Research and Application of Foundation Post-grouting Concrete of Immersed Tubes of Hong Kong-Zhuhai-Macau Bridge

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Abstract. In this research, a kind of ultra-low strength underwater self-compacting concrete is studied. The results of laboratory and field tests show that the average compressive strength of the concrete in 28 days is 1MPa and 8m in-air and underwater self-leveling is realized. After high pressure pumping and water scouring, the strength is measured to be 0.9MPa, the pH to be 9.7 and the content of suspended matter to be 134mg/L. Underwater invisible construction is fully verified for the first time through field tests of underwater grouting of wood mould, fluidity and permeability of air (water) tank, and successfully applied to the foundation post-grouting construction of immersed tubes E31-E32 of Hongkong-Zhuhai-Macau Bridge (HZMB). It can provide reference for the engineering of similar underwater foundation post-treatment.

1. Research background
There are generally two methods of foundation treatment of immersed tube tunnel, namely pre-bedding and post-filling \(^{[1]}\). In China, cases of using pure sand, ultra-fine cement paste, cement mortar and bentonite cement mortar, etc \(^{[2-3]}\) as post-filling materials have been reported. Outside of China, only the the Sakishima immersed tunnel in Osaka Port, Japan adopts the filling of non-separable concrete in water \(^{[4-5]}\).

In the immersed tube tunnel of HZMB, a kind of ultra-low strength underwater self-compacting concrete is used to fill the serpentine gravel-ridge furrow foundation of immersed tubes. With underwater self-compacting performance, it can improve the filling saturation; with the ultra-low strength, it can realize the secondary distribution of stress after disturbance and uneven settlement of foundation. That can avoid the damage of immersed tubes caused by stress concentration. Based on this, the configuration and construction performance of foundation post-grouting concrete are studied and verified.

2. Raw materials and test scheme
The main raw materials used in the test include P•II42.5 cement produced by China Resources Cement Holdings Limited and Grade I fly ash produced by Jianbi power plant (Zhenjiang), which are mixed in proportion with coarse aggregate (with a diameter of 5~10mm and 10~20mm). The fine aggregate is river sand from Xijiang River, and high performance polycarboxylic acid admixture with compound tackifier is adopted as the additive. The oxide components of cement and fly ash are listed in Table 1.
Table 1. Major oxide components of the cement and fly ash

| Oxides | Al₂O₃ | SiO₂ | SO₃ | K₂O | CaO | TiO₂ | Fe₂O₃ | CO₂ |
|--------|-------|------|-----|-----|-----|------|-------|-----|
| Cement | 26.10 | 53.94 | 1.17 | 1.75 | 6.50 | 1.18 | 5.07  | 0.77 |
| FA     | 24.00 | 57.97 | 0.93 | 0.84 | 5.55 | 1.16 | 4.43  | 3.23 |

In this research, ultra-low strength underwater self-compacting concrete is prepared through indoor mix proportion test. Its performance indexes and test methods are shown in Table 2. Its pumpability, fillibility, underwater self-compactness and other performances are tested through field tests of underwater grouting of wood mould, fluidity of air (water) tank and pressure bleeding, etc and underwater invisible construction is fully verified. The concrete is applied to the foundation post-grouting of immersed tubes of HZMB to test its filling saturation.

Table 2. Performance indexes of foundation grouting concrete

| Performance of the newly mixed cement paste | Test methods |
|--------------------------------------------|--------------|
| Slump extension (mm)                       | 650±50       |
| V75 funnel time (s)                        | 7~20         |
| T500 (s)                                   | 3~15         |
| Performance of hardened cement paste       | Test methods |
| Compressive strength on the 28th day        | 0.5~1.5      |

3. Test results and analysis

3.1. Mix proportion test

In the mix proportion test, with a low cement content and a relatively high water-binder ratio, the ultra-low strength of concrete is achieved by adding a great number of bubbles and inert admixtures. The high fluidity of concrete is realized through sufficient paste, good gradation and proper admixtures. The good underwater non-dispersing performance of concrete is realized by using underwater non-dispersing agent with good performance. Through the experiment, it is recommended to use the mix proportion as is presented in Table 3. The performance indexes are listed in Table 4.

Table 3. Mix proportion of concrete (kg/m3)

| No. | Cement | Fly ash | Sand | Gravel 5-10mm | Gravel 10-20mm | Water | AD-300B | FF-55 |
|-----|--------|---------|------|----------------|----------------|-------|---------|-------|
| 1   | 20     | 280     | 698  | 508            | 338            | 285   | 3.0     | 3.0   |

Table 4. Performance of concrete

| No. | Extension mm | Volumetric weight kg/m³ | Compressive strength on the 7th day | Compressive strength on the 28th day | Underwater compressive strength on the 28th day | T500S | V-shaped funnel | PH value | Turbidity |
|-----|--------------|-------------------------|-----------------------------------|-----------------------------------|-----------------------------------------------|-------|----------------|----------|-----------|
| 1   | 610          | 2170                    | 0.4                               | 0.8                               | 12.5                                          | 16.4  | 8.1            | 136      |           |

3.2. Underwater grouting test of wood mould
A wood mould with the size of 100cm×100cm×50cm is filled with water to simulate the underwater environment. Grouting holes and exhaust holes are arranged on the top surface, as is shown in Figure 1. After pumping over a distance of 254m, grouting is carried out to verify the pumpability and underwater fillibility of concrete.

![Figure 1. Sketch of the mould](image1)

![Figure 2. Appearance after mould removal](image2)

Table 5 presents the performance of foundation post-grouting concrete after pumping over a long distance. The results show that the concrete has good pumpability, and the fluidity improves after pumping. The pH value of the water from exhaust holes is 9.7, and the content of suspended matter is 134mg/L, indicating a high underwater non-dispersing performance. After 10 days, the mould is removed, with the appearance shown in Figure 2. It can be observed that the mould is fully filled and there is no signs of mass loss of concrete paste after washing. The average strength of retained blocks is 0.9Mpa.

| Mix proportion | Before and after pumping | Slump extension (mm) | T500 s | V funnel s | Note |
|----------------|--------------------------|----------------------|--------|-----------|------|
| Mix proportion 1 | After pumping            | 670×660              | 13.0   | 8.0       |      |
|                 |                          | 700×710              | 13.0   | 6.0       | After 1 hour |

3.3. Fluidity test of air (water) tank
The fluidity test is carried out in a 12m×3m gravel-paved pond to simulate the fluidity of concrete grouting in the base and evaluate the natural flow distance of concrete. As is seen in Figure 3, the difference of natural flow heights of the concrete poured in two times is 3~4cm/12m.

Ordinary pressure simulation test is carried out to simulate situation of concrete grouting in the base. The model is arranged in a 4m×5m×1m tank full of sea water. The base is carpeted with a bed of gravel. Openings are arranged in the outlet end and two sides of the pump to distribute the water and reduce the scouring strength of sea water. The underwater anti-dispersion performance of of concrete under the construction conditions of pumping distribution and sea water scouring is simulated (turbidity measured after grouting); The whole construction technology of underwater grouting of concrete is verified; The underwater fluidity of concrete and permeability resistance of foundation bed is verified through pumping test.

The results show that grouting concrete has good scouring resistance and underwater non-dispersing performance and meet the construction requirements. The grouting process is smooth and the construction technology is reasonable. There is little difference between the underwater fluidity and the fluidity in anhydrous dry environment. The permeability resistance of the foundation bed is consistent with the results of quantitative permeability test, and there is basically no permeation.
3.4. Permeability test

In order to determine whether permeation and leakage of concrete occur in the gravel bed and ensure the saturation and quality of foundation post-grouting, the underwater permeability of concrete in the gravel bed is simulated. The experiment is carried out in a 100×100×120cm water tank (Figure 5). The bottom of the tank is covered with a layer of 20-60mm gravels (59cm high). A steel bucket with a height of 50cm and a diameter of 60cm is placed on the layer of gravels. Concrete is poured into the barrel. During the whole text process, test clerks make sure that the concrete is completely immersed in water. The results suggest that there is no obvious permeation and change of liquid level within 7 days. After 20 days, pump the water to conduct quantitative measurement, and there is almost no permeation into the gravels.
4. Foundation post-grouting of immersed tubes E31-E32
A reinforcement cage pushing airbag is laid on the layer of gravels and geotechnical cloth is arranged before horizontal backfill. The cloth is pressed by locking gravels with enough thickness to form a “closed cavity”. Through pre-buried grouting pipes, high pressure foundation is post-grouted from the mixing ship on the sea surface. The diagram of the scheme is shown in Figure 6. Before grouting, 5 soil pressure gauges are laid at the bottom of the tanks, with a maximum range of 0.7MPa. When the pressure of the soil pressure gauge reaches 0.6MPa, it will alarm in time. The layout of the gauges is shown in Figure 7.

In the grouting, the goals of joint-settlement coordination, pre-compaction of foundation bed and adjustment of pipe joint attitude are realized. The measured parameters are basically consistent with predicted parameters. The whole grouting process lasts for 17 hours, and the grouting rate gradually decreases after 12 hours. A total of 340m$^3$’s concrete is grouted, and the grouting volume and effect are presented in Table 6:

| Lift of pressure | Grouting volume and analysis | Lift of the pipe joint |
|------------------|-----------------------------|------------------------|
| Predicted: water pressure + 0.15 MPa | Predicted: 350m$^3$ | Maximum lift: 3.7cm |
| Measure: water pressure + 0.13 MPa | Actual: 340m$^3$ | After stabilization: 1.6cm |

The pressure monitoring curve obtained during the grouting of the bottom of the immersed tubes is shown in Figure 8, with the left displaying the change of pressure in the early stage and the right displaying the change of pressure in the later stage. It can be seen from the figure that the grouting consists of 3 phases: filling stage (160m$^3$, no change of attitude), formation of closed cavity (rising of pressure) and lifting of pipe joint (falling of pressure). In the later stage, the concrete gains strength, the pressure disperses and dies away with non-residual pressure.
readings of pressure, indicating that it has good underwater fluidity. The pressure remains stable for a long time, and the grouting concrete shows good resistance of base permeation.

5. Conclusions
Through the research and model test verification of foundation post-grouting concrete and the successful foundation post-treatment of E31-E32 joints, the following conclusions are arrived at:

1) Ultra-low strength non-dispersing concrete can be used to improved the stability and safety of immersed tube structures. Its good filling performance and ultra-low strength can adapt to the the secondary distribution of stress under foundation deformation.

2) The key points of mix proportion design for this kind of concrete include: low cement content, adding inert admixtures, relatively high powder content, relatively high water-binder ratio, small gravel diameter, a large number of micro-bubbles, using high-efficiency water reducer, a great deal of tackifier or dispersion resistance agent.

3) In the test, the underwater foundation post-treatment technology is fully verified, and the field construction process is smooth with good effect.

4) The concrete and construction method can not only meet the requirements of foundation post-treatment, but also can make certain adjustment of the attitude of underwater structure through the formation of closed cavity and the controlling of grouting volume and grouting pressure.

References:
[1] Tang, J., (2004)Analysis of the foundation treatment method of immersed tunnels [J]. Railway Survey and Design,8(3):67-69
[2] Zhu,T., Xu,WJ.,(2008) Study on the foundation treatment method of outer ring immersed tunnel of Shanghai city[J]. Urban Roads Bridges & Flood Control, 6(11):105-107
[3] Shen,HC., Zhuang,DQ.,(1994) Experimental study on the grouting of tube bottom of Yongjiang underwater tunnel [J]. Port & Waterway Engineering, 8(6):45-47
[4] Chen,SZ., Ren,XS.,(1996) Foundation treatment method of immersed tunnel of Zhujiang River [J]. World Tunnels, 7(6):34-39
[5] Du,CW., Wang,XY., (2009)Key technology of design and construction on immersed tube tunnel[J]. (7): Engineering Sciences, 11(7):76-80