Full-Scale Model Experimental Research on Concrete Construction Technology of Steel Shell Immersed Tube Tunnel

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Abstract. A full-scale model experiment was carried out to research the effects of the Self-Compacting Concrete (SCC) construction technologies including SCC working performances, casting speeds and the arrangement methods of vent holes on the filling quality of the steel shell immersed tube tunnel compartments. The experimental results showed that in order to guarantee the bearing capacity of structure mainly by reducing the voids as many as possible to meet the related requirements of Guide, the total area ratio of voids with the depth more than 5.0 mm in the whole top surface of compartments must be less than 5%, the initial slump flow of SCC should be improved to 670±50 mm on account of the flowability loss caused by the particle migration of coarse aggregates during pumping and at least ten vent holes distributed around the top plate of a steel shell compartment parts of which were located on the both ends of T ribs far from the pouring holes are needed, simultaneously the appropriate pouring speeds of SCC are respectively 30 m³/h and 15 m³/h when the distances from fresh concrete level to compartment roof are more and less than 20 cm.

1. Introduction
With the development of China's society and economy, as well as people's awareness of natural environmental protection, the need for underwater tunnels to cross rivers, bays and straits has become more and more urgent. Compared with bridges, underwater tunnels have many advantages such as all weather transportation, less interference to shipping and aviation and better protection to the original ecological and natural environment [1-2].

In the constructed and under-construction immersed tunnel projects in China, there is only one single-layer steel shell immersed tunnel in Hong Kong, while the others are all reinforced concrete immersed tunnels. The immersed tunnel of the Hong Kong-Zhuhai-Macao Bridge, which was completed and opened to traffic on October 24, 2018, is a typical reinforced concrete immersed tunnel. Various design measures such as high grade concrete, ultra thick structural plates and large amount of reinforcement were adopted to cope with its large embedded depth and heavy load, which put forward higher requirements to construction [3].

At present, the Shenzhen to Zhongshan Cross-river Channel (hereafter called Shenzhong Link) located on upstream of the Hong Kong-Zhuhai-Macao Bridge is a comprehensive cluster of engineering project including ultra wide and long subsea immersed tube tunnel, super large cross-sea bridges, deep water artificial islands and underwater communication. The immersed tube tunnel has
the maximum width and span in the world, meanwhile it also has the characteristics of large siltation, deep burial and so on. Because of the above mentioned factors, it is difficult to meet the mechanical and durable properties requirements of the immersed tube tunnel by using traditional reinforced concrete structure. Therefore, the structural type of steel shell immersed tunnel has been adopted in Shenzhong Link engineering.

The steel shell is used to wrap plain concrete in the steel shell immersed tunnel structure. Compared with the traditional reinforced concrete immersed tunnel, it has many advantages such as the flexible prefabrication site selection (steel shell prefabrication and concrete casting separately), excellent waterproof performance (concrete is completely wrapped by steel shell), greatly shortened construction time and good adaptability to uneven settlement [4]. However, there are some technical problems in steel shell concrete structure compared with reinforced concrete structure. In which one of the most obvious problems is how to ensure that the steel shell can be completely filled with concrete without vibration, especially the core concrete contacts the roof of steel shell closely avoiding defects such as large area separation in order to guarantee co-working between the core concrete and steel shell and improve the structural carrying capacity. In view of the above, the full-scale model experimental research has been carried out to optimize the core concrete working performance and its construction process based on which a series of technical measures has been formed to provide the basis for fairly well solving these problems in this paper.

2. Experimental Purpose and the Structure of Full-Scale Model of Steel Shell Immersed Tunnel

The cross sectional size and its detail structure of the full-scale model of the steel shell immersed tunnel used in this experiment are completely consistent with the Class I steel shell in the construction drawing of Shen-Zhong Link project, as well as all the compartments sizes. As shown in figure 1, the full-scale model is 18 meters long, 23 meters wide and 10.6 meters high. About 737 tons of steel was used to build it and 1417 m³ of concrete will be cast during the experiment research. The full-scale model is divided into multiple compartments in which there are 36 bottom plates, 10 walls and 32 top plates. As shown in figure 2, numerous T ribs, one pouring hole and some vent holes are set up in all the compartments.

During the experiment, the production, transportation and concrete casting of the full-scale model were under the same construction conditions of the actual steel shell immersed tunnel. The effect of self-compacting concrete workability, vent holes arrangements and concrete casting speed on the casting compactness of compartments, especially the compactness of the top surface of steel shell has been experimental researched based on which a research report has been developed to guide the future construction of steel shell immersed tube tunnel.

Figure 1. Schematic diagram of full-scale model.
3. Experimental Methods and Process

3.1. Self-Compacting Concrete (SCC) Workability

The application of concrete smart dynamic to realize structure self-filling and compacting function is a significant technological revolution that utilizes materials properties to solve structure durability problems caused by construction factors. Increased productivity, enhanced environmental consciousness and improved working environment have brought high priority into the development of building industry over the last three decades. Self-compacting concrete (SCC), considered as a concrete which can be placed and compacted under its self-weight with no compaction energy and use of vibrators in site even in the presence of dense reinforcement, and which is at the same time robust and cohesive enough to be handled without segregation, sedimentation or bleeding. Besides, SCC has the same mechanical properties, durability and volume stability as traditional vibrating concrete [5-6].

SCC is used to fill all the compartments of steel shell immersed tunnel of Shen-Zhong Link in the designing scheme. Therefore, the workability of SCC affects the casting quality directly. The raw materials, mix ratio and working performance of SCC used in the experiment are shown in tables 1-2 respectively which can meet the requirements of Guide for Preparation and Construction Key Technology of High-robustness and Low-shrinkage SCC applied in Steel Shell Immersed Tunnel of Shen-Zhong Link except some slump flow and the working performance parameters has been further optimized with the slump flow increasing. The compactness of standard size compartments (3m×3.5m×1.5m) filled by SCC with different slump flow was studied to determine whether the working performance indicators proposed by the original guide should be revised in the experiment.

| Material | Cement | Fly ash | Slag | Fine aggregate | Coarse aggregate | Coarse aggregate | Water | Admixture |
|----------|--------|---------|------|----------------|------------------|------------------|-------|-----------|
| Specification | P•II42.5 Grade I S95 | River sand | 5-10 mm | 10-20 mm | Drink water | Polycarboxylate superplasticizer |
| Amount | 275 | 192 | 83 | 834 | 500 | 334 | 172 | 6.32 |

Table 1. Raw materials and mix ratio of SCC in the full-scale model experiment (kg/m³).

| Parameters | Requirements of guide | Test results |
|------------|-----------------------|--------------|
| Filling ability | Slump flow (mm) 650±50 | Compartment 1: 630 | Compartment 2: 670 | Compartment 3: 720 |
| | Slump flow time $T_{50}$ (s) 2~5 | 3.9 | 3.0 | 2.5 |
| Passing ability and segregation resistance | V-funnel time (s) 5~15 | 13 | 9.8 | 8.1 |
| | L-instrument ($H/H$) ≥0.8 | 0.88 | 0.90 | 0.95 |
| Others | Dry capacity (kg/m³) 2300~2370 | 2330 | 2330 | 2355 |
| | Air content (%) ≤4% | 2.7 | 2.9 | 2.4 |

Table 2. Working performance of SCC in the full-scale model experiment.

3.2. Arrangement Methods of Vent Holes

The gas discharge results are directly affected by the arrangement methods of vent holes of the steel shell immersed tube tunnel during SCC casting, therefore it is necessary to optimize it. Three main arrangement methods of vent holes in standard size compartments with four T ribs on the top plate
were adopted based on which the filling quality was compared to select the best one during the full-scale model experimental research.

(1) Method one. As shown in figure 2(a), there were one pouring hole and eight vent holes on the top plate of steel shell. The pouring hole was located in the center of compartment while the vent holes were located on both sides of it.

(2) Method two. As shown in figure 2(b), two vent holes were added on the other two sides of the top plate of steel shell and there were one pouring hole and ten vent holes compared to method one.

(3) Method three. As shown in figure 2(c), the vent hole 2# was arranged on the T rib No. 1 to research its effect on the concrete filling quality of compartment. The vent holes 3# and 7# were arranged on different sides of the T rib No. 4 and closely to the vent hole 4# and the T rib No. 3 respectively to research their effects on the concrete filling quality of compartment. The location of vent hole 6# stayed the same as a contrast.

![Figure 2. Arrangement methods of vent holes in standard size compartments.](image)

3.3. SCC Pouring Speeds

The air can’t be vented timely and will be trapped under the top plates of the compartments of steel shell immersed tube tunnel when SCC pouring speed is too fast. On the other hand, too slow SCC pouring speed reduces production efficiency. Therefore, it is very important to choose an appropriate SCC pouring speed. The typical pouring speeds combinations of SCC during the full-scale model experiment are shown in table 3 and the pouring speeds were slowed by half when the distance from
fresh concrete level to compartment roof was less than 20 cm compared to the distance was more than 20 cm. The effects of different pouring speeds combinations on the concrete filling quality of compartments have been researched.

Table 3. Typical casting speeds of SCC during model experiment (m³/h).

| Working condition | Distance from fresh concrete level to compartment roof more than 20 cm | Distance from fresh concrete level to compartment roof less than 20 cm |
|-------------------|-------------------------------------------------|-------------------------------------------------|
| 1                 | 20                                              | 10                                              |
| 2                 | 30                                              | 15                                              |
| 3                 | 40                                              | 20                                              |

4. Experimental Results

4.1. Influences of SCC Working Performances on the Filling Quality of Steel Shell Immersed Tube Tunnel Compartments

The effects of SCC working performances, arrangements of the vent holes and SCC casting speeds on the filling quality of steel shell immersed tube tunnel were experimental researched. As shown in table 2, the working performances such as slump flow time T50, V-funnel time and L-instrument (H2/H1) which characterized the filling ability, passing ability and segregation resistance of SCC were further optimized with the increase of slump flow while the dry capacity and air content of SCC changed little which met the requirements of Guide well. The situation that the fresh concrete raised out of the steel shell after it filling the compartment of steel shell immersed tube tunnel fully is shown in figure 3.

As shown in figure 4, in this test, the concrete filling quality of compartments was mainly judged by opening the top plates of steel shell oxygen acetylene flame used and analyzing the voids between it and the core hardened concrete. Subsequently, the scanning impact-echo method will be used for quantitative analysis of the voids. The experimental results showed that the slump flow of SCC reduced by 50–80 mm after about 100 meters long distance pumping and the lower the slump flow of SCC before pumping was, the higher the slump flow loss during pumping was. Therefore, the slump flow of SCC decreased obviously after pumping and couldn’t meet the requirements of Guide when it was less than 630 mm before pumping which resulted in lots of voids between the core hardened concrete and top plates of steel shell especially the T ribs nearby.

Based on the above experimental results, the permissible value of SCC Slump flow before pumping has been improved to 670±50 mm in the Guide for Preparation and Construction Key Technology of High-robustness and Low-shrinkage SCC applied in Steel Shell Immersed Tunnel of Shen-Zhong Link while the other requirements of SCC working performances stayed the same, which is more conducive to the filling quality control of steel shell immersed tube tunnel compartments.
4.2. Influences of the Arrangement Methods of Vent Holes on the Filling Quality of Steel Shell Immersed Tube Tunnel Compartments

The influences of the arrangement methods of vent holes on the filling quality of steel shell immersed tube tunnel compartments have been compared under the condition that the slump flow of SCC was controlled as 670±50 mm before pumping and the analyzed results of large area voids with the max depth more than 5.0 mm between the core hardened concrete and top plates of steel shell are shown as follows.

(1) Method one. (a) The void 1# is located on the T rib No. 1 and close to the side of vent hole 1# which roughly appeared as type “□” with the max depth 15.2 mm, the max length 354 mm and the max width 100 mm. (b) The void 2# is located on the T rib No. 1 and close to the side of vent hole 5# which also roughly appeared as type “□” with the max depth 16.3 mm, the max length 235 mm and the max width 56 mm. (c) The void 3# is located on the T rib No. 4 and close to the side of vent hole 8# which roughly appeared as type “△” with the max depth 12.6 mm, the max length 250 mm and the max width 52 mm. (d) The void 4# is located on the outside of T rib No. 1 between the vent holes 1# and 5# appeared as type “△” with the max depth 10.4 mm, the max length 310 mm and the max width 84 mm. (e) The void 5# is located on the outside of T rib No. 4 between the vent holes 4# and 8# appeared as type “□” with the max depth 13.5 mm, the max length 287 mm and the max width 106 mm.

(2) Method two. (a) The void 1# is located on the T rib No. 1 and close to the side of vent hole 5# which roughly appeared as type “△” with the max depth 12.0 mm, the max length 213 mm and the max width 85 mm. (b) The void 2# is located on the T rib No. 4 and close to the side of vent hole 4# which roughly appeared as type “□” with the max depth 11.5 mm, the max length 230 mm and the max width 72 mm. (c) The void 3# is located on the T rib No. 4 and close to the side of vent hole 4# which roughly appeared as type “△” with the max depth 15.3 mm, the max length 226 mm and the max width 135 mm.

(3) Method three. There is a void on the T rib No. 1 and close to the side of vent hole 5# which roughly appeared as type “△” with the max depth 7.4 mm, the max length 134 mm and the max width 52 mm, the total area ratio of which with the depth more than 5.0 mm in the whole top surface of steel shell immersed tube tunnel compartment is less than 2% while the depths of other voids are all lower than 5.0 mm.

The voids between the core hardened concrete and top plates of steel shell with depths more than 5.0 mm reduce the bearing capacity of structure are defined as the harmful ones according to Guide for Preparation and Construction Key Technology of High-robustness and Low-shrinkage SCC applied in Steel Shell Immersed Tunnel of Shen-Zhong Link. As the above testing results of harmful voids shown, they regularly existed on the both ends of T ribs No. 1 and No. 4 far from the pouring holes on the top surfaces of compartments when the first two arrangement methods of vent holes were adopted. In addition, lots of honeycomb voids distributed on the top surfaces of compartments, especially on the regions outside of the T ribs No. 1 and No. 4 under the vent holes arrangement method one. However, two vent holes were added in the mentioned regions under the vent holes arrangement method two because of which the honeycomb voids problems were solved effectively.

The third arrangement method of vent holes was adopted in the experimental research based on the analysis of existing problems caused by the first two which improved the air vent ability of the regions on the both ends of T ribs No. 1 and No. 4 far from the pouring holes during SCC pouring construction. The results indicated that the serious voids on the ends of T ribs were almost eliminated after the above optimization of vent holes and the top surface of concrete kept flat. The statistical results showed that the total area ratio of voids with the depth more than 5.0 mm in the whole top surface of steel shell immersed tube tunnel compartments were 7.4%, 5.2% and 1.7% respectively when the three arrangement methods of vent holes were orderly adopted. The main existing defects were the slight voids with depth lower than 5.0 mm under the vent holes arrangement method three which well met the control requirement of Guide that the ratio must be less than 5% to guarantee the bearing capacity of structure.
4.3. Influences of the Pouring Speeds on the Filling Quality of Steel Shell Immersed Tube Tunnel Compartments

The influences of different SCC pouring speeds on the filling quality of steel shell immersed tube tunnel compartments were further researched based on the optimization of SCC working performances and vent holes arrangement during the full-scale model experiment. As shown in Table 3, the SCC pouring process was divided into two stages with different pouring speeds and the filling quality of compartments was tested by opening the top plates of steel shell and analyzing the voids between it and the core hardened concrete.

The testing results indicated that the number and total area of voids increased in the order of working condition 1, 2 and 3 obviously. That is to say, the higher the pouring speed was, the more voids generated. Especially under the working condition 3, there existed lots of voids the total area of which went beyond the requirement of Guide because the air couldn’t escape in time at high concrete pouring speed, while the voids area showed little differences between working condition 1 and 2 both of which met the requirement Guide well.

Therefore, considering both of the filling quality and work efficiency of the steel shell immersed tube tunnel, the pouring speeds of SCC are explicitly stipulated in Guide which indicates that they should be strictly controlled within 30 m³/h and 15 m³/h when the distances from fresh concrete level to compartment roof are more and less than 20 cm.

5. Discussion

5.1. Flowability Loss during Pumping

Since the casting speed of current experiments varies from 15 m³/h to 40 m³/h, the time span for concrete stays in the pumping pipe of 100 m is 2 to 5 min. Keeping this time range in mind we are now focusing on the phenomenon of particle migration since it is known that the shear induced particle migration is at the origin of the flowability loss of SCC during pumping [7]. The characteristic shear induced particle migration time $T_{shear}$ can be estimated as the following form [7]:

$$ T_{shear} = \frac{D^2}{10d^2 \phi_d^2 \gamma} $$

Where D is the diameter of the pumping pipe (m), d is the particle size (m), $\phi_d$ is the volume fraction of particles and $\gamma$ is the average shear rate (s⁻¹). We then find that the $T_{shear}$ for the coarse aggregates in current study is of the order of 10 s which is much lower than the time span of SCC that stays in the pumping pipe. This means that the coarse aggregates reach its full extent at initial pumping stage.

Furthermore, the maximum variation in particle volume fraction $\Delta \phi_{shear} d$ owing to shear induced particle migration after $T_{shear}$ can be computed according to:

$$ \Delta \phi_{shear} d = \Delta \phi_d (1 - \frac{\phi_d}{0.8 \phi_{dm}}) $$

Where $\phi_{dm}$ is maximum packing fraction of the migrated particles, which is herein the case of coarse aggregates. We then find a variation in $\Delta \phi_{shear} d$ around 10% for the largest grains in the mixture. In terms of yield stress variation, we simply apply here the Chateau and Ovarlez model [8-9]:

$$ \tau_{SCC} = \tau_{mor} \sqrt{ \frac{1 - \phi_d}{(1 - 0.8 \phi_{dm})^2} } $$

Where $\tau_{SCC}$ is the yield stress of SCC (Pa), $\tau_{mor}$ is the yield stress of corresponding mortar (Pa). We then obtained a variation of 70% of $\tau_{SCC}$ after migration of coarse aggregate. Compared to the slump
flow loss of 50 - 80 mm for the three SCC mixtures after pumping, an increase of yield stress of around 50% - 100% can be found according to the following yield stress – slump spread conversion relationship [10-11]:

\[ \tau_0 = \frac{225 \rho \Omega^2}{128 \pi^2 R^5} \]  

(4)

Where \( \tau_0 \) is the yield stress (Pa); \( \rho \) is the bulk density of the mixture (kg/m\(^3\)); \( R \) is the spread radius (m); \( \Omega \) is the volume of the testing mixture (m\(^3\)) and equals to 6 L in this study.

However, it should be noted that equations (3-4) stay controversial when they are applied to concrete scale. But the above calculation results of yield stress are compatible with each other meaning that the particle migration of coarse aggregates dominates the slump flow loss of SCC during pumping.

5.2. Robustness Assessment of SCC

Robustness issue plays important role during SCC preparation and casting process [12]. Therefore, it is worth analyzing the potential robustness of SCC used for the current work. According to the gathered results, controlling the slump flow or yield stress of SCC mixture is the key step to ensure a satisfactory casting process. It is known from section 4.1. that the increase of the yield stress shall be around 70% after running through the pumping pipe. We then expect a decrease of slump flow of around 10% since \( \tau_0 \sim R^3 \).

If we simply estimate the minimum slump spread that can meet the casting requirement is around 580 mm which is in between of the mixtures in Compartment 1 and Compartment 2. We then expect a yield stress of around 40 Pa after pumping. According to the following calculation of robustness index (RI) [13]:

\[ RI = \frac{\tau_{\text{increase}} - \tau_{\text{reference}}}{\tau_{\text{reference}}} \times 100\% \]  

(5)

In case of SCC in Compartment 2 (initial yield stress around 35 Pa), the robustness index of yield stress shall be 14%. However, in case of SCC in Compartment 3 (initial yield stress around 25 Pa), the robustness index of yield stress shall be 60% which is much tolerant than that of the former SCC. In terms of slump spread, the robustness index shall be 3% and 10% for SCC in Compartment 2 and Compartment 3, respectively.

The above assessment shows the global range of yield stress and slump spread that our SCC should not exceed. This also provides an insight which aiming at linking typical engineering test to rheological properties of SCC.

6. Conclusion

The relevant conclusions are as follows:

(1) Shenzhong Tunnel innovatively adopts the steel-shell concrete immersed tunnel structure in China to ensure that the concrete pouring in the steel shell is compact and no void, which is the key to play the function of the combined structure.

(2) The full-scale model test results show that the workability of SCC, the arrangement of vent holes and the pouring speed of SCC have a great influence on the quality of steel immersed tunnels. The SCC slump expansion is controlled at 670±50 mm, the number of vent holes on the top of the steel shell is not less than 10 and located on both sides of T-ribs. the pouring speed should be controlled not exceed 15 m\(^3\)/h when the last 20 cm from the top can significantly improve the quality of the pouring and meet the guideline.

(3) In the subsequent model tests, the effects of different pumping distances, pouring heights, the arrangement of vent hole on T rib and end pouring conditions on the quality of steel shell immersed
tunnels, and the guideline will be further improvement based on the test results in order to provide as much detailed guidance as possible for the construction of engineering structures.

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References
[1] Chen S Z and Chen Y 2002 Design and Construction of Immersed Tube Tunnel Science Press pp 1-15.
[2] Lin M, Liu X D and Lin W 2017 General discussion on the planning of immersed tunnel project China Harbour Engineering 37(1) 1-7.
[3] Chen S Z, Su Z X and Chen Y 2015 New technologies used for immersed tunnel of Hongkong-Zhuhai-Macao Bridge project Tunnel Construction 35(5) 396-403.
[4] Xu G P and Huang Q F 2018 General design of Shenzhen-Zhongshan River-crossing link project Tunnel Construction 38(4) 627-637.
[5] Hajime O and Masahiro O 2003 Self-compacting concrete Journal of Advanced Concrete Technology (1) 5-15.
[6] Liu Y H, Xie Y J and Long G C 2007 Progress of research on self-compacting concrete Journal of the Chinese Ceramic Society 35(5) 671-678.
[7] Spangenberg J, Roussel N, Hattel J H, Stang H, Skocek J and Geiker M R 2012 Flow induced particle migration in fresh concrete: Theoretical frame, numerical simulations and experimental results on model fluids Cement & Concrete Research 42(4) 633–641.
[8] Hafid H, Ovarlez G, Toussaint F, Jezequel P H and Roussel N 2015 Effect of particle morphological parameters on sand grains packing properties and rheology of model mortars Cement and Concrete Research 80 44–51.
[9] Zuo W Q, Liu J P, Tian Q, Xu W, She W, Feng P and Miao C W 2017 Optimum design of low-binder Self-Compacting Concrete based on particle packing theories Construction & Building Materials 163 938–948.
[10] Roussel N, Stefani C and Leroy R 2005 From mini-cone test to Abrams cone test: Measurement of cement-based materials yield stress using slump tests Cement and Concrete Research 35(5) 817–822.
[11] Roussel N and Coussot P 2005 “Fifty-cent rheometer” for yield stress measurements: From slump to spreading flow Journal of Rheology 49(3) 705–718.
[12] Zuo W Q, Liu J P, Tian Q, Xu W, She W and Miao C W 2017 Norm method to define and evaluate robustness of self-compacting concrete due to component quantity variations Construction and Building Materials 161 246–253.
[13] Gonza I 2018 Robustness of self-compacting recycled concrete: analysis of sensitivity parameters Materials and Structures 51(8) 8.