known, compressive strength tests for three consecutive samples
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are needed and the following criteria should be satisfied,

$$\overline{X}_N - 0.7\sigma \geq f_{cu,k}, \quad (3)$$

$$X_{\min} + 0.7\sigma \geq f_{cu,k}, \quad (4)$$

$$X_{\min} \geq \lambda_1 f_{cu,k}, \quad (5)$$

in which $f_{cu,k}$ is the characteristic value of concrete strength, detailed in (GB/T 50107, 2010), \overline{X}_N and X_{\min} are the mean value and the minimum value of the three measures, λ_1 is equal to 0.9 when $f_{cu,k}$ is higher than 20 MPa and equal to 0.85 otherwise. For each lot with standard deviation σ is unknown, compressive strength tests for at least 10 samples are needed and the following criteria should be satisfied,

$$\overline{X}_N - \lambda_2 S_X \geq f_{cu,k}, \quad (6)$$

$$X_{\min} \geq \lambda_3 f_{cu,k}, \quad (7)$$

in which S_X is the standard deviation of the measures, λ_2 and λ_3 are the acceptance constants whose values depends on the sample size, N , as listed in Table 1.

Table 1 Acceptance constants for the conformity control of concrete strength

N	10~14	15~19	≥ 20
λ_2	1.15	1.05	0.95
λ_3	0.90	0.85	0.85

Be noted that the parameters above can't quantify the material's diffusivity precisely. The rapid chloride migration (RCM) test conforming to NT Build 492 (Nordtest, 1999) can measure the non-steady-state migration coefficient, D_{nssm} , which was commonly used in practice to quantify the diffusivity. Existing studies measured the D_{nssm} with the various types of aggregates and binders, various water-to-binder ratios and various compressive strengths (Nilsson et al., 1996; Bogas & Gomes,

2015; Choi et al., 2017; Li et al., 2018); it's found that there is a poor correlation between D_{nssm} and these parameters, and the material's diffusivity should not be estimated on the basis of these parameters. For example, the D_{nssm} (in $10^{-12}m^2/s$) for the concrete with the age of 28 days and various water-to-binder ratio, w/b , in (Nilsson et al., 1996; fib, 2006; Bogas & Gomes, 2015; Choi et al., 2017) are shown in Fig. 1, which suggests high variations in estimating D_{nssm} based on water-to-binder ratio.

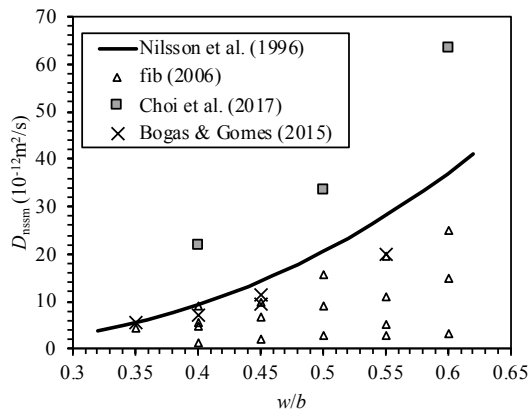


Fig. 1 Relation between D_{nssm} and w/b

Identifying the problem, the Chinese codes (GB/T 50476, 2019) suggests that, for important structures, additional demands on concrete chloride diffusivity should be designated before construction, e.g., critical value of non-steady state migration coefficient measured by rapid chloride migration (RCM) test, $D_{nssm,cr}$, and its value is recommended no larger than those in Table 2.

Table 2 Existing critical levels on diffusion coefficient in Chinese code (GB/T 50476, 2019)

Design service life	100 years		50 years	
	III-D	III-E	III-D	III-E
$D_{nssm,cr}$ ($10^{-12}m^2/s$)	≤ 7	≤ 4	≤ 10	≤ 6

The Chinese code GB/T 50082 (2009) further suggests the standard procedures of the RCM test for the purpose of measuring concrete diffusivity. It's recommended that at least 3 standard concrete specimens should be tested; among the measured values, those fall beyond 85%~115% of the medium

value are considered as exception values and abandoned, and the average of the other values is considered as the representative of the specimens; for example, to decide whether the chloride diffusivity of the concrete satisfy the aforementioned critical level when the sample size is 3, the following criteria are used,

(1) for $(D_{nssm,2} - D_{nssm,1}) \leq 0.15D_{nssm,2}$ and $(D_{nssm,3} - D_{nssm,2}) \leq 0.15D_{nssm,2}$,

$$\frac{D_{nssm,1} + D_{nssm,2} + D_{nssm,3}}{3} \leq D_{nssm,cr} \quad (8)$$

(2) for $(D_{nssm,2} - D_{nssm,1}) > 0.15D_{nssm,2}$ and $(D_{nssm,3} - D_{nssm,2}) \leq 0.15D_{nssm,2}$,

$$\frac{D_{nssm,2} + D_{nssm,3}}{2} \leq D_{nssm,cr} \quad (9)$$

(3) for $(D_{nssm,2} - D_{nssm,1}) \leq 0.15D_{nssm,2}$ and $(D_{nssm,3} - D_{nssm,2}) > 0.15D_{nssm,2}$,

$$\frac{D_{nssm,1} + D_{nssm,2}}{2} \leq D_{nssm,cr} \quad (10)$$

(4) for $(D_{nssm,2} - D_{nssm,1}) > 0.15D_{nssm,2}$ and $(D_{nssm,3} - D_{nssm,2}) > 0.15D_{nssm,2}$,

$$D_{nssm,2} \leq D_{nssm,cr} \quad (11)$$

in which $D_{nssm,1}$, $D_{nssm,2}$ and $D_{nssm,3}$ are the values of non-steady state migration coefficient of the three samples at the age of 28 days in ascending order.

3.2 The semi-empirical method

The semi-empirical conformity control for concrete diffusivity was adopted in HZM project. The project used D_{nssm} to quantify the concrete diffusivity, performed the RCM test to measure the samples' diffusivity, and adopted the acceptance criteria with the same mathematical form and the same acceptance constants as those used in the conformity control for concrete strength in Chinese codes (JTJ/T 272, 1999). It's suggested that, to accept the lot, Eq. (12) and (13) should be satisfied when the sample size N is 2 ~ 4,

$$\overline{D}_N + \sigma \leq D_{\text{nssm},k}, \quad (12)$$

$$D_{\text{max}} - 0.5\sigma \leq D_{\text{nssm},k}; \quad (13)$$

and when N is larger than 4, Eq. (14) and (15) should be satisfied,

$$\overline{D}_N + S_D \leq D_{\text{nssm},k}, \quad (14)$$

$$D_{\text{max}} - \lambda\sigma \leq D_{\text{nssm},k}; \quad (15)$$

in which \overline{D}_N , D_{max} and S_D are the mean value, maximum value and standard deviation of the measures respectively, σ is the standard deviation of the lot, $D_{\text{nssm},k}$ is the expected value of D_{nssm} in durability design, λ is a constant equaling 0.7 when N is 5 ~ 9, 0.9 when N is 10 ~ 19, and 1.0 when N is larger than 19.

In the HZM project, the value of $D_{\text{nssm},k}$ is determined according to the reliability-based durability design, which considers the “corrosion initiation” as the limit state, and adopts the following design function,

$$Rel_t \leq \Phi^{-1} \left\{ 1 - P \left[C(x, t_{\text{sl}}) \leq C_{\text{cr}} \right] \right\}, \quad (16)$$

in which Rel_t is the target reliability index, C_{cr} is the critical chloride concentration (mass percentage of binder, or “%binder”), $\Phi^{-1} \{ \}$ is the inversed cumulative function of standard normal distribution, $P[\]$ represents the probability of the inequality in the bracket, and $C(x, t_{\text{sl}})$ is the chloride concentration (%binder) at the concrete cover thickness x (mm) and design service life t_{sl} (s). According to Fick’s second law, $C(x, t_{\text{sl}})$ can be calculated as,

$$C(x, t_{\text{sl}}) = C_0 + (C_s - C_0) \left\{ 1 - \text{erf} \left[\frac{x}{2 \sqrt{D_{\text{a0}} \left(\frac{t_0}{t_{\text{tr}}} \right)^n t_{\text{sl}}}} \right] \right\}, \quad (17)$$

in which $\text{erf}[\]$ is the error function, C_s is the surface chloride concentration (% binder), C_0 is the original

chloride concentration (% binder), D_{a0} is a reference diffusion coefficient (m^2/s) determined at time t_0 (s), n is the factor concerning the aging effect of diffusion coefficient and t_{tr} is the truncated age (s) of the aging effect, valued as 30 years in HZM project. The parameters, C_s , D_{a0} , x , and n , are considered as random variables; and the mean value of D_{a0} at the age of 28 days is considered as the design value, $D_{a0,d}$. Given the target reliability index Rel_t being 1.3 and the design service life t_{sl} being 120 years, the value of $D_{a0,d}$ can be determined according to Eq. (16) and (17). For conformity control of concrete diffusivity, the relation between $D_{a0,d}$ and $D_{nssm,k}$ was established in (Zhang et al., 2013) as follows,

$$D_{a0,d} = EAD_{nssm,k}^B \quad (18)$$

Be noted that in code JTJ/T 272 (1999), the acceptance criteria correspond to the expected value of concrete strength in design with a 95% confidential level, while in Eq. (12)~(15) with same acceptance constants, the expected value $D_{nssm,k}$ corresponds to the mean value with a confidential level of about 50%. Therefore, there is no sufficient evidence that the actual reliability of the products after conformity control using this method will reach the target level of Rel_t being 1.3 and t_{sl} being 120 years, which will be discussed in the next section.

4. Case study: Reliability analysis of the schemes by existing methods

An accessory building of the Shantou Harbor, which is located in the coast of South China Sea, is taken as the example in this section. The target reliability index of 1.5 and the design service life of 50 years were adopted for its reliability-based durability design. Deterministic value and statistic properties of durability design parameters are listed in Table 3.

Table 3 Deterministic values and statistic properties of durability parameters.

Parameters	Distribution	Statistic properties
C_s (% binder)	Lognormal	mean = 4.5, std. = 0.9

c (mm)	Uniform	mean = 61.5, std. = 3.8
D_{a0} ($10^{-12}\text{m}^2/\text{s}$)	Lognormal	mean = 2.3, coefficient of variation = 0.3
n	---	0.37
C_{cr} (% binder)	---	1.0

Conformity control schemes established by the above two methods are given as follows, and their performances are examined in this section:

(1) Scheme by the empirical method

Consider the sample size to be 3, and Eq.(8) ~ Eq.(11) are adopted as the conformity control criteria. As stipulated by GB/T 50476 (2019), $D_{nssm,cr}$ in Eq.(8) ~ Eq.(11) should be no larger than $6.0 \times 10^{-12}\text{m}^2/\text{s}$. In this section, it is considered that $D_{nssm,cr}$ equals $6.0 \times 10^{-12}\text{m}^2/\text{s}$.

(2) Scheme by the semi-empirical method

Consider the sample size to be 3, and Eq. (12) and Eq.(13) should be satisfied to accept the lot; in which $D_{nssm,cr}$ in Eq.(12) and Eq.(13) should be equal to the design value $D_{nssm,d}$, which is $7.5 \times 10^{-12}\text{m}^2/\text{s}$.

4.1 Evaluation of reliability corresponding to the AQL and the LQL

Be noted that the AQL and the LQL of the above two criteria are not clear; and they are firstly examined in this section. As defined in Eq. (1) and (2), the probability of erroneous rejection when the lot's quality is AQL is the producer's risk α , and should not be larger than the limit $[\alpha]$; and the probability of erroneous acceptance when the lot's quality is LQL is the consumer's risk β , and should not be larger than the limit $[\beta]$. Consider the limit $[\alpha]$ and $[\beta]$ to be 5% and 10% respectively as the code (ISO, 2006) suggested, the actual level of AQL and LQL of the above criteria can be found through simulation:

Step 1: Suppose that the D_{nssm} of products in each lot follows lognormal distribution with the

mean of μ_D and standard deviation of σ_D .

Step 2: Simulate the distribution of D_{nssm} with $\mu_D = \mu_{D,i} \in [\mu_{D,l}, \mu_{D,u}]$ and $\sigma_D = \sigma_{D,i} \in [\sigma_{D,l}, \sigma_{D,u}]$.

Step 3: Randomly select the samples from the distribution and examine if the above criteria are satisfied.

Step 4: Repeat Step 3, count the number of times that the criteria are satisfied (which means the simulated lot is accepted), and calculate the proportion of acceptance and the proportion of rejection.

Step 5: Check if the proportions equal to the limit $[\alpha]$ (which is the AQL) or $[\beta]$ (which is the LQL); and

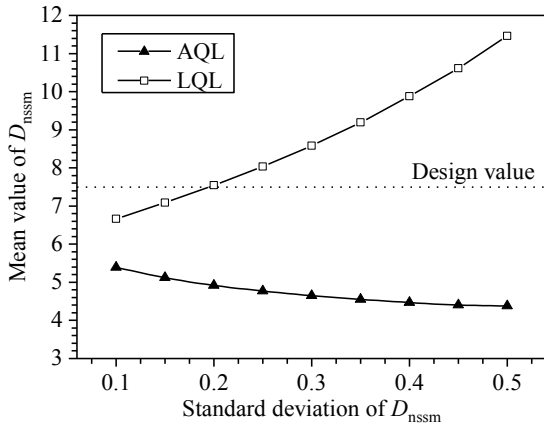
(1) if not, based on the fact that α and β vary monotonically as the values of μ_D and σ_D change,

narrow the ranges $[\mu_{D,l}, \mu_{D,u}]$ and $[\sigma_{D,l}, \sigma_{D,u}]$ with the value $\mu_{D,i}$ and $\sigma_{D,i}$, and then repeat Step

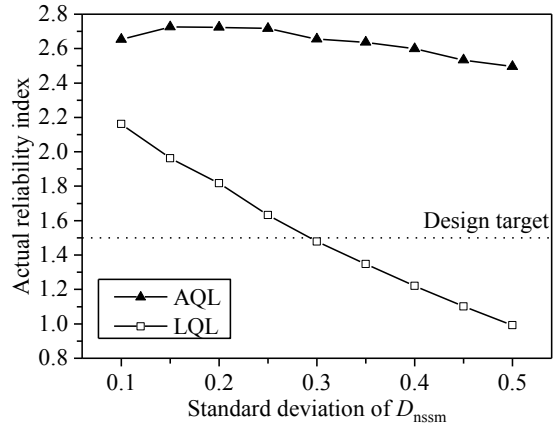
2~5;

(2) if so, obtain the values of μ_D and σ_D , which correspond to the AQL or the LQL.

For the scheme by the empirical method, the mean values μ_D and standard deviations σ_D for the products with the quality level of AQL and LQL respectively can be calculated through the above steps, and there are shown in Fig. 2(a); the actual value of μ_D and σ_D of the products will correspond to a dot in the figure, and as mentioned in Section 2, the probability of accepting those above the “LQL” curve is the consumer’s risk and should be less than $[\beta]$, and the probability of accepting those below the “AQL” curve is the producer’s risk and should be less than $[\alpha]$. According to Table 3 and Eq. (16), the corresponding reliability indices of AQL and LQL can also be calculated, as shown in Fig. 2(b). Similar analysis can be made for the scheme by the semi-empirical method, as shown in Fig. 3.

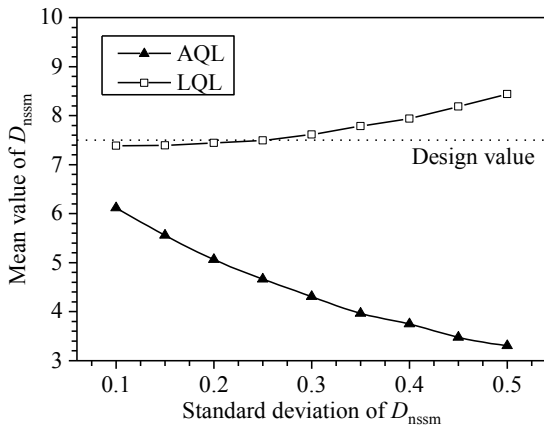


(a) The “ $\mu_D - \sigma_D$ ” relation

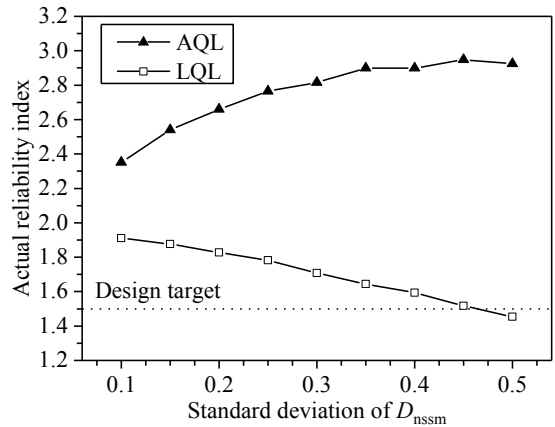


(b) Reliability level

Fig. 2 The “ $\mu_D - \sigma_D$ ” relation and reliability level corresponding to the AQL and LQL for the scheme by the empirical method



(a) The “ $\mu_D - \sigma_D$ ” relation



(b) Reliability level

Fig. 3 The “ $\mu_D - \sigma_D$ ” relation and reliability level corresponding to the AQL and LQL for the scheme by the semi-empirical method

For the scheme by the empirical method, as shown in Fig. 2, the AQL corresponds to the reliability index of around 2.6, which means that to let the lot be accepted with the probability of more than 95%, the reliability index of the lot should be at least 2.6, instead of the target reliability index of 1.5; at the meantime, the LQL corresponds to the reliability index of 1.0~2.2, which means that there is unneglectable probability that the lot with the reliability index of less than 1.5 will be accepted.

1 Comparing to the scheme by the empirical method, the scheme by the semi-method is loose when
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3 σ_D is no more than 0.2, and much stricter when σ_D is larger than 0.3. For the case with σ_D is 0.1, the
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5 AQL and LQL correspond to the reliability index of about 2.4 and 1.9 respectively, both higher than
6
7 1.5. For the case with σ_D is 0.5, the LQL corresponds to a reliability index of about 1.5, however, the
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9 AQL corresponds to a reliability index of up to 2.8; which means that there is significant probability
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11 that the criteria will reject those products with reliability index between 1.5 and 2.8. It's unnecessary
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13 for both the cases since the design target Rel_t is 1.5.
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20 **4.2 Assessment for the probability of acceptance**

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23 The probability of erroneous rejection for both the schemes can be calculated and shown in Fig.
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25 4 and Fig. 5. These figures show the probability of acceptance for the different actual reliability index
26
27 of the products with σ_D is 0.1, 0.15, ..., and 0.5, respectively. The ideal criteria for acceptance sampling
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29 will accept those with an actual reliability index higher than 1.5 and reject those with an actual
30
31 reliability index lower than 1.5, which are shown as the bold dash curves in both Fig. 4 and Fig. 5.
32
33 Because the judgement for the lot's quality is made by examining the quality of a few samples, it's
34
35 unlikely to achieve the ideal in acceptance sampling; those criteria with curves that is closer to the
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37 ideal will better represent the demands in design. As shown in Fig. 4 and Fig. 5, with any value of σ_D ,
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39 the gaps between the curves and the ideal are significant, in both the schemes. Be noted that in the
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41 scheme by the empirical method, the $D_{nssm,cr}$ values as the maximum limit as shown in Table 2; for
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43 $D_{nssm,cr}$ adopting the other values, the criteria will be stricter, and will result to a larger gap. These
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45 results are specified for the case in this section and may differ in other cases; and it's worth to mention
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47 that since the target reliability is not explicitly considered in the empirical method and in the semi-
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49 empirical method, the designer will not know the actual probabilities of acceptance (e.g., those in Fig.
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4 and Fig. 5) when designing the scheme by either method, unless such analysis in this section is done.

In this case, it will result to the unnecessary strict demands on concrete diffusivity and will hamper the producer's benefit, and it is also inconvenient for designing or modifying the conformity control criteria in practice.

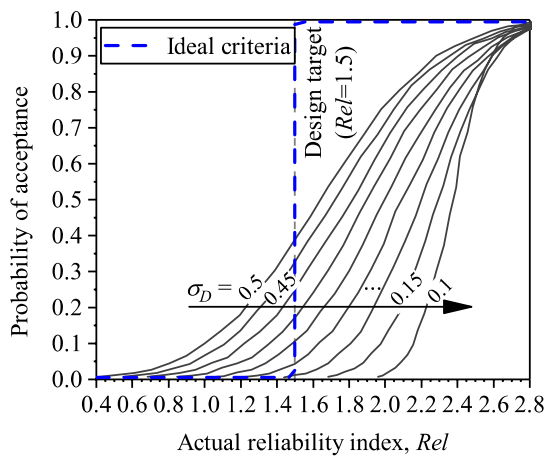


Fig. 4 The probability of acceptance for different actual reliability indices with various σ_D for the scheme by the empirical method

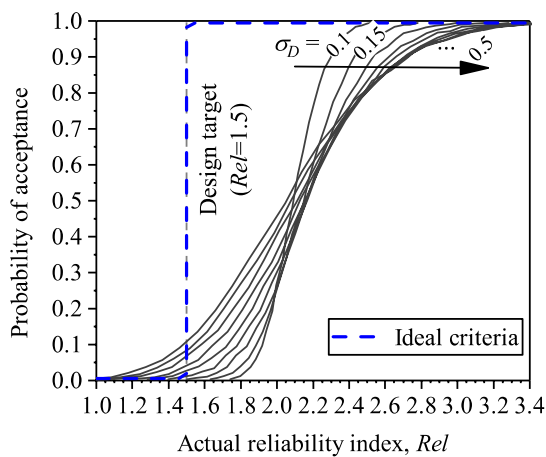


Fig. 5 The probability of acceptance for different actual reliability indices with various σ_D for the scheme by the semi-empirical method

As concluded from the above analysis, due to the unclear AQL and LQL in establishing the criteria, both the existing method may lead to the over-strict criteria that actually correspond to some unnecessarily high demands on AQL and LQL in some cases.

5. Reliability-based conformity control method

The aforementioned problem can be fixed by using the reliability-based conformity control method. Recent related study suggested the conformity control scheme of diffusivity with a reliability-based LQL for HZM project, in which the LQL is clear and related to the target reliability index in design. In this section, the reliability-based conformity control method is developed from this basis, with the standard amendment for the relation between D_{nssm} and D_{a0} .

5.1 Scheme with reliability-based LQL for HZM project

Based on the data provided by (Zhang et al., 2013), Ye et al. (2021) suggested the relation between D_{a0} and D_{nssm} for the conformity control in HZM project through regression,

$$D_{\text{a0}} = \lambda_1 \cdot D_{\text{nssm}}^{\lambda_2} \cdot \varepsilon, \quad (19)$$

in which λ_1 is 0.5, λ_2 is 1.0, and ε is the error term, log-normally distributed with a mean value of 1.0 and coefficient of variation of 0.25, representing the model uncertainty. Under the assumption of D_{nssm} follows the lognormal distribution, the conformity control criteria were suggested to be about $X = \ln D_{\text{nssm}}$ instead of D_{nssm} for simplicity (Ye et al., 2021). Therefore, to ensure the target reliability level of the products after conformity control being reached, the following function should be satisfied,

$$Rel_t \leq Rel(t_{\text{sl}}) = \Phi^{-1} \left\{ 1 - P \left[C(c, t_{\text{sl}}) \leq C_{\text{cr}} \right] \right\}$$
$$\text{where } C(c, t_{\text{sl}}) = C_s \left[1 - \text{erf} \left(\frac{c}{2\sqrt{k_1 \varepsilon \exp(k_2 X) t_0^n t_{\text{sl}}^{n-1}}} \right) \right], \quad (20)$$

where Rel_t is the target reliability index, $Rel(t_{\text{sl}})$ is the reliability index with respect to the design service life t_{sl} , c is the concrete cover thickness (mm), t_{sl} is the design service life (s), $\Phi^{-1}\{\}$ is the inversed cumulative function of standard normal distribution, and $P[\]$ represents the probability of the event in the bracket.

Given a target reliability index Rel_t and the pre-determined value for other parameters, the margin of Eq. (20) can be linearly approximated as follows (Ye et al., 2021),

$$\mu_X = X_k + z_k \sigma_X, \quad (21)$$

in which z_k and X_k are the parameters obtained by linear regression analysis. Since the fraction of defectives is defined as the probability of X is smaller than X_k , by specifying the LQL as the design target, its corresponding fraction of defectives, p_L , is equal to,

$$p_L = p_k = P(X \leq X_k) = \Phi(-z_k). \quad (22)$$

The fraction of defectives at AQL is assumed to be 0.05 in (Ye et al., 2021). Then, the acceptance criteria with undetermined constants can be provided as follows,

(1) for continuous production with the standard deviation of diffusivity σ_X is known,

$$m_X + k_1 \sigma_X \geq X_k, \quad (23)$$

$$X_{\max} \leq X_k + C, \quad (24)$$

(2) for the cases with σ_X is unknown,

$$m_X + k_2 S_X \geq X_k, \quad (25)$$

$$X_{\max} \leq X_k + C, \quad (26)$$

in which m_X is the mean value of the samples; S_X is the sample standard deviation; X_{\max} is the maximum value of the samples; X_k is the characteristic diffusivity; k_1 , k_2 and C are the acceptance constants, and their values depend on the sample size N and were determined based on the statistical acceptance sampling theory introduced in Section 2, as given in (Ye et al., 2021); and the essential formula are listed as follows,

$$k_1 = -\frac{\Phi^{-1}([\beta])}{\sqrt{n}} - \Phi^{-1}(p_L), \quad (27)$$

$$k_2 = -\frac{F_t^{-1}\left(1 - [\beta] \mid -\sqrt{n}\Phi^{-1}(p_L), n-1\right)}{\sqrt{n}}, \quad (28)$$

$$C = A\sigma_X, \quad (29)$$

$$A = \Phi^{-1}\left(\sqrt[3]{g_{A0}}\right) + \Phi^{-1}(p_A), \quad (30)$$

in which g_{A0} is equal to 0.99. The process of deciding the values of k_1 , k_2 and A can be summarized by the following flowchart in Fig. 6 and also detailed in (Ye et al., 2021).

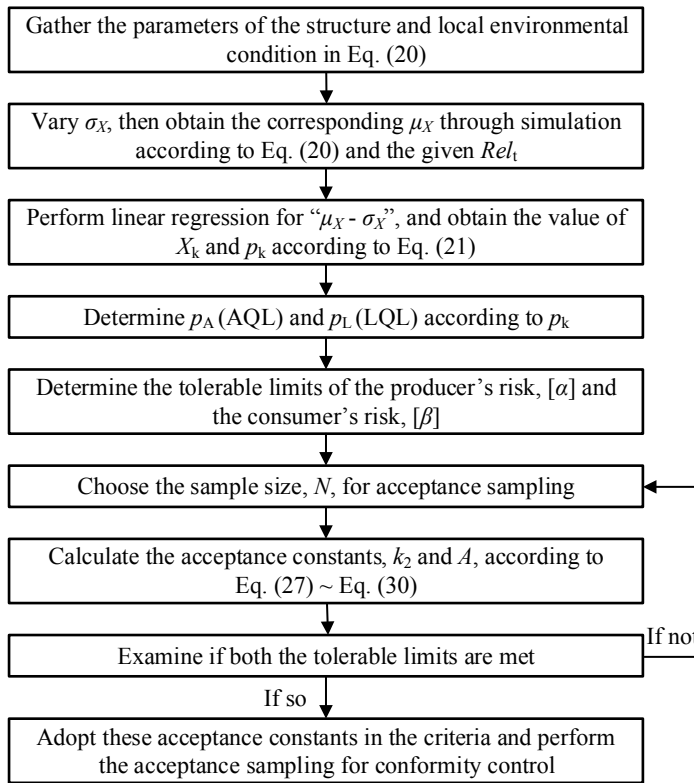


Fig. 6 Flowchart of the reliability-based conformity control for HZM project.

5.2 Standard amendment for the relations between D_{nssm} and D_{a0}

Be noted that the regression results of Eq. (19) in Section 5.1 was based on the in-situ data (as shown in Fig. 7) in Zhanjiang Harbor. Because the location of the HZM project is close to Zhanjiang Harbor, the relation is specified for the climate condition of HZM project's location. For other engineering project, due to the differences in the local temperature and humidity, the values of parameters λ_1 , λ_2 as well as the statistic properties of ε may be different and should be re-calibrated

1 based on in-situ data.

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3 However, costs of the re-calibration may be huge, and the amount of available data may be limited
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5 for common RC building structures. It is currently unrealistic to re-calibrate the parameters for every
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7 coastal/marine project; and standardizing the relation between D_{nssm} and D_{a0} may be workable to let
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9 the knowledge in HZM project be utilizable in other projects. Studies on climate effects on diffusion
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11 coefficients are used towards this aim. Saetta et al. (1993) suggested equations to consider the climate
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13 effects on diffusion coefficient as follows,
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$$18 D_c = D_{c,ref} f_1 f_2 f_3, \quad (31)$$

$$19 f_1 = \exp \left[\frac{U_c}{R} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right], \quad (32)$$

$$20 f_2 = \left(\frac{t_{ref}}{t} \right)^n, \quad (33)$$

$$21 f_3 = \left[1 + \frac{(1-h)^4}{(1-h_c)^4} \right]^{-1}, \quad (34)$$

22 where U_c is the activation energy of the chloride diffusion process in kJ/mol, R is the gas constant (R
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24 = 8.314 J/(mol K)), T_{ref} is the reference temperature at which the reference diffusion coefficient, $D_{c,ref}$,
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26 has been evaluated ($T_{ref}=276$ K), T is the actual absolute temperature inside the concrete in K, t_{ref} is
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28 the time of exposure at which $D_{c,ref}$ has been evaluated ($t_{ref} = 28$ days), t is the actual time of exposure
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30 in days, n is the age reduction factor, h is the actual pore relative humidity and h_c is the humidity at
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32 which D_c drops halfway between its maximum and minimum values, which is constant for different
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34 concretes or cement pastes and equals to 0.75 as (Bazant & Najjar, 1972) suggested.
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53 This model is used in (*fib*, 2006; Bastidas-Arteaga et al., 2020; Truong et al., 2022) for considering
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55 the climate effect of apparent diffusion coefficient, which will also be adopted in this paper. Bastidas-
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Artega (2018) used a sinusoidal formulation to model the periodical changes of environmental temperature and humidity, and simulate the chloride profiles inside the concrete. Although the apparent diffusion coefficient can be calculated from these profiles, the modelling and simulation process is complicated and may not be suitable for engineering practice. In this paper, we use the yearly-average temperature to consider the temperature effect on D_{a0} for simplicity, and adopt the standard amendment formulation for D_{a0} with correction factors f_1 and f_3 as follows,

$$D_{a0,am} = \frac{D_{a0}}{f_1 f_3}, \quad (35)$$

in which, D_{a0} is the apparent diffusion coefficient under the condition of temperature T and relative humidity h , and $D_{a0,am}$ is the standardized apparent diffusion coefficient, which is under the saturated condition with temperature T_{ref} .

The products' D_{nssm} are commonly measured under the same temperature and humidity as stipulated by NT Build 492 method, and therefore, the standardization amendment for D_{nssm} is unnecessary. But for those D_{nssm} measured under other conditions, additional standardizations are needed.

The yearly-average temperatures and relative humidity of Harbor Zhanjiang can be obtained from the China Meteorological Data Service Center, which is 23.6°C and 81.3%, respectively. Therefore, the correction factors f_1 and f_3 are 1.04 and 0.76, respectively according to Eq. (32) and (34). According to Eq. (35), the data are standardized as shown in Fig. 7; and the regression is made according to Eq. (19), as shown in Fig. 7, and it suggests that $\lambda_1=0.6$, $\lambda_2=1.0$, and ε follows a lognormal distribution with its logarithmic mean value is 0 and its logarithmic standard deviation is 0.3.

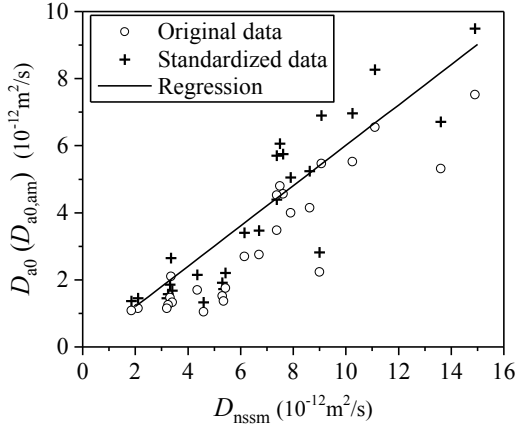


Fig. 7 Regression between the standardized $D_{a0,am}$ and D_{nssm} .

5.3 General method of the reliability-based conformity control

Based on the relation between the standardized $D_{a0,am}$ and D_{nssm} , the following function is established to substitute Eq. (20) to ensure the target reliability level of the products after conformity control,

$$Rel_t \leq Rel(t_{sl}) = \Phi^{-1} \left\{ 1 - P \left[C(c, t_{sl}) \leq C_{cr} \right] \right\}$$

$$\text{where } C(c, t_{sl}) = C_s \left[1 - \operatorname{erf} \left(\frac{c}{2\sqrt{k_1 \varepsilon \exp(k_2 X) f_1 f_3 t_0^n t_{sl}^{n-1}}} \right) \right]. \quad (36)$$

The values of correction factors f_1 and f_3 can be calculated by Eq. (32) and (34) according to the local temperature and humidity.

Based on the suggested process in (Ye et al., 2021) as introduced in Fig. 6, the general method of the reliability-based conformity control can be established. As shown in Fig. 8, an additional procedure of determining the values of correction factors f_1 and f_3 is needed before processing the other procedures.

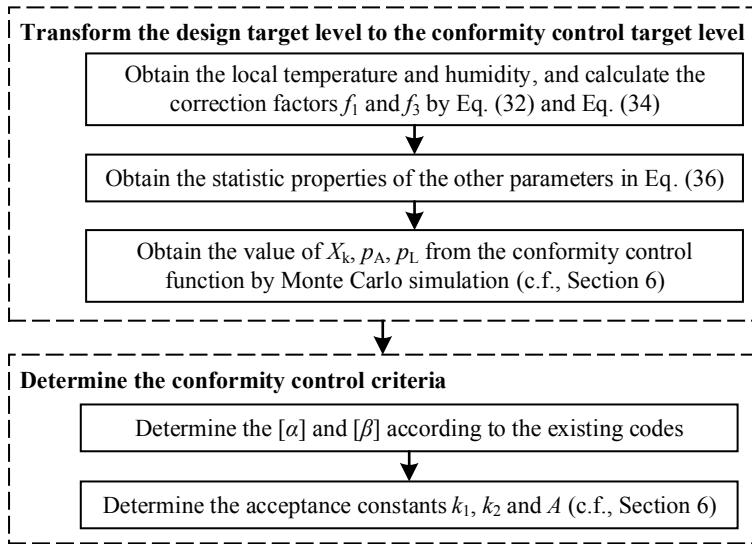


Fig. 8 Schematic diagram for the steps of the proposed method

6. Case study: Conformity control by the proposed method

The same structure in Section 4 is used herein to show how to perform the conformity control by the proposed reliability-based method. The local temperature and relative humidity of Shantou City is 22.6°C and 75.2%, respectively. Therefore, according to Eq. (32) and Eq. (34), the correction factor $f_1 f_3 = 0.50$. Considering the standardization and the regression results in Fig. 7, the corresponding non-steady-state migration coefficient design value $D_{nssm,d}$ is 7.5 (in $10^{-12} \text{m}^2/\text{s}$).

The reliability-based scheme is established according to the target reliability, which is 1.5 for the design service life of 50 years in this case. However, it's hard to design the acceptance sampling criteria that will accept all the lot with reliability indices high than 1.5 and reject those with reliability indices lower than 1.5, due to the limits of sample size. As introduced in Section 2, the AQL and LQL should be firstly designated and consented by both the producers and consumers; those with quality higher than AQL should be mostly accepted and those lower than LQL should be mostly rejected. Apparently, both AQL and LQL should be around the design target; when the gap between AQL and LQL get narrower, the number of samples, N , should be larger to gain adequate information, and the outputs of

conformity control will approach to the design target.

According to the flowchart in Fig. 3, the “ $\mu_X - \sigma_X$ ” relation should be firstly obtained to determine the AQL and LQL. By varying the σ_X from 0.15 to 0.45 and using the statistic properties of other parameters in Table 3, we can obtain the corresponding μ_X according to Eq. (36) through Monte Carlo simulations for different reliability levels, as shown in Fig. 9.

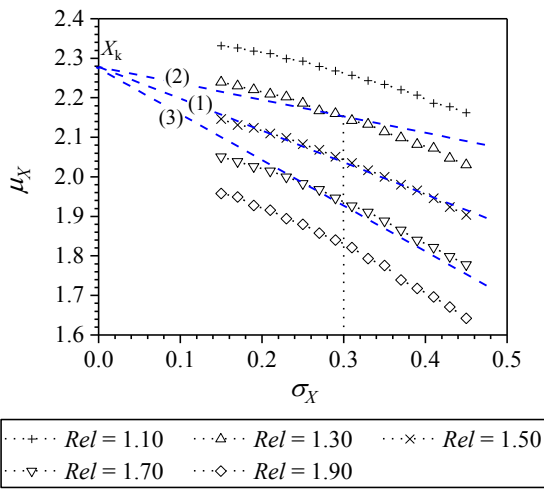


Fig. 9 “ $\mu_X - \sigma_X$ ” relation for the project

Because the target reliability index of the project is 1.5, shown as the line (1) in Fig. 9, the intercept of the linear regression for $Rel = 1.5$, X_k , is used as the characteristic value of diffusivity, which is 2.278; and the slope is -0.805. As studied in (Ye et al., 2021), the cumulative probability of standard normal distribution at the value of the slope, is defined as the fraction of defectives, denoted as p_k and equal to $\Phi(-0.805) = 0.21$ for this project. In this case, the design target of $Rel = 1.5$ is equivalent to the characteristic value $X_k = 2.278$ and fraction of defectives $p_k = 0.21$ for concrete diffusivity; and the AQL and LQL can be determined accordingly. For instance, if the producers and consumers agree that the LQL is the line (2) in Fig. 9, which is below the target level with a reliability index of about 1.3, and the AQL is the line (3) in Fig. 9, which is above the target level with a reliability index of about

1.7, then, it can be determined that p_L is 0.34 and p_A is 0.13. According to Eq. (27) and Eq. (30), the acceptance constants X_k , k_1 and A in Eq. (23), Eq. (24) and Eq. (29) are 2.278, 0.779 and 2.007 for sample size $N=12$, respectively, based on the calculation procedures demonstrated in detail in (Ye et al., 2021).

It can be seen from Fig. 9 that either the line (1) or the line (3) doesn't fully coincide with the corresponding curve; and when $\sigma_X = 0.1$ or $\sigma_X = 0.5$, the bias is apparent. To evaluate the actual level of the AQL and the LQL corresponding the criteria, similar analysis as those in Section 4 is performed, and the results are shown in Fig. 10. It can be founded that both the AQL and the LQL are closer to the design target of $Rel = 1.5$ than those in Fig. 2 and Fig. 3.

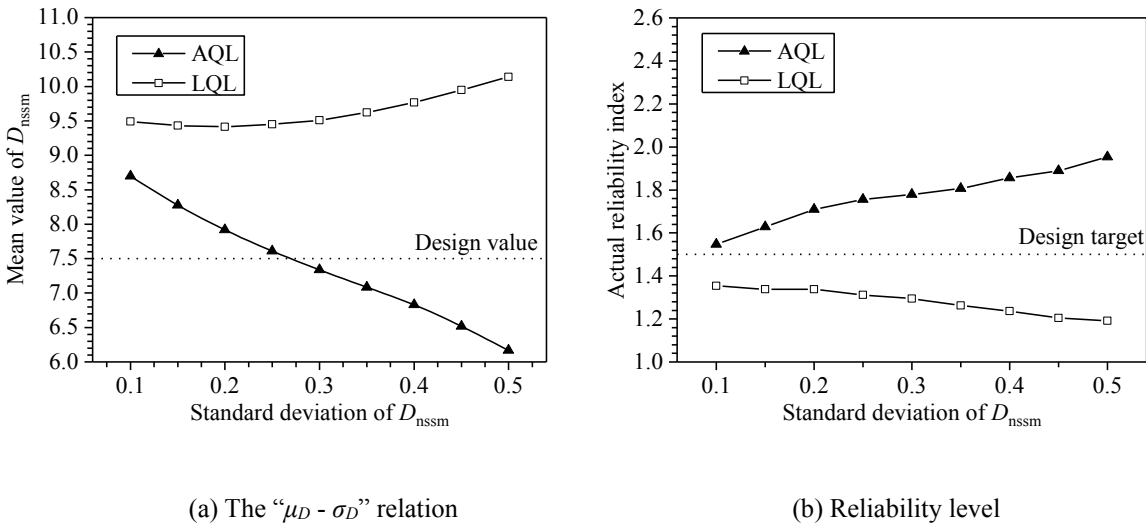


Fig. 10 The “ $\mu_D - \sigma_D$ ” relation and reliability level corresponding to the AQL and LQL for the scheme by the reliability-based method

The probability of acceptance for different actual reliability indices with various σ_D can also be calculated. As shown in Fig. 11, the slopes of all the curves reach the maximum when the actual reliability index Rel is about 1.5, the target level in reliability-based durability design, which is consistent with the ideal curve.

As mentioned above, the AQL and the LQL herein are assigned as the actual quality levels that correspond to $Rel = 1.7$ and 1.3 respectively. In practice, the AQL and LQL are assigned under the consideration of both the producers' and the consumers' benefits. Given the design target of $Rel = 1.5$, the producers and the consumers may adopt other combinations of the AQL and the LQL; in those cases, the corresponding scheme can be established according to the values of p_A and p_L , by the same method.

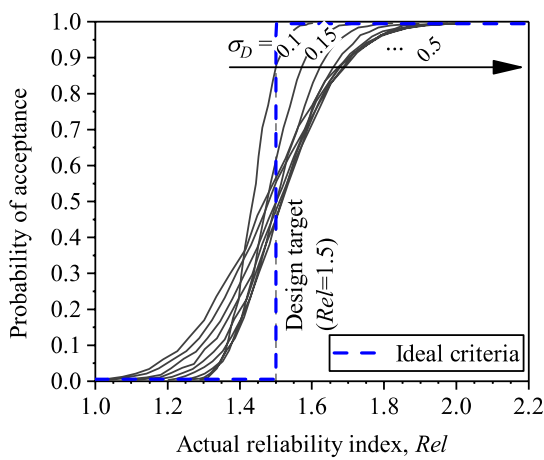


Fig. 11 The probability of acceptance for different actual reliability indices with various σ_D for the scheme by the reliability-based method

To assess the performance of the reliability-based criteria, we simulate the conformity control for 1000 production lots of concrete with the variation in quality of diffusivity. In the original 1000 lots, the non-steady-state migration coefficient D_{nssm} data are assumed to follow a series of lognormal distribution; their coefficients of variation are constant and equal to 0.3, and their mean values follow a uniform distribution with the mean value of 7.5 (in $10^{-12}m^2/s$) and the standard deviation of 2.3 (in $10^{-6}mm^2/s$). Statistic properties of the other parameters in Table 3 are adopted. The reliability level in terms of concrete's durability, Rel , can be calculated by Eq. (36); they are between 0.7 and 3.5 , and the histogram is shown in Fig. 12. Conformity control is simulated, adopting the aforementioned criteria,

the acceptance constants and sample sizes. The histogram of the *Rel* of those lots accepted by the criteria are shown in Fig. 12.

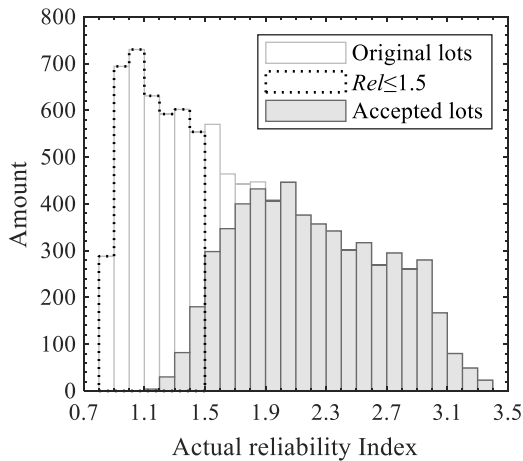


Fig. 12 Statistic counting of the lots accepted by the schemes respectively.

As shown in Fig. 12, the majority of the lots with the *Rel* lower than 1.5 are rejected, and the majority of those higher than 1.5 are accepted. It can be computed that the percentage of the lots with the *Rel* lower than 1.5 is decreased from 40.9% to 5.1%; the percentage of erroneously rejecting the lots with the *Rel* higher than 1.5 is 10.6%, and the percentage of erroneously accepting the lots with the *Rel* lower than 1.5 is 5.1%. These results are consistent with the reliability-based durability design and the pre-given limits for the risks in conformity control; they suggest the good performance of the reliability-based conformity control scheme, which will protect both the consumer's benefits and producer's benefits.

7. Conclusion

This paper proposed a general conformity control method for concrete chloride diffusivity of coastal RC building construction projects, based on the existing research in the conformity control for concrete diffusivity in HZM project. The proposed method considers the effects of local environmental condition and therefore can be used in other RC projects in coastal/marine environment. The method

1 was compared to the existing empirical method in Chinese codes and the semi-empirical method in
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3 practice, with respect to their “implicit” AQL and LQL, their probabilities of acceptance for various
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5 actual reliability levels, and their improvements on products reliability. The main conclusions are listed
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7 as follows:
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13 semi-empirical method are unclear; it may result in the unnecessarily high demand on the
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15 products’ quality, which is significantly higher than the expected in durability design.
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19 2 Effect of temperature and humidity on concrete chloride diffusivity should be considered in the
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21 conformity control scheme. Through standardization, the relation between D_{nssm} and D_{a0}
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23 established in the HZM project can be used in building up the conformity control scheme for
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25 concrete chloride diffusivity in other projects.
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29 3 Based on the standardized relation, the proposed method of establishing the reliability-based
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31 criteria for conformity control of concrete chloride diffusivity could be used in other
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33 engineering practices.
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37 4 Because of the reliability-based determination of the AQL and the LQL, the curve of the
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39 probability of acceptance for the proposed method is closer to the ideal than those for the
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41 empirical method and the semi-empirical method.
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45 5 In the proposed method, the AQL and LQL are linked to the target reliability level in durability
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47 of coastal RC building structures. The proposed method can accept most of the lots whose
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49 qualities are higher than AQL and reject most of those lower than LQL, to protect both the
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51 consumer’s benefits and producer’s benefits.
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