

影响地下隧道衬砌混凝土抗蚀性因素的优化设计

胡红梅¹, 马保国², 钱刚³(1. 厦门大学建筑与土木工程学院, 福建 厦门 361005; 2. 武汉理工大学材料学院, 武汉 430070;
3. 厦门东通道工程现场指挥部总监办, 福建 厦门 361009)

摘要: 从提高混凝土本体的密实性与防腐能力和维持钢筋钝化性能的化学环境出发, 对影响地下隧道衬砌混凝土抗蚀性的主要因素进行了研究。通过对胶凝材料组分与颗粒级配、高效减水剂与新型高效钢筋阻锈剂进行优化设计, 实现了对水化产物相和界面结构的调控与优化。研究表明: 地下隧道衬砌混凝土的优化配比为 5%~10%(质量分数, 下同)硅灰与 30%~40%大掺量粉煤灰复合内掺, 1.30%萘系或 1.25%聚羧酸系高效减水剂与 8%还原铁粉或 0.05%D-葡萄糖酸钠阻锈剂复合外掺, 该多元组分混凝土满足抗渗等级>P20, 氯离子扩散系数 $D_{RCM} < 1 \times 10^{-12} \text{ m}^2/\text{s}$, 抗硫酸盐腐蚀系数 $K > 0.80$ 的高防水抗蚀要求。

关键词: 地下隧道; 衬砌; 混凝土; 抗蚀性; 优化设计

中图分类号: TU528 文献标识码: A 文章编号: 0454-5648(2008)01-99-06

OPTIMUM DESIGNS OF INFLUENCE FACTORS FOR THE CORROSION RESISTANCE OF CONCRETE LINING FOR UNDERGROUND TUNNELS

HU Hongmei¹, MA Baoguo², QIAN Gang³

(1. School of Architecture and Civil Engineering, Xiamen University, Xiamen 361005; 2. School of Material Science and Engineering, Wuhan University of Technology, Wuhan 430070; 3. Site Headquarter of East Passageway Submarine Tunnel (Xiang'an Tunnel) Office of Chief Supervision Engineer, Xiamen 361009, China)

Abstract: The influence factors for the corrosion resistance of concrete lining for underground tunnels is studied with a view to improving the compactness and corrosion resistance of the concrete body and maintaining the chemical environment of rebar passivation performance. With optimum designs of the components of binding materials and grain composition, as well as a high-efficiency water reducers and a new type high-efficiency corrosion inhibitors, control and optimization of the phase and interface structure of hydrated products have been achieved. The results show that, multi-component concrete with internal mixing of 5%–10% fume and 30%–40% fly ash, and external mixing of 1.3% naphthalene-series or 1.25% polycarboxylic acid-series high-efficiency water reducer and reducing iron powder of 8% or D-glucose sodium salt corrosion inhibitor of 0.05%, meet the high waterproofing and corrosion resistance requirements including the impermeability grade>P20, chloride ion diffusion coefficient $D_{RCM} < 1 \times 10^{-12} \text{ m}^2/\text{s}$ and sulfate corrosion resistance coefficient $K > 0.80$.

Key words: underground tunnels; lining; concrete; corrosion resistance; optimum design

Compared with structures in the atmospheric environment, underground tunnels are mostly located between high-temperature, moist or high-pressure and water-rich rock strata, and multiple factors are in integrated interaction, which accelerates the process of corrosion and damage.^[1] The main body of a tunnel structure, built with reinforced concrete lining made with prefabricated duct pieces and the on-site pump concrete pouring process, is the fundamental guarantee of the

waterproofing and corrosion resistance of the tunnel. The main influence factors for the corrosion resistance of concrete lining for underground tunnels include: (1) the impermeability and chloride and sulfur binding effects of the concrete body; (2) degree of structural compactness, controlling the transmission of harmful substances, and cutting off the corrosion channel; and (3) maintaining the chemical environment of rebar passivation performance, and improving the long-term stability of the rebar in the

收稿日期: 2007-06-25。 修改稿收到日期: 2007-09-10。

基金项目: 国家“863”计划(2005AA332010)资助项目。

第一作者: 胡红梅(1962—), 女, 硕士, 教授。

Received date: 2007-06-25. Approved date: 2007-09-10.

First author: HU Hongmei (1962—), female, master, professor.

E-mail: hhm@xmu.edu.cn

concrete. In earlier stage research indicates, adopt optimum designs of multiple material composition and whole grain composition, that is dual mixing technique with the internal compound mixing of silica fume and Grade I fly ash, and the compound external mixing of high-efficiency water reducer and corrosion inhibitor, is the key technique of enhancing the corrosion resistance of concrete lining for underground tunnels. On this basis, further optimization design and experimental study to the corrosion resistance of concrete lining for underground tunnels are carried on.

1 Experimental procedure

1.1 Materials

The binding materials were “Jianfu”-brand grade 42.5 ordinary portland cement (P·O, specific surface area is $350\text{ m}^2/\text{kg}$), grade I fly ash from Xiamen Songyu Power Plant (FAI, specific surface area is $504\text{ m}^2/\text{kg}$), and silica fume produced by Chengdu Donglanxing (SF, specific surface area is $30\ 100\text{ m}^2/\text{kg}$). The chemical composition is given in Table 1. The aggregates were medium sand with a modulus of fineness $M_x=2.86$, and crushed granites of consecutive grades 5–25 mm. The high-efficiency water reducers included: (1) naphthalene-series water reducer: Point-500 slow-setting high-efficiency water reducer (powder), produced by Fujian Kezhijie Company; and(2)polycarboxylic acid-series high-efficiency water reducer: 8604-JSS polycarboxylic acid superplasticizer (liquid, solid content 20%), produced by Henan Gongyi Special Building Materials Plant. The corrosion inhibitors included: a) Point-AC enhancer for concrete resistance against chloride ion penetration, powder; b) reducing iron: iron content 98%; and c) D-glucose sodium salt: analytically-pure, white powder.

Table 1 Chemical component of cement and mineral admixtures

	w/%							
Binding materials	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	R ₂ O	IL
Cement	21.68	5.74	3.96	58.26	2.00	2.40	0.76	2.84
Fly ash	46.23	30.85	5.84	14.83	0	0.60		2.21
Silica fume	95.48	0.40	0.032	0.44	0.40	0.42	0.97	0.9

1.2 Testing methods

Concrete impermeability was tested with the hydraulic method specified in the GBJ82–85. Each group contained six samples. Pressure started from 0.2 MPa; after the pressure had been maintained for 8 h, the water pressure was increased by steps of 0.2 MPa and was gradually increased to 2.4 MPa. After the pressure had been maintained for 8 h, the machine was stopped. After the mould was removed, the samples were cut and the actual seepage height was measured, based on which the impermeability of the concrete lining for tunnels under

high-pressure and water-rich conditions was assessed.

The Unsteady-state Chloride Ion Migration Test Method (the RCM Method), recommended by the China Civil Engineering Society Standard (CCESO1–2004), was adopted for the test of the chloride ion penetration resistance of the concrete in order to measure the diffusion coefficient of the unsteady-state rapid migration of chloride ion in concrete samples which had undergone 28 d and 90 d standard curing and to conduct a quantitative assessment of the ability of the concrete to resist chloride ion diffusion.

The sulfate resistance of concrete was tested with a combination of methods in details.^[2–3] Test samples, sized $100\text{ mm}\times 100\text{ mm}\times 100\text{ mm}$, were made in mixing ratio shown in Table 2. Each group contained three samples. They were removed after 28 d of standard curing, and then immersed in 2% (in mass), MgSO₄ solution, natural seawater and freshwater; the immersion periods were 56 d and 180 d. Upon the expiration of these periods, the pressure resistance strength of the concrete samples with the same immersion period and the same mixing ratio in two corrosive solutions and clean water was measured, in order to find out their corrosion resistance coefficient. During the immersion period, the corrosive solution was replaced every 28 d.

Corrosion resistance coefficient $K=\sigma_1/\sigma_2$ (σ_1 is pressure resistance strength of concrete in corrosive solution; σ_2 is pressure resistance strength of concrete in clean water).

2 Optimum design of corrosion-resistant concrete

(1) Design objectives: To achieve high corrosion resistance and durability of more than 100 years while satisfying strength and workability requirements (concrete design strength level C50, mixing strength 59.87 MPa); Workability requirements: I. Site poured concrete lining: large mobility, low slump loss over elapsed time, pump incoming slump $T=(160\pm 60)\text{ mm}$, 2 h slump loss $\leq 50\text{ mm}$; II. Concrete lining for prefabricated duct pieces: slump $T=(30\text{--}50)\text{ mm}$. Durability requirements: Impermeability grade $\geq \text{P}20$; indicator of resistance against chloride ion penetration—chloride ion diffusion coefficient $D_{\text{RCM}} \leq 1\times 10^{-12}\text{ m}^2/\text{s}$; indicator of resistance against sulfate corrosion—corrosion resistance coefficient $K>0.80$.

(2) Trial mixing schemes: Two series of trial mixing schemes for two rounds of optimized selection have been designed.

Two series: Naphthalene-series water reducers (N series) and polycarboxylic acid-series water reducers (J series).

Two rounds of trial mixing: I) 1st-round trial mixing, the benchmark mixing ratio of binding materials, sand, stone, water determined in prior tests is 500:690:

1 050: m_w ; binding materials include cement, silica fume and fly ash. On the precondition of maintaining the total quantity of binding materials, sand and stone, the orthogonal test design [$L_9(3^4)$] method is used to investigate the impact of the four factors, including water to binder ratio, the amount of water reducer added, and the amount of fly ash added, and the amount of silica fume added, at different levels on the workability and mechanical property of the concrete. In the initial-round optimized selection, it was determined that the ratio of cement, silica fume, fly ash is 50:10:40, the water to

binder ratio is 0.33 and the appropriate amount of naphthalene-series and polycarboxylic acid-series water reducers added is 1.3% and 1.25%, respectively. II) 2nd-round trial mixing: on the basis of the first-round trial mixing and added the corrosion inhibitor, the second-round mixing scheme was drawn up (see Table 2) to investigate related corrosion resistance indicators, such as concrete impermeability, resistance against chloride ion penetration and sulfate resistance, in order to identify a mixing scheme for concrete with high corrosion resistance which satisfies the design objectives.

Table 2 Mixing ratio scheme for concrete corrosion resistance research

Group	Binding material /($\text{kg}\cdot\text{m}^{-3}$)			Mixing ratio/($\text{kg}\cdot\text{m}^{-3}$)			Water reducer	Corrosion inhibitor
	Cement	Silica fume	fly ash	Sand	Stone	Water		
S'_0	500	0	0	690	1 050	185	0	0
S_0	250	50	200	690	1 050	185	0	0
S_1	250	50	200	690	1 050	165	1.3%naphthalene-series	0
S_2	250	50	200	690	1 050	165	1.25%polycarboxylic acid-series	0
S_3	250	50	200	690	1 050	165	1.3%naphthalene-series	15%point-AC (inner add)
S_4	250	50	200	690	1 050	165	1.3%naphthalene-series	0.05%D-gluconate sodium
S_5	250	50	200	690	1 050	165	1.3%naphthalene-series	0.10%D-gluconate sodium
S_6	250	50	200	690	1 050	165	1.3%naphthalene-series	8%reducing iron powder
S_7	250	50	200	690	1 050	165	1.3%naphthalene-series	10%reducing iron powder
S_8	250	50	200	690	1 050	165	1.25%polycarboxylic acid-series	8%reducing iron powder
S_9	250	50	200	690	1 050	165	1.25%polycarboxylic acid-series	0.05%D-gluconate sodium

3 Concrete corrosion resistance

3.1 Impermeability analysis

The durability performances of all concrete is closely related to its impermeability and reflects the concrete compactness and internal porosity structure. Better impermeability means lower overall porosity, smaller most probable pore diameters, and smaller aperture connection, which make it more difficult for corrosive substances to penetrate. This results in higher corrosion resistance. Ten groups of impermeability test samples were made based on the mixing ratio designed according to Table 2 and subject to standard curing for 28 d; then, the impermeability of groups S_0 – S_9 was tested according to the modified hydraulic method. The testing results are shown in Fig.1.

Under effect of the 2.4 MPa hydraulic pressure, none of the 60 samples in the 10 groups were permeated by water, exhibiting much higher impermeability than ordinary concrete. Judging from the height of water seepage, after high-efficiency water reducer was added, polycarboxylic acid-series water reducers exhibited better water reduction and impermeability results. After the corrosion

inhibitor was added, the height of water seepage continued to drop while the impermeability performance continued to improve, showing that the corrosion inhibitor and water reducer have good compatibility, and indicating that the double compound technique of dually mixed silica fume and fly ash and dually mixed water reducer and corrosion inhibitor is feasible. The testing results of concrete impermeability suggest that the concrete has

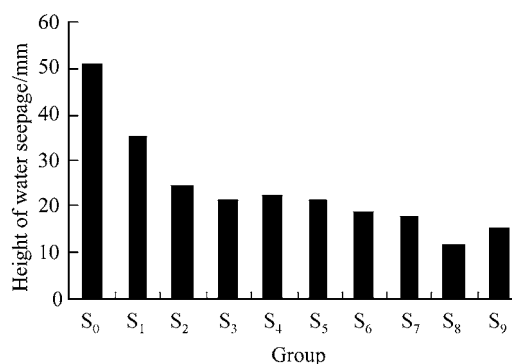


Fig.1 Testing results of concrete impermeability

high corrosion resistance.

3.2 Resistance against chloride ion penetration

Chloride salt abounds in groundwater and seawater. Table 3 shows the test results of chemical composition of the coastal sea water in the Xiamen. According to the data, Cl^- is the primary component in seawater, followed by SO_4^{2-} and Mg^{2+} . Chloride salt is an extremely powerful electrolyte, capable of seeping into the concrete through the pores in an ion state, which not only improves the solubility of calcium hydroxide and increases the “dissolving” corrosion of the concrete, but also facilitates freezing and thawing damage to the concrete and in some cases gives rise to crystalline corrosion. Nevertheless, the essential damaging effect of chloride salt is the corrosion of rebar wrapped in concrete, which has been generally recognized as the primary cause to the damage to the reinforced concrete structure.^[4] For this reason, concrete lining for underground tunnels must have high resistance against chloride ion penetration.

Table 3 Chemical composition of the coastal sea water in Xiamen g/L

SO_4^{2-}	Mg^{2+}	Cl^-	Ca^{2+}	Total salt amount
2.140	1.172	16.600	0.385	27.800

Note: The pH of sea water is 8.16.

The RCM method was adopted to measure the chloride ion diffusion coefficient D_{RCM} of concrete test samples in groups S_0' – S_9 , which had been placed under standard curing for 28 d and 90 d. Its assessment criteria were then used to assess the resistance of concrete against chloride ion penetration. The test results are shown in Table 4 and Fig.2.

Table 4 Test results of resistance against chloride ion penetration

Group	28 d		90 d	
	$D_{\text{RCM}} \times 10^{12} / (\text{m}^2 \cdot \text{s}^{-1})$	Assessment	$D_{\text{RCM}} \times 10^{12} / (\text{m}^2 \cdot \text{s}^{-1})$	Assessment
S_0'	7.65	Good	7.62	Good
S_0	1.35	Very good	1.05	Very good
S_1	0.95	Very good	0.74	Very good
S_2	1.02	Very good	0.70	Very good
S_3	0.38	Very good	0.18	Very good
S_4	1.04	Very good	0.41	Very good
S_5	0.82	Very good	0.28	Very good
S_6	0.51	Very good	0.14	Very good
S_7	0.41	Very good	0.24	Very good
S_8	0.57	Very good	0.30	Very good
S_9	0.80	Very good	0.34	Very good

The test results show that dually mixed silica fume and fly ash play a significant role in improving the resistance of concrete against chloride ion penetration, and

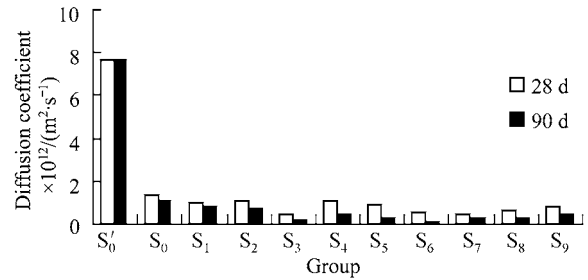


Fig.2 Diffusion coefficient of chloride ion of test samples in each group

that, the high-efficiency water reducer, which enhances the corrosion resistance of concrete as a result of water reduction, can produce even better corrosion resistance results after it is further mixed with the corrosion inhibitor. With the extension of the curing period, the diffusion coefficient of chloride ion exhibits a noticeable downward tendency, indicating it is important to strengthen on-site curing. With the exception of group S_0' , which was not mixed with any mineral admixture, in all concrete test samples in groups S_0' – S_9 , $D_{(\text{RCM}, 28)}$ is less than $2 \times 10^{-12} \text{ m}^2/\text{s}$ and $D_{(\text{RCM}, 90)}$ is less than $1 \times 10^{-12} \text{ m}^2/\text{s}$, indicating that the resistance against chloride ion penetration had reached the “very good” assessment criteria, suitable for the harsh underground environment and completely up to design target requirements. A comparison of corrosion results among the three kinds of corrosion inhibitors shows that iron powder and Point-AC are about the same and both are slightly superior to D-glucose sodium. The combined results of the corrosion inhibitor and water reducer indicates that there is little difference between the naphthalene series and polycarboxylic acid series, and that the corrosion inhibitor can be combined and mixed with any one of the water reducers.

Adding rebar corrosion inhibitor to concrete serves two purposes: on one hand, it allows more Cl^- to enter into the concrete and raises the “critical value” of rebar corrosion caused by Cl^- , thereby delaying the occurrence of rusting on the rebar; on the other hand, it slows down the development of rebar corrosion. Point-AC itself is a multi-functional additive comprising multiple organic and inorganic combined ingredients, including various ultra-fine mineral admixtures, high-efficiency water reducers, and nanometer ultra-fine organic fibers, and achieves high corrosion resistance results through the filling and compacting effects of various ultra-fine mineral powders and ultra-fine fibers and through water reducing and compactness enhancing effects of water reducers. As to the reducing iron powder in the chloride salt environment, Fe atoms scattered throughout the concrete and Cl^- that has diffused into the inside of the concrete react with Fe first, thus solidifying or holding part of the Cl^- which would otherwise possibly have reached the rebar surface. This delays the occurrence of rebar

rusting, thus reducing the risks of Cl^- reacting directly with electrochemical corrosion. The rust inhibiting effects of D-glucose sodium mainly take place through the adhesion of D-glucose acid radical to the rebar surface by competing with corrosive Cl^- , thereby forming a depositional membrane layer on the rebar surface, which strengthens the passivation effects, increasing resistance in the mass transfer process, and slows the development of rebar corrosion.^[5]

3.3 Resistance against sulfate corrosion

In addition to chloride salt, there are also considerable amounts of sulfates and magnesium salts in underground river water, seawater and the water between rock strata. Sulfate corrosion is a common type of corrosion in tunnel projects. Of all sulfates, magnesium sulfate causes the strongest corrosion, as both Mg^{2+} and SO_4^{2-} are sources

of corrosion and their superposition not only produce sulfate corrosion with expansive corrosion characteristics, but also causes magnesium corrosion with dissolving corrosion characteristics. For this reason, 2% (in mass) MgSO_4 water solution and Xiamen's natural seawater were used as corrosive solutions while clean water was taken as the reference solution, and concrete test samples that had been placed under standard curing for 28 d were immersed in the above three kinds of solutions for 56 d and 180 d, respectively. The strength of the test samples immersed in the solutions was measured at the end of the immersion periods, and the corrosion resistance coefficient K value was calculated. If $K > 0.8$, it means that the resistance against sulfate corrosion is conforming.^[2] The test results are shown in Table 5.

Table 5 Test results of sulfate resistance

Group	Immersion solution	Immersed for 56 d		Immersed for 180 d	
		Standard cubic strength/ MPa	Corrosion resistance coefficient K_{56}	Standard cubic strength/ MPa	Corrosion resistance coefficient K_{180}
S ₀ '	Clean water	50.6	1	63.2	1
	2%MgSO ₄ solution	50.1	0.99	60.9	0.96
	Natural seawater	48.2	0.95	57.4	0.91
S ₀	Clean water	51.3	1	66.3	1
	2%MgSO ₄ solution	51.0	0.99	63.6	0.96
	Natural seawater	49.6	0.97	64.5	0.97
S ₁	Clean water	67.3	1	80.9	1
	2%MgSO ₄ solution	68.7	1.02	72.3	0.89
	Natural seawater	64.9	0.96	82.1	1.01
S ₂	Clean water	62.0	1	71.6	1
	2%MgSO ₄ solution	61.4	0.99	69.9	0.98
	Natural seawater	59.7	0.96	72.8	1.02
S ₃	Clean water	38.8	1	54.9	1
	2%MgSO ₄ solution	42.8	1.10	45.1	0.82
	Natural seawater	39.1	1.01	50.4	0.92
S ₄	Clean water	57.0	1	66.9	1
	2%MgSO ₄ solution	57.1	1.00	53.5	0.81
	Natural seawater	62.1	1.09	69.8	1.04
S ₅	Clean water	62.9	1	73.6	1
	2%MgSO ₄ solution	76.0	1.21	74.9	1.02
	Natural seawater	57.8	0.92	61.7	0.83
S ₆	Clean water	69.0	1	70.1	1
	2%MgSO ₄ solution	59.2	0.86	74.8	1.07
	Natural seawater	80.9	1.17	77.3	1.10
S ₇	Clean water	60.8	1	74.2	1
	2%MgSO ₄ solution	70.0	1.15	66.2	0.89
	Natural seawater	71.2	1.17	72.3	0.97
S ₈	Clean water	68.1	1	73.1	1
	2%MgSO ₄ solution	68.9	1.01	70.4	0.96
	Natural seawater	59.3	0.87	64.4	0.88
S ₉	Clean water	62.4	1	63.4	1
	2%MgSO ₄ solution	50.6	0.81	73.1	1.15
	Natural seawater	60.8	0.97	66.6	1.05

After being immersed in the two kinds of solutions for 56 d and 180 d, respectively, all groups had a K value exceeding 0.8, and some were even larger than 1, indicating that the resistance against sulfate corrosion was up to standards. Judging from the absolute value of strength, only the 56 d and the 180 d concrete strength in Group S_3 failed to reach the level of Group S_0' while the strength of all other groups was higher than that of Group S_0' . Research also shows that the 56 d strengths of concrete test samples in all groups are basically on the same level, with the exception of groups S_5 and S_6 , where the differences are large, and that, the strength of some test samples subject to corrosion is even higher than that of samples immersed in clean water. Analysis indicates that this is attributable to the effective action of active mineral admixtures. Due to their pozzolanic effects and filling and compacting effects, free $\text{Ca}(\text{OH})_2$ and C_3AH_6 are consumed, the molar ratio of calcium to silica and the calcium to aluminum of the hydrated calcium silicate and hydrated calcium aluminate are reduced. More importantly, due to the extremely strong concrete impermeability, SO_4^{2-} and Mg^{2+} can hardly penetrate the concrete; even if a small amount has penetrated the concrete, due to the shortage or lack of $\text{Ca}(\text{OH})_2$ and C_3AH_6 , it is hard for form sufficiently damaging substances such as gypsum, ettringite, and magnesium hydrate to be formed. These primary intrusive substances or reaction products in limited quantities are not enough to do harm; instead, they may fill up the capillary pores in the concrete to make it more compact, which leads to the improvement of strength.^[6-9]

4 Conclusions

(1) Through the optimum design of the components of binding materials, additives and grain composition, the control and optimization of the composition and structure of cement hydrated products and interface transitional zone can be accomplished, thus providing a fundamental solution to the thorny issue of providing waterproofing and corrosion resistance of underground tunnel lining.

(2) Silica fume and high quality fly ash can remarkably improve the corrosion resistance of concrete. Naphthalene-series water reducers offer stable performance and moderate price, while polycarboxylic acid-series water reducers provide good slumping protection, and these two kinds of water reducers show no big differences in water reduction, strength and corrosion resistance. Reducing iron powder and D-glucose sodium have good compatibility with water reducers, and provide strength, rust inhibition, environmental protection effects and no toxicity. Reducing iron powder facilitates setting, suitable for

prefabricated duct piece lining, whereas D-glucose sodium slows setting, suitable for pump-delivered site-poured lining.

(3) Mixing ratio tests and research, the following optimized formulating scheme has been obtained: highly corrosion resistant tunnel concrete lining suitable for prefabricated duct piece or pump-delivery site pouring construction, with C50 grade, impermeability grade >20, chloride ion diffusion coefficient $D_{\text{RCM}} < 1 \times 10^{-12} \text{ m}^2/\text{s}$ and sulfate corrosion resistance coefficient $K > 0.80$, can be formulated by adopting Grade 42.5 ordinary cement, medium sand particles and 5–25 mm crushed stones and by internally mixing them with 5%–10% silica fume and 30%–40% fly ash and externally mixing them with naphthalene-series or polycarboxylic acid-series water reducers and reducing iron powder in a modest amount (8%) or D-glucose sodium corrosion inhibitor in a trace amount (0.05%).

References:

- [1] QU Liqing, LI Yuanyi, CHI Peiyun, et al. Study on the application technology of high performance concrete in Qingdao trans-oceanic bridge pile [J]. Concrete (in Chinese), 2006, 205(7): 10–13.
- [2] HAN Sufang, LU Laijun, HAN Xianfu et al. Research on green high-performance concrete [A] //Collection of Papers from the National Exchange Seminar on the Research and Engineering Application Techniques of High-performance Concrete and Mineral Admixtures [C] (in Chinese), Zhuhai, China, 2006: 1–19.
- [3] PU Xincheng. Super High Strength High Performance Concrete [M](in Chinese). Chongqing: Chongqing University Press, 2004: p134.
- [4] HU Hongmei, MA Baoguo. The influence of mineral function materials on chloride ion penetration of concrete [J]. J Wuhan Univ Technol Mater Sci, 2005, 20(1): 106–110.
- [5] ZHAO Bing, DU Ronggui, LIN Changjian et al. Electrochemical research on the rebar rust inhibiting effects of three organic corrosion inhibitors [A] //Collection of Papers from the 2005 Annual Conference of Xiamen Science and Technology Association and the 5th Academic Satellite Conference of Fujian Science and Technology Association [C] (in Chinese), Xiamen, China, 2005: 216–220
- [6] PANDEY S P, SHARAMA R L. The influence of mineral additives on the strength and porosity of OPC mortar [J]. Cem Concr Res, 2000, 30(1): 19–23.
- [7] KDUREKOVIC A. Cement pastes of low water to solid ratio: an investigation of the porosity characteristics under the influence of a superplasticizer and silica fume [J]. Cem Concr Res, 1995, 25(2): 365–375.
- [8] HU Hongmei, MA Baoguo. Binding capability of mineral function materials with chloride Ion [J]. J Build Mater (in Chinese), 2004, 7(4): 406–410
- [9] MOHAMMED TU, HAMADA H. Durability of concrete made with different water-reducing chemical admixtures in tidal environment [J]. ACI Mater J, 2003, 28(3): 194–202.