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Water–Binder Ratio Monitoring as a Quality Control Tool for the High-Performance Concrete Used in the Construction of the Submerged Tunnel

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ABSTRACT

The designed service life of Hong Kong-Zhuhai-Macao Bridge is 120 years. Concrete quality control for the submerged tunnel of the project is an important work to assure the designed service life. This article is to present an advanced concrete performance prediction method based on water–binder ratio (w/b) monitoring, which is used to serve for concrete quality control. During experiments in the lab, the w/b of submerged tunnel concrete mix proportion was designed to fluctuate up and down, while the other compositions were kept constant. Concretes with different w/b were prepared. The w/b of fresh concrete was tested, followed by preparation of specimens for compressive strength and chloride diffusion coefficient tests. The compressive strength and chloride diffusion coefficient of the hardened concrete were tested. Relationships between the tested w/b and the compressive strength and chloride diffusion coefficient were established. The fitting curves were taken as the prediction models. During construction of submerged tunnel in field, w/b of fresh concrete was tested. The compressive strength and chloride diffusion coefficient of the concrete were calculated using the established models. In addition, specimens of the tested concrete were prepared and cured for compressive strength and chloride diffusion coefficient tests. Finally, the predicted results and the tested results were analyzed, and the predicted deviation was calculated. Results of the calculations show that the prediction deviations of compressive strength and chloride diffusion coefficient are <10%. The present prediction method is promising for advanced field quality control of concrete before the structure is constructed.

1. INTRODUCTION

Hong Kong-Zhuhai-Macao Bridge is a large clustered marine project composed of island, bridge, and tunnel. The service life of the main project is designed as 120 years. The bridge is located in the south of China where the environment is highly salty, highly humidity, and the temperature is high. The corrosion condition of the project is severe. Therefore, the quality control of concrete during the construction of the submerged tunnel is very important, especially for control of durability. During the construction of concrete in field, water content of sand and gravel usually varies frequently, which may cause w/b fluctuation of the fresh concrete. Different water–binder ratios (w/b) may lead to different strengths and durability. The quality of the constructed concrete is hard to control due to the uncontrolled w/b. In traditional quality control, compressive strength and chloride diffusion coefficient of the constructed concrete are assessed by testing the reserved specimens in field or the specimens drilled from the structures (MOHURD, 2002; MOT, 2011). This quality control method is hysteretic and not satisfying.

For a given concrete, quantitative relationships between w/b and compressive strength, permeability are approved to exist (Mehta & Monteiro, 2006). For concrete with different cementitious materials, the relationships may be different. In this article, a monitoring method of fresh concrete w/b is introduced. Quantitative relationships between w/b and compressive strength and chloride diffusion coefficient are established for the submerged tunnel using high-performance concrete. An advanced quality control method based on the prediction of compressive strength and chloride diffusion coefficient is presented.

2. METHODS

2.1 High-performance concrete for submerged tunnel of hong kong-zhuhai-macao bridge

High-performance concrete with a w/b of 0.35 and a compressive strength level of C50 is used for the submerged tunnel of Hong Kong-Zhuhai-Macao Bridge. High-volume fly ash and slag are incorporated in the concrete to obtain satisfied durability, low heat release, and low shrinkage. The details of the concrete mix proportion are shown in Table 1. Indexes for compressive strength and chloride diffusion coefficient control are required in the service life design.

Table 1. Mix proportion of submerged tunnel used high-performance concrete (kg/m^3).

Cement	Slag	Fly ash	Sand	Gravel	Water	Sp
189	126	105	775	1047	147	5.04

2.2 Water–binder ratio monitoring method of fresh concrete

For a fresh concrete, when the water content is constant, the higher the air content, the lower the density. Meanwhile, when the air content is constant, the higher the water content, the lower the density. During the construction of concrete in field, the contents of sand and gravel may be kept constant easily, whereas the content of water may fluctuate. The w/b of fresh concrete can be calculated as follows:

For a given fresh concrete of 1 m^3, the air content can be given by

$$\alpha = 1-(V_G + V_S + V_B + V_W),$$

where α is air content of the fresh concrete; V_G, V_S, V_B, and V_W are the volume of gravel, sand, binder, and water. The equation above can be transformed into

$$1-\alpha = \frac{M_G}{\rho_G} + \frac{M_S}{\rho_S} + \frac{M_B}{\rho_B} + \frac{M_W}{\rho_W}, \quad (1)$$

where M_G, M_S, M_B, and M_W are mass of gravel, sand, binder, and water, whereas ρ_G, ρ_S, ρ_B, and ρ_W are density of gravel, sand, binder, and water. Values of ρ_G, ρ_S, ρ_B, and ρ_W can be obtained from the mix proportion design. Because the fluctuations of sand and gravel are very small, mass of them can be taken as constant during the calculation process. The value of volume of gravel and sand is given as constant A.

$$\frac{M_G}{\rho_G} + \frac{M_S}{\rho_S} = A$$

Equation (1) can be transformed to

$$1-\alpha = A + \frac{M_B}{\rho_B} + \frac{M_W}{\rho_W} \quad (2)$$

For the given fresh concrete, the unit weight can be given by

$$W_0 = \frac{M_G + M_S + M_B + M_W}{1-\alpha} \quad (3)$$

Values of M_G and M_S are as constants. The sum of them is given as B.

$$M_G + M_S = B$$

Equation (3) can be transformed to

$$W_0(1-\alpha) = B + M_B + M_W \quad (4)$$

Value of M_W and M_B can be calculated according to Equations. (2) and (4) as follows.

$$M_W = \frac{(\rho_B \cdot \rho_W - W_0 \cdot \rho_W)(1-\alpha) - A \cdot \rho_B \cdot \rho_W + B \cdot \rho_W}{\rho_B - \rho_W} \quad (5)$$

$$M_B = \frac{\rho_B(W_0 - \rho_W)(1-\alpha) - A \cdot \rho_B \cdot \rho_W + B(2\rho_W - \rho_B)}{\rho_B - \rho_W} \quad (6)$$

According to Equations (5) and (6), the w/b of the given fresh concrete can be calculated by

$$w/b = \frac{M_W}{M_B}$$

During the construction in field, w/b of the fresh concrete can be obtained by monitoring the unit weight and air content.

To simulate the variation of w/b in field, the w/b of the experimental concretes was designed to fluctuate around the designed w/b, while the other composites were kept constant. As a result, concretes with w/b of 0.33, 0.34, 0.35, 0.36, 0.37, and 0.38 were prepared. Unit weight and air content of the fresh concrete were tested, and the w/b was calculated according to above-mentioned equations. Additionally, comparative analysis of the calculated and designed w/b was carried out. The deviation of the calculated w/b was obtained finally.

2.3 Prediction of compressive strength and chloride diffusion coefficient

Specimens of 100 mm × 100 mm × 100 mm and Φ100 mm × 200 mm were prepared using above concretes. The specimens were cured under standard condition. Compressive strength and chloride diffusion coefficient at 28 and 56 days were tested, respectively, according to GB/T 50081-2002 and GB/T 50082-2009.

Relationships between the calculated w/b and the compressive strength and chloride diffusion coefficient were established. The fitting curves were used to predict compressive strength and chloride diffusion coefficient during construction in field.

2.4 Quality control for concrete in field

During the construction in field, the unit weight and air content of the fresh concrete were monitored, followed by the calculation of the w/b. The compressive strength and chloride diffusion coefficient of the monitored concrete were calculated according to the fitting curves. The calculated values were compared with the designed indexes of project. If the designed indexes are not satisfied, the mixing process of concrete in field should be adjusted. As a result, the quality control for concrete compressive strength and chloride resistance can be carried out before the structures are constructed. In addition, the tested fresh concrete was casted and cured for compressive strength and chloride diffusion coefficient tests. The deviation between the calculated values and the tested values was analyzed.

3. RESULTS AND DISCUSSION

3.1 Water–binder ratio monitoring of fresh concrete

The w/b calculated results of concretes with different designed w/b in the laboratory are shown in Table 2. The results were calculated based on the tests of unit weight and air content.

Table 2. w/b calculated results of fresh concrete in lab.

Mixes	Designed w/b	Air content (%)	Unit weight (kg/m³)	Calculated w/b
1	0.33	2.82	2383.9	0.337
2	0.34	2.53	2386.0	0.345
3	0.35	2.13	2392.2	0.351
4	0.36	2.49	2377.3	0.361
5	0.37	2.30	2376.3	0.371
6	0.38	2.35	2375.1	0.382

The relative deviation between the calculated and designed w/b is shown in Figure 1. It can be found that during the w/b calculation of the six concretes, the relative deviations of five concretes are between −2% and 2%, while one concrete is 2.1%. It appears that the w/b calculation method has a high accuracy.

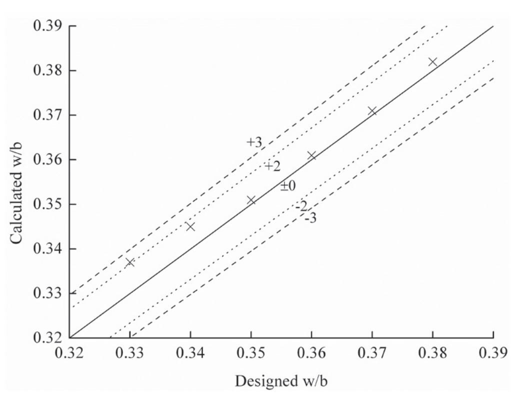

Figure 1. Relative deviation analysis between calculated and designed w/b.

3.2 Prediction curves for compressive strength

Compressive strength of the above concretes was tested at the ages of 28 and 56 days, where each value is averaged from the results of six cubes. The results are shown in Table 3. It is observed that there is a decrease trend for compressive strength along with the increase of w/b. However, one exception is found for concrete with designed w/b of 0.37, which may be due to test error.

Table 3. Results of compressive strength and chloride diffusion coefficient

Designed w/b	Calculated w/b	Compressive strength (MPa)		Chloride diffusion coefficient ($\times 10^{-12}$ m²/s)	
		28 days	56 days	28 days	56 days
0.33	0.337	67.1	72.7	4.4	2.8
0.34	0.345	65.2	71.2	4.3	3.1
0.35	0.351	61.2	69.0	4.6	3.0
0.36	0.361	59.5	69.3	4.8	3.1
0.37	0.371	60.0	67.2	5.0	3.6
0.38	0.382	57.0	66.8	5.4	4.0

Figure 2 shows the relationships between the designed w/b and compressive strength, while Figure 3 shows the relationships between the calculated w/b and compressive strength. Abrams' water–cement ratio rule is applied to fit the relation curves between w/b and compressive strength (Mehta & Monteiro, 2006). It is clear that the strength of concrete decreased with an increase of w/b, both for the ages of 28 and 56 days. It can be seen from Figures 2 and 3 that the compressive strength correlates better with the designed w/b than with the calculated w/b. This might be due to the calculated error of w/b for fresh concrete. According to the fitting results, Equations (7) and (8) are used to predict compressive strength of 28 and 56 days for the C50 concrete of the submerged tunnel, respectively, based on the w/b calculation of fresh concrete.

$$y = 212.77 \times 31.98^{-x} \tag{7}$$

$$y = 135.12 \times 6.45^{-x} \tag{8}$$

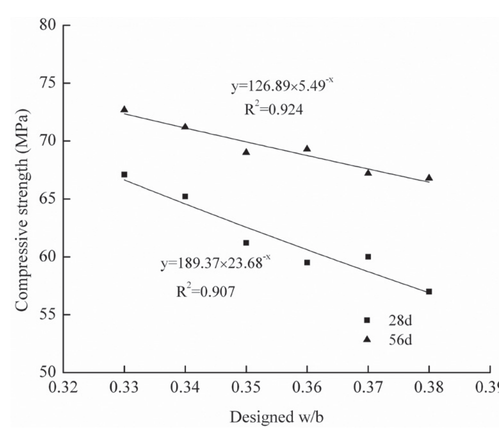

Figure 2. Relationships between designed w/b and compressive strength.

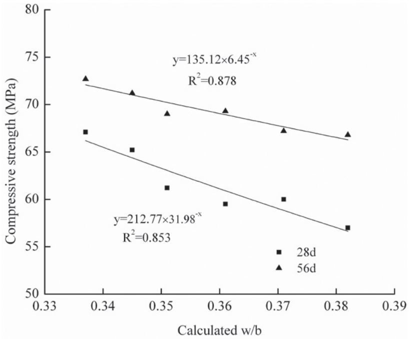

Figure 3. Relationships between calculated w/b and compressive strength.

3.3 Prediction curves for chloride diffusion coefficient

Chloride diffusion coefficient of the above concretes was tested at the ages of 28 and 56 days, where each value is averaged from the results of three specimens. The results are given in Table 3. It seems that there is an increasing trend of chloride diffusion coefficient when w/b increases. However, some exceptions exist. This might be explained by a small interval of w/b and test deviation of chloride diffusion coefficient. Additionally, it is clear that chloride diffusion coefficient tested at 56 days is much lower than that tested at 28 days for all concretes. This might be due to the continuous hydration of the mineral admixtures (Ramezanianpour, 1995).

The relationships between designed w/b and chloride diffusion coefficient are shown in Figure 4, while the relationships between calculated w/b and chloride diffusion coefficient are shown in Figure 5. Quadratic equations are applied to fit the relations. It appears that the chloride diffusion coefficient correlates well both with the designed w/b and the calculated w/b. The values of R^2 for the four fitting curves are higher than 0.93. According to the fitting results, Equations (9) and (10) are used to predict chloride diffusion coefficient for the submerged tunnel used C50 concrete at 28 and 56 days, respectively, based on the w/b calculation of fresh concrete.

$$y = 309.1x^2 - 198.8x + 36.23 \quad (9)$$

$$y = 495.2x^2 - 331.2x + 58.25 \quad (10)$$

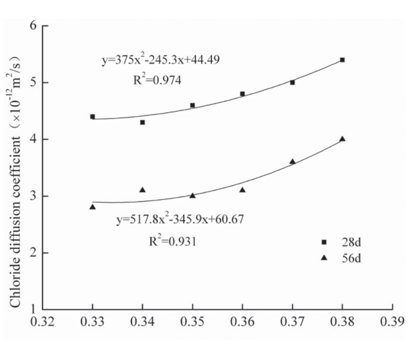

Figure 4. Relationships between designed w/b and chloride diffusion coefficient.

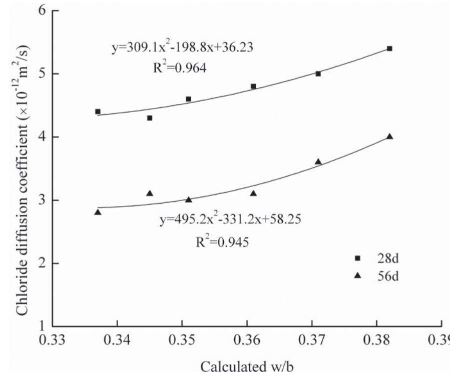

Figure 5. Relationships between calculated w/b and chloride diffusion coefficient.

3.4 Concrete quality control in field

During the construction of the submerged tunnel concrete, unit weight and air content of fresh concrete were monitored. The w/b of the fresh concrete in field was calculated. The result of unit weight, air content, and monitored w/b is given in Table 4. Samples for the monitoring were obtained from the construction in field during 1 week. It appears that all values of the monitored w/b are between 0.35 and 0.36, which demonstrates that concrete w/b is controlled very well during the construction of submerged tunnel in field.

Table 4. Monitored unit weight, air content, and w/b of fresh concrete in field

Sample	Unit weight (kg/m³)	Air content (%)	Monitored w/b
1	2386	1.5	0.353
2	2382	1.8	0.352
3	2398	1.2	0.358
4	2383	1.3	0.357
5	2383	1.1	0.360
6	2389	1.5	0.360
7	2404	1.5	0.356
8	2393	2.1	0.352
9	2400	1.7	0.355
10	2390	1.9	0.359

Compressive strength and chloride diffusion coefficient of the concrete were predicted according to the prediction equations above. Meanwhile, specimens for compressive strength and chloride diffusion coefficient tests were prepared for the tested fresh concrete. Compressive strength and chloride diffusion coefficient at the ages of 28 and 56 days were tested under standard curing condition. Results of tested and predicted compressive strength and chloride diffusion coefficient are given in Table 5. It is observed that compressive strength and chloride diffusion coefficient of all the monitored concrete are satisfied to the design indexes.

Table 5. Results of tested and predicted compressive strength and chloride diffusion coefficient

Sample	Monitored w/b	Tested compressive strength (MPa)		Predicted compressive strength (MPa)		Tested chloride diffusion coefficient (×10^{-12}m^2/s)		Predicted chloride diffusion coefficient (×10^{-12}m^2/s)	
		28 days	56 days	28 days	56 days	28 days	56 days	28 days	56 days
1	0.353	61.7	69.8	62.6	70.0	4.5	2.9	4.6	3.0
2	0.352	62.1	68.7	62.8	70.1	4.5	2.8	4.6	3.0
3	0.358	61.2	69.0	61.5	69.3	4.2	3.3	4.6	3.1
4	0.357	60.8	66.9	61.8	69.5	4.3	2.9	4.7	3.1
5	0.360	59.9	68.3	61.1	69.1	4.4	3.1	4.7	3.2
6	0.360	57.1	64.1	61.1	69.1	4.5	3.3	4.7	3.2
7	0.356	61.3	67.7	62.0	69.6	4.3	3.0	4.6	3.1
8	0.352	60.4	67.5	62.8	70.1	4.5	3.2	4.6	3.0
9	0.355	60.4	66.8	62.2	69.7	4.3	3.0	4.6	3.1
10	0.359	60.5	67.4	61.3	69.2	4.4	3.0	4.7	3.2

The relative deviations between the predicted values and tested values for compressive strength and chloride diffusion coefficient are shown in Figures 6 and 7, respectively. It can be seen that the relative deviation of compressive strength prediction is between 0 and 10%, while the relative deviation of chloride diffusion coefficient prediction is between 8 and 10%. It is revealed that the prediction equations of compressive strength and chloride diffusion coefficient established above have high accuracy.

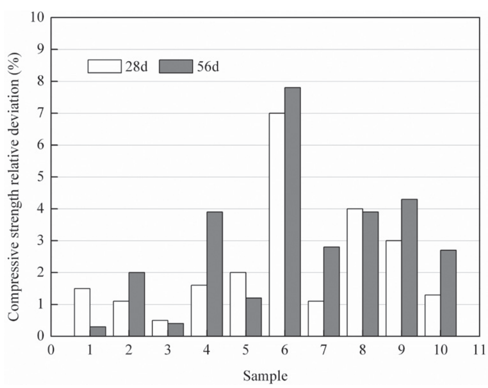

Figure 6. Relative deviation of compressive strength.

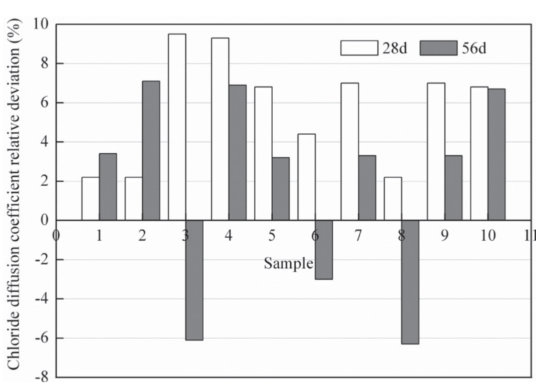

Figure 7. Relative deviation of chloride diffusion coefficient.

During the quality control in field, the w/b is monitored before the concrete is constructed, followed by the calculation of compressive strength and chloride diffusion coefficient of 28 and 56 days. If the predicted values are not aligned satisfactorily to the design indexes, the concrete preparation process should be adjusted.

As a result, an advanced quality control of strength and durability can be carried out, which may improve the uniformity of the constructed concrete and reduce the safety risk of the project.

4. CONCLUSIONS

The aim of this study is to present an advanced quality control method of concrete strength and durability for the submerged tunnel of Hong Kong-Zhuhai-Macao Bridge. Based on the results and discussion, the following conclusions can be drawn.

1. The monitoring method of w/b for fresh concrete with high-volume mineral admixtures based on tests of unit weight and air content is feasible. The calculation deviation is lower than 3%.
2. The prediction equations of strength and durability for high-performance concrete are established. The compressive strength and chloride diffusion coefficient of concrete can be predicted before the concrete is constructed in field, based on the w/b monitoring of the fresh concrete. High-prediction accuracy is acquired.
3. Based on the prediction of compressive strength and chloride diffusion coefficient, an advanced quality control technique for concrete strength and durability is established.

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