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Probabilistic method and its application for evaluating carbonation life of newly-built concrete structures

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Abstract: In order to evaluate the carbonation life of newly-built concrete structures, two kinds of nondestructive methods are adopted to test the thickness of the concrete cover and the ultrasonic velocity of two newly-built tunnel structures. Simultaneously a probabilistic method is proposed based on the relationship between the accelerated carbonation rate and the ultrasonic velocity. This proposed method is applied to evaluate the carbonation related lives of two newly-built tunnels and the results indicate that even under nearly the same environment and CO_2 combining conditions, there exits a big difference in the probabilistic carbonation lives between the two tunnels; i. e., the probabilistic lives of Tunnel A and Tunnel B are 94. 0% and 82. 3% and the corresponding maximum discrepancies are 11. 6% and 27. 0%, respectively. Thus, it can be concluded that the scattered quality of the concrete cover is attributed to the differences in construction technique, which eventually leads to the diversity in the evaluated probabilistic carbonation lives of the two tunnels.

Key words: probabilistic carbonation life; newly-built structure; concrete-cover quality

The prediction models for anti-carbonation durability has been intensively studied in the past 30 years by adopting different methods, such as accelerated carbonation testing, long-time exposure testing and some investigations on field buildings. Papadakis et al. [1] presented a mathematical model to predict the carbonation depth with time. Saetta et al. [2-3] developed a mathematical-numerical method to predict the corrosion initiation time of reinforced concrete structures due to carbonation. Ballim et al. [4] analyzed the steel corrosion of concrete structures in the lab by testing the conductance of concrete. Niu et al. [5] put forward a model to predict the carbonation depth of concrete elements according to field investigation results. Zhao et al. [6] provided a probabilistic model for evaluating the carbonation life of concrete structures. Ding et al. [7] made an investigation on practical buildings as research bases and advanced a stochastic model for the prediction of the carbonation depth of concrete structures. A time-dependent reliability analyzing method for concrete structures in normal services was presented in Ref. [8].

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It can be seen from the above mentioned accelerating experiments and field investigations that the prediction model for carbonation related service life seemed to aim only at old concrete buildings. It is well known that the newly-built concrete structures have a short service time and show no obvious signs of carbonation, and therefore it is meaningless to drill concrete cores, which can also destroy the beauty of new structures. Thus it is necessary to develop a much more scientific and practical method to evaluate the anti-carbonation life of newly-built concrete structures. This paper proposes a probabilistic method for evaluating the anti-carbonation service life of newly-built structures based on nondestructive testing and also reports its application in two newly-built underground tunnels.

1 Probabilistic Method for Evaluating Anti-Carbonation Durability of New Concrete Structures

To some extent, the environmental variability as well as the randomness of the inherent quality of concrete inevitably leads to high uncertainty regarding the anti-carbonation durability of concrete structures, which can be explained by the stochastic characteristics of the concrete cover and the carbonation rate. The quality of the concrete cover mainly includes its thickness and compactness, which can be examined by non-destructive testing methods in this study. Supposing that the randomness of the cover quality conforms to normal distribution, a probabilistic method for evaluating the anti-carbonation life of newly-built structures is proposed. In terms of this method, the anti-carbonation life of a new structure can be calculated and Fig. 1 illustrates the specific calculation procedures.

It can be seen from Fig. 1 that the first calculation step is

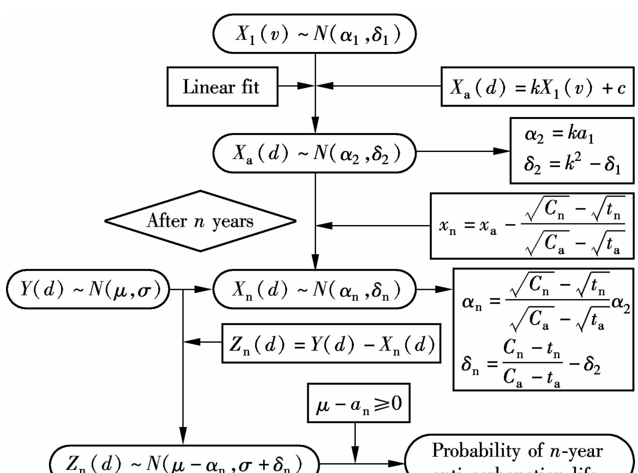

Fig. 1 Process of evaluating carbonation life of concrete structures

to measure the ultrasonic velocity of the concrete denoted as $X_1(v)$ supposing that it conforms to normal distribution $N(\alpha_1, \delta_1)$. Next, according to the relationship between $X_1(v)$ and accelerating carbonation depth $X_a(d)$[9], $X_a(d)$ can be deduced and obeys the normal distribution $N(\alpha_2, \delta_2)$. And then, after n-years of service, the natural carbonation depth named $X_n(d)$ may be calculated and it also conforms to the normal distribution $N(\alpha_n, \delta_n)$ in terms of the connection between natural carbonation depth and accelerated carbonation depth. In addition, supposing that the measured cover thickness $Y(d)$ obeys $N(\mu, \sigma)$, the residual cover thickness ($Z_n(d) = Y(d) - X_n(d)$) conforms to $N(\mu - a_n, \sigma + \delta_n)$ as well. Finally, the corresponding probability can be calculated as long as the average $Z_n(d)$ is greater than zero ($\mu - a_n > 0$) and the probability is just the anti-carbonation life after n years.

From the above calculating process, it can be observed that there are three key factors determining the evaluation results. First, the cover thickness conforms to normal distribution, and the second is the relationship between the ultrasonic velocity and the accelerated carbonation depth. The third factor is the interrelationship of natural and accelerated carbonation depths.

As for the cover thickness, the measured results show that it certainly obeys the normal distribution. The relationship between the ultrasonic velocity and the carbonation depths is given as[9]

$$X^{90} = X^{120} = -3.10V_u + 30.5 \qquad (1)$$

where X^{90} and X^{120} are the 28-day accelerated carbonation depths cured for 90 and 120 d, respectively; and V_u is the ultrasonic velocity.

The interrelationship of natural and accelerated carbonation depths can be validated in terms of the classical prediction model for carbonation depth [10],

$$x_n \approx x_a \frac{\sqrt{C_n t_n}}{\sqrt{C_a t_a}} \qquad (2)$$

where x_n is the natural carbonation depth; x_a is the accelerated carbonation depth; C_n is the natural concentration of CO_2; C_a is the accelerated concentration of CO_2; t_n is the time of natural carbonation; t_a is the time for accelerated carbonation.

2 Evaluation of Carbonation Durability of Newly-Built Under-Lake Tunnels

There are two newly-built under-lake tunnels named A and B, both of which are located nearby cities. For each tunnel the designed compressive strength and anti-carbonation life are C30 and 100 years, respectively. The average temperature per year is at 15 to 28 ℃ and the average relative humidity per year is 50% to 70%.

Tab. 1 and Tab. 2 show the concrete mixture and corresponding chemical compositions of cementicious materials (mass fraction) used for both the tunnels.

Tab. 1 Experimental proportions kg/m³

Constituents	Tunnel A	Tunnel B
Cement	250	280
Fly-ash	80	85
Slag	40	
Water	148	150
Gravel	1 080	1 060
Sand	782	792
SP	3. 08	3. 00

Tab. 2 Chemical composition of cementicious materials %

Oxides	Tunnel A			Tunnel B	
	Cement	Fly ash	Slag	Cement	Fly ash
CaO	61. 10	5. 53	35. 70	61. 00	5. 80
SiO_2	21. 30	50. 30	32. 30	21. 80	49. 00
Al_2O_3	6. 03	33. 80	17. 50	6. 00	32. 80
SO_3	3. 83	0. 51	2. 13	4. 00	0. 51
Fe_2O_3	3. 29	5. 19	0. 26	2. 89	5. 40
MgO	2. 54	0. 71	10. 20	2. 54	0. 71

2.1 Probabilistic evaluation results of two tunnels

Adopting the probabilistic evaluation method shown in Fig. 1, the anti-carbonation life of tunnels A and B are assessed. Fig. 2 and Fig. 3 present the corresponding probabilistic anti-carbonation lives of the two tunnels. It can be seen from Fig. 2 and Fig. 3 that there exists great discrepancy between the two tunnels even among their own corresponding sectors. For three sectors of tunnel A, their probabilistic anti-carbonation lives are 87. 9%, 94. 5% and 99. 5%, respectively and the maximum discrepancy is 11. 6%. While for five sectors of tunnel B, the probabilistic anti-carbonation lives are 72%, 100%, 84. 5%, 82% and 73%, respectively and the maximum discrepancy is 27%, which is obviously lower than that of tunnel A.

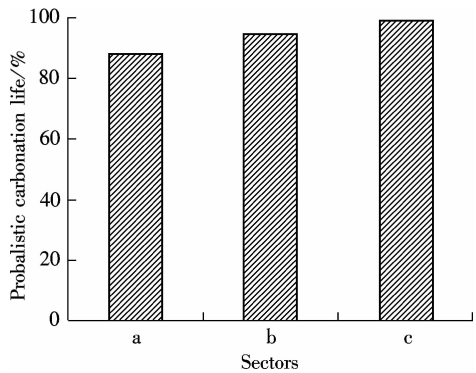

Fig. 2 Probabilistic carbonation life of tunne1 A

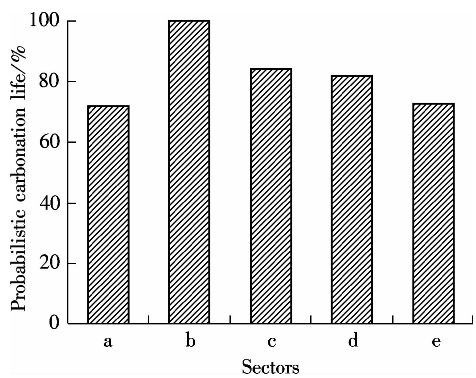

Fig. 3 Probabilistic carbonation life of tunnel B

2.2 Analysis of probabilistic evaluation results

As the above description shows, the environmental conditions such as temperature and RH for tunnels A and B are similar and the designed compressive strengths and service conditions are in great discreteness. However, the evaluation results exhibit such great differences for the two tunnels, which can be attributed to the differences between two crucial factors such as CO_2 combining capability and cover quality.

1) Comparison of CO_2 combining capability

Provided that the influence of environmental conditions are not considered, the anti-carbonation capability of concrete is determined by its CO_2 combining capability. Thus, referring to the denoting method of slag [11], the absolute basicity K_{AB} of cementicious material, which is the mass fraction of CaO per cubic meter concrete, is used to express the CO_2 combining capability,

$$K_{AB} = \sum \{C_\lambda[M_{CaO} - (1.65M_{Al_2O_3} + 0.35M_{Fe_2O_3})]\} \quad (3)$$

where M_{CaO}, $M_{Al_2O_3}$ and $M_{Fe_2O_3}$ are the mass fractions of CaO, Al_2O_3, and Fe_2O_3 for a certain kind of cementicious material, respectively. C_λ represents the mass fraction of a certain kind of cementitious materials in per cubic meter concrete.

It can be seen from Eq. (3) that the inherent CO_2 combining capability is determined by K_{AB} of cementicious materials. The much higher K_{AB}, the larger content of $Ca(OH)_2$ in concrete bulk is, and then the higher CO_2 combining capability the concrete has.

According to Tab. 1, Tab. 2 and Eq. (3), the K_{AB} of tunnel A and tunnel B are deduced to be 86.05 and 97.57 kg/m^3, respectively. Obviously the K_{AB} of tunnel B is a little greater than that of tunnel A. This implies that the capability of combining the CO_2 of tunnel B is a bit higher than that of tunnel A. Thus the inherent K_{AB} of concrete is yet not the main reason for the big difference between the evaluation results.

2) Comparison of concrete-cover quality

The quality of the concrete cover mainly includes the thickness and compactness, which are very important factors for concrete durability and they are also very crucial parameters for evaluating the anti-carbonation life. Fig. 4 and Fig. 5 show the frequency distribution of the concrete-cover thickness of the two tunnels. The statistical testing results prove that the thickness of the concrete cover conforms to the normal distribution, which indicates that the anti-carbonation life of the two tunnels can be evaluated by the proposed method. It can be seen from Fig. 4 and Fig. 5 that the distribution of concrete-cover thickness for tunnel A is of greater uniformity than that for tunnel B.

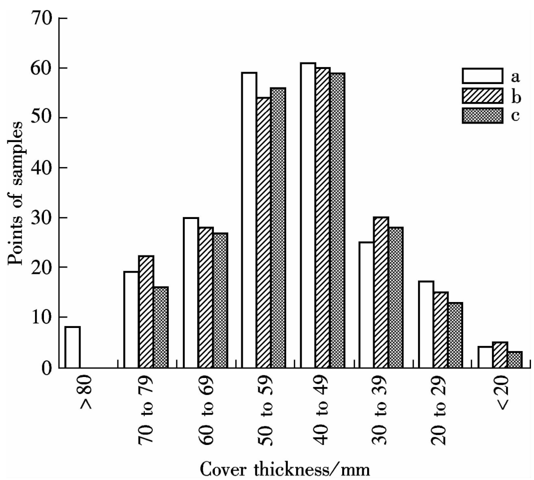

Fig. 4 Distribution of cover thickness for tunnel A

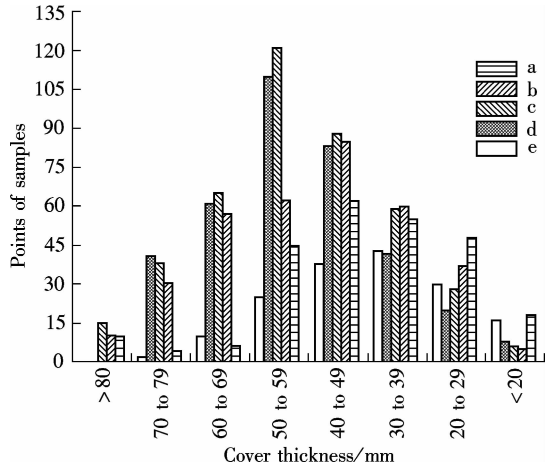

Fig. 5 Distribution of cover thickness for tunnel B

As we all know, the ultrasonic velocity and compactness are interrelated. Fig. 6 and Fig. 7 give the frequency distribution of the ultrasonic velocity for tunnel A and tunnel B, which also conforms to the normal distribution by statistical testing. As shown in Fig. 6 and Fig. 7, the average ultrasonic

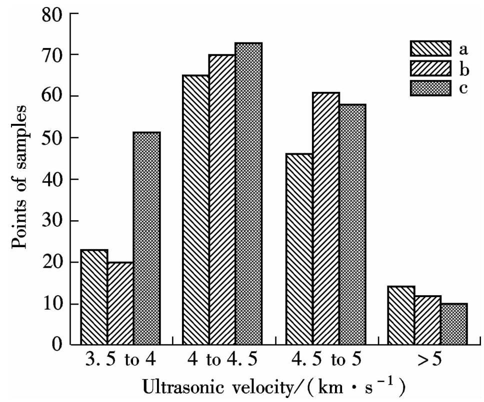

Fig. 6 Distribution of ultrasonic velocity for tunnel A

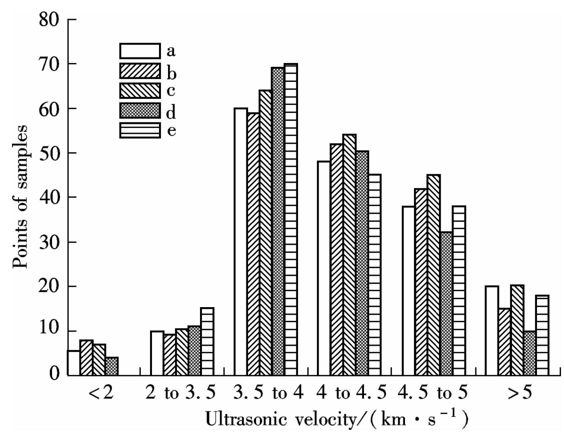

Fig. 7 Distribution of ultrasonic velocity for tunnel B

velocity of tunnel A is 4.11 km/s and its standard deviation for the three sectors are 0.64, 0.51 and 0.70, respectively. While the average ultrasonic velocity of tunnel B is only 3.76 km/s and the standard deviation for the five sectors are 0.79, 0.78, 0.73, 0.82 and 0.77, respectively. This means that the compactness of tunnel A is much better than that of tunnel B.

Accordingly, the cover quality of tunnel A is better than that of tunnel B, which is just the reason for the differences of carbonation life between tunnel A and tunnel B.

3 Conclusion

It is practical to measure the quality of the concrete cover of newly-built structures by the non-destructive testing methods and the results indicate that the thickness and compactness of the concrete cover conform to the normal distribution. By using the relationship between the accelerated carbonation rate and the ultrasonic velocity, a probabilistic method for evaluating the carbonation life of newly-built concrete structures is proposed in this paper based on the quality of the concrete cover. The probabilistic lives of carbonation for two newly-built underground tunnels are evaluated by the proposed method and the evaluation results are also analyzed. The analysis results illustrate that the proposed method has great feasibility and practicability and can be used not only to assess the probabilistic life of carbonation for newly-built concrete structures but also to supervise and instruct construction quality.

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新建混凝土结构碳化寿命概率评估方法及其应用

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摘要:为了对新建混凝土结构进行碳化耐久性评估,采用无损检测方法对新建隧道混凝土结构保护层密实度和厚度进行了检测,并基于混凝土碳化速度和超声波传播速度之间的线性关系,提出一种用来对新建混凝土结构进行概率碳化寿命评估的方法,并使用该方法对2个隧道混凝土结构进行了概率碳化寿命评估.结果表明:在环境条件及对 CO_2 结合能力基本相同的条件下,2个隧道概率碳化寿命相差较大,其中隧道A的概率碳化寿命均值为94.0%,各标段最大离差为11.6%;隧道B的概率碳化寿命均值为82.3%,各标段最大离差为27.0%.由评估结果分析可知,施工技术水平的不同造成2个新建隧道混凝土结构保护层质量分布出现离散性,从而最终导致2个隧道概率碳化寿命评估结果出现差异.

关键词:概率碳化寿命;新建结构;保护层质量
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