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Durability Design of Concrete Foundation in Acidic Soil

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Abstract: The durability design of concrete foundation in acid soil deserves much attention, which is closely related with the mix proportion of concrete. In this paper, mix proportion of acid resistant concrete is proposed for HengYi Power Plant located in Guangdong Province of China, considering its surrounding environment and choosing electric flux, anti-permeability grade, expansion rate and corrosion depth as indexes. 5 groups of acid resistant concrete specimens used in the foundation engineering of HengYi Power Plant are prepared according to the above mix proportion. Then electric flux, anti-permeability grade, expansion rate and corrosion depth of these specimens are measured through accelerated laboratory tests. It is concluded that concrete made according to the above mix proportion shows good performance in acid resistance. Based on the corrosion depth fitting formula for the specimen, the corrosion depth through the service period of 50 years is calculated approximately, and concrete cover thickness needed to insure the safety during the service life is recommended.

1. Introduction

Although concrete is a kind of durable materials, it has degradation problems. One of the main causes for deterioration in concrete structures is the corrosion of concrete due to its exposure to harmful chemicals that may be found in nature, such as in some ground waters, industrial effluents, acid rain, acid mist, and seawater (Shannang et al 2003). In recent ten years, durability of concrete is drawing more and more attention of the people, especially the durability of concrete constructions underground, such as concrete piles. Comparing with the over ground structure, concrete piles are perennial in the soil where they are difficult to be detected when corrosion occurs. Furthermore, it costs a lot of money when the piles underground need to be repaired and replaced. It has been estimated that repair and replacement of piling systems costs the U.S. over $1 billion annually (Lampo, 1996).

HengYi Power Plant is located in Guangdong Province of China. According to the geotechnical engineering survey report of the proposed new structure, aggressive media in the soil and underground water mainly include aggressive carbon dioxide, hydrogen ion, sulfate ion and chlorine ion. The minimum pH value is 2.26. The maximum sulfate ion content is 4440mg/L. This paper presents the durability design process of concrete component needed in foundation engineering for the proposed new structure at HengYi Power Plant, such as cast-in-situ piles (CSP) and tubular piles (TP).

2. Acid resistant concrete quality controlling indexes and evaluation methods

According to environmental characteristics, environment may be classified into severely corrosive environment (SCE) and medium corrosive environment (MCE). Severely corrosive environment: pH=2.0~4.0， SO_4^{2-} ＞4000mg/L. Moderately corrosive environment: pH=4.0~5.5， 1000mg/L＜ SO_4^{2-} ≤4000mg/L.

Compaction degree and chemical corrosion resistance are chosen as indexes reflecting durability of concrete in this project. Compaction degree is accessed by electric flux and anti-permeability grade. Specification about concrete compaction degree is summarized in Table 1.

Table1: Concrete compaction degree index value

Assessments type	Concrete in severely corrosive environment	Concrete in moderately corrosive environment
Electric flux 28d (Coulomb)	＜1000	＜800
Anti-permeability grade	≥P10	≥P12

Chemical corrosion resistance is accessed by expansion rate for sulphate corrosion and corrosion depth for acid corrosion. Specifications about concrete chemical corrosion resistance are summarized in Table 2.

Table2: Concrete chemical corrosion resistance index value

Chemical corrosion resistance index	Concrete in severely corrosive environment	Concrete in moderately corrosive environment
Expansion rate (%)	0.4~0.35	≤0.25
Corrosion depth 28d (mm)	≤0.5	≤0.3

3. Materials

3.1 Cement

Cement used in laboratory tests is P·Ⅱ52.5 made in china. Main performances of the cement are summarized in Table 3.

Table3: Main performance of the cement

Cement type	Folding strength (MPa)		Compression strength (MPa)		Normal consistency water (%)	Stability
	3d	28d	3d	28d		
P·Ⅱ 52.5	4.5	7.6	25.9	56.1	27.0	qualified

3.2 Fine aggregate

Natural river sands are adopted as fine aggregate. Main performances of the sands are summarized in Table 4.

Table4: Main performances of the sands

solidity	Apparent density (kg/m3)	Clay content (%)	Fineness modulus	Sand grading standard region
2%	1450	0.5	2.68	Ⅱ

3.3 Coarse aggregate

Coarse aggregate is made up of granite, quartz stone, dolerite, and feldspar. Main properties of the Coarse aggregate are summarized in Table 5 and Table 6.

Table5: Main properties of the coarse aggregate

Main components	solidity	Clay content	Water absorption	Flaky particle content
granite, quartz stone, feldspar	3%	0.5%	0.7%	4%

Table6: Sieve analysis coarse aggregate

Sieve size (mm)	Weight retained (g)	Cumulative weight retained (g)	Weight retained in (%)	Cumulative weight retained in (%)
25	0	0	0	0
20	1594	1594	32.2	32.2
16	1281	2875	26.0	58.2
10	1726	4601	34.9	93.1
5	296	4897	6.0	99.1
0	46	4943	0.9	100

3.4 Silica fume

Silica fume used in the test is manufactured by Norway Elkem company. Main properties of the Silica fume are summarized in Table 7.

Table7: Properties of silica fume

Items		Unit	Reference value	Measured value	Assessment
Chemical properties	Loss of ignition	%	≤6	1.6	Qualified
	Cl— content	%	≤0.02	0.01	Qualified
	SiO2 content	%	≥85	91	Qualified
	Activation index(28d)	%	≥85	121	Qualified
Physical properties	Specific surface area	m^2/kg	≥15000	18000	Qualified
	Moisture content	%	≤3.0	0.7	Qualified

3.5 Slag powder

Slag powder used in the test is manufactured by Shanghai Bao Tian New Building Materials Corporation in china. Main properties of the Slag powder are summarized in Table 8.

Table8: Main properties of the slag powder

Items		Unit	Reference value	Measured value	Assessment
density		g/cm3	≥2.8	2.9	Qualified
Specific surface area		m2/kg	≥350	420	Qualified
Activation index	7d	%	≥75	82	Qualified
	28d	%	≥95	101	Qualified
Fluidity ratio		%	≥90	95	Qualified
Moisture content		%	≤1.0	0.8	Qualified
SO3 content		%	≤4.0	3.8	Qualified
Cl— content		%	≤0.02	0.02	Qualified
Loss of ignition		%	≤3.0	2.8	Qualified

3.6 Water-reducer and water

Water-reducer used in the test is manufactured by Shanghai Tong Shu Corporation in china. Water used in the test is tap water.

Mix proportion of acid resistant concrete is proposed for the proposed new structure at HengYi Power Plant, considering its surrounding environment and choosing electric flux, anti-permeability grade, expansion rate and corrosion depth as indexes. Laboratory mix proportions of acid resistant concrete are summarized in Table 9. The properties of the materials listed in Table 9 are presented previously from Table 3 to Table 8.

Table9: Summary of laboratory mix proportions of acid resistant concrete (kg/m3)

Concrete type*	Cement	Silica fume	Slag powder	Aggregate		Water	Water-reducer
				Fine	Coarse		
C35(CSP / SCE)	300	30	120	769	1061	165	7
C35(CSP / MCE)	275	25	100	790	1090	160	7
C45(SCE)	310	40	150	680	1110	160	8
C45(MCE)	310	30	160	680	1110	160	8
C80(TP)	350	50	150	614	1306	130	9

*Attention: In the above table CSP means cast-in-situ piles, and TP means tubular piles. SCE means Severely Corrosive Environment, and MCE means Moderately Corrosive Environment. This attention applies to the following table as well.

4. Test methods and results

4.1 Anti-permeability

Anti-permeability is a long-term performance of concrete. Usually anti-permeability grade and water penetration height are measured to estimate anti-permeability of concrete when outer hydraulic pressure is applied. According to the mixture proportions in Table 9, the specimens in permeability test were molded into cylinders with 175 mm top diameter, 185 mm bottom diameter and 150mm length. The equipment used to measure the anti-permeability grade is illustrated in Figure 1.

Figure 1: Permeability test equipment HS-40X

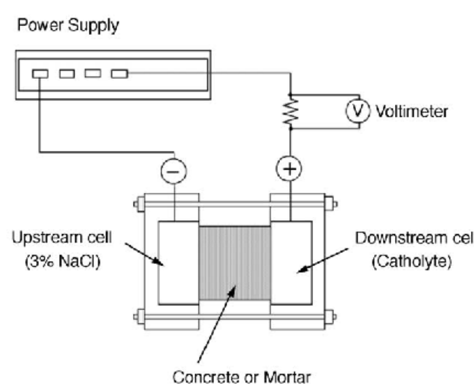

Figure 2: Schematics of the test configuration

The specimens were maintained until the day before the test started (Youzhi Wang et al, 2008). After the surfaces of the specimens were dried, a layer of paraffin was painted on the lateral face of the specimens. Then six specimens as a group were put into the permeability test equipment to perform the test as follow: initial water pressure was 0.1MPa. Then the water pressure increased 0.1MPa every 8 hours progressively. During this time, it is important to verify whether there is seepage appearing. Stop the test as soon as three of the six specimens appear seepage on the top surface or the number of specimens appearing seepage is not greater than 3 until the preset water pressure value is reached. At the same time, that water pressure H is recorded. Then Anti-permeability of concrete P can be calculated as Eq. 1.

[1] $$P = 10H - 1$$

The Anti-permeability of two groups of C35 concrete measured was P12 and P11 respectively. The other specimens did not appear seepage when the preset water pressure value 1.3 MPa was reached. Then the specimens were taken out from the anti-permeability equipment. After 24 hours the specimens were put on the universal material testing machine and splited vertically. The maximum permeated height was measured. The average permeated height of six specimens in one group was calculated. Detailed results are summarized in Table 10.

Table10: Concrete permeability test result

Concrete type	Anti-permeability grade	Average permeated height (mm)
C35(CSP / SCE)	P12	—
C35(CSP / MCE)	P11	—
C45(SCE)	≥P12	9.8
C45(MCE)	≥P12	11.9
C80(TP)	≥P12	7.6

It can be seen from Table 10 that C35 concrete meet the requirement about anti-permeability. Anti-permeability grades of C45 and C80 concrete are larger than P12. Obviously it is concluded that concrete made according to the above mix proportion listed in Table 9 shows good performance in compaction degree.

4.2 The electrical method for measurement of the diffusivity of concrete

The electric flux method is adopted according to Byung Hwan Oh (2004). Usually this test method covers laboratory evaluation of the electrical conductance of concrete specimens to provide a rapid indication of their resistance to chloride ion penetration. The cylinder concrete specimens with 100 mm diameter and 200mm length were cast according to the mixture proportions in Table 9, and were cured in 20℃ water. Before the test, a 50-mm-thick slice was taken from the center of the cylinder specimen, the lateral surface of which was sealed with acrylic sealant. After the sealant was dry, the slice was placed in between the diffusion cells for the test. The diffusion cells and the test configuration are illustrated in Figure 2 (Byung Hwan Oh, 2004) and 3[see also the rapid chloride penetration test of ASTM C 1202-97 (1997)].

(a) (b)

Figure 3: Test set-up for diffusion coefficient measurement

A potential difference of 60V DC was maintained across the ends of the specimen, one of which was immersed in a 3% sodium chloride solution, the other in a 0.3mol/L sodium hydroxide solution. The amount of electrical current passed through the specimen was monitored during a 6-hour period and the current was recorded every 30 minutes for the calculation of the total charge passed. The average amount of electrical current passed through the six specimens in one group was calculated. The rating criteria of chloride permeability of concrete are listed in Table 11. Detailed results of chloride ion penetrability based on charge passed are summarized in Table 12. The values of charge passed through the concrete samples made according to the above mix proportion listed in Table 9 are smaller than 1000. It indicated that chloride ion penetrability of the samples are very low.

Table11: Chloride ion penetrability based on charge passed (ASTM C 1202-05,1997)

Charge passed(Coulombs)	Chloride ion penetrability
>4000	High
2000~4000	Moderate
1000~2000	Low
100~1000	Very low
<100	Negligible

Table12: Test result of chloride permeability of concrete

Concrete type	Charge passed (Coulombs)	Chloride ion penetrability
C35(CSP / SCE)	791	Very low
C35(CSP / MCE)	897	Very low
C45(SCE)	769	Very low
C45(MCE)	787	Very low
C80(TP)	557	Very low

4.3 Sulfate corrosion test

Sulfates present in soils, groundwater, seawater, decaying organic matter, and industrial effluent surrounding a concrete structure pose a major threat to the long-term durability of the concrete exposed to these environments. Sulfate attack of concrete may lead to cracking, spalling, increased permeability, and strength loss (Paulo J.M. monteiro et al, 2003).

According to the mixture proportions in Table 9, 6 mortar bars with sizes of 25 mm×25mm×285 mm were prepared in the present investigation. At the same time, 9 mortar cubes with sizes of 70.7 mm×70.7mm×70.7 mm were prepared.

mortar bars and cubes were moved into 35±3℃ curing box. After curing 24 hours, the specimens were demould and then placed in the saturated solution of calcium hydroxide. The compression strength of mortar cubes with sizes of 70.7 mm×70.7mm×70.7 mm were measured. When the compressive strength reached 20MPa, 3 mortar bars and mortar cubes were immersed in 5% sodium sulfate solution, while the rest specimens were immersed in water. The temperature of solution and water was 23±2℃.

Initial lengths of mortar bars were measured at first. After being immersed in 5% sodium sulfate solution, the lengths of bars were measured every week at the first four weeks. Length change and expansion rate were calculated at the fifteenth week.

The results of the expansion test of mortar bars subject to 5% sodium sulfate solution are shown in Table 13. When the average expansion rate of the specimen is smaller than 0.4%, it means the resistance of sulfate attacks qualified according to Chinese standard named standard for test methods long-term performance and durability of ordinary concrete.

Table 13: Expansion rate of mortar bars in sulfate solution tested

Concrete type	Length change (mm)	Expansion rate (%)	Assessment
C35(CSP / SCE)	0.623	0.22	Qualified
C35(CSP / MCE)	0.817	0.29	Qualified
C45(SCE)	0.567	0.20	Qualified
C45(MCE)	0.619	0.22	Qualified
C80(TP)	0.538	0.19	Qualified

4.4 Acid corrosion test

According to the mixture proportions in Table 9, specimens with sizes of 100 mm×100mm×160 mm were prepared in the present investigation with 3 specimens per group. The cement paste and concrete specimens were left to harden for 7 days in water and then the specimens were immersed in a corrosive solution illustrated in Table 14. The corrosion depth was measured afterwards.

Table14: Corrosive fluid content

[H+]mol/L	pH value	[SO42-]mg/L	Temperature /℃
0.01	2.0	6000	20±1

The exposure tests were carried out in full immersion. In order to ensure the specimens to be fully immersed, the height of the water level should be 2cm higher than that of the specimen top surface and the interval of each specimen was more than 2cm. In addition, specimens were placed on the wood cushion blocks. The photograph of the cement paste and concrete specimens immersed into the acid solution in the laboratory is showed in Figure 4.

Figure 4: Immersion of concrete specimen in corrosive solution

Acid was added everyday to adjust the pH to approximate 2 after measuring the pH value of solution with acidity meter. All the test solutions were renewed every 5 days. Specimens were taken out from the solution at an appropriate immersion corrosion age. Loosened corrosion layer in the specimen side was grinded off with sandpaper. Corrosion depth can be evaluated by half of the sectional dimension difference between before and after corrosion through vernier caliper. There were 3 specimens in each group. 5 measuring points were arranged equidistantly for each specimen. Then the corrosion depth of the specimen is determined by averaging the 15 measurement values. Detailed results of corrosion depth of measurement for cement paste are summarized in Table 15 and that for concrete are summarized in Table 16.

Table15: The corrosion depth of cement paste

Cement paste specimens		immersion corrosion age (d)		
		21	35	49
Corrosion depth of measurement(mm)	C35(CSP / SCE)	0.17	—	—
	C35(CSP / MCE)	0.19	—	—
	C45(SCE)	0.17	0.25	0.28
	C45(MCE)	0.19	—	—
	C80(TP)	0.16	0.23	0.29
Corrosion depth of calculation by Eq.2 (SCE) (mm)		0.18	0.25	0.32

Table16: The corrosion depth of concrete

Concrete specimens		immersion corrosion age(d)		
		14	28	56
Corrosion depth of measurement(mm)	C45(SCE)	—	0.11	0.15
	C80(TP)	—	0.09	0.13
	C35(CSP / SCE)	0.10	0.12	—
	C35(CSP / MCE)	0.10	0.13	—
	C45(MCE)	0.10	0.12	—

It was found that the dependence of the depth of corroded cement paste upon the time of action of acid solutions can expressed by Eq. 2.

[2] $$d = a \cdot t^{b}$$

Where: d is the depth of corroded cement paste (mm), t is time of aggressive action of acid solution (days), a and b are constants related to cement paste. For the cement paste used in this test, constant a and b are 0.0198 and 0.7159 respectively. The correlation coefficient is greater than 0.97. Detailed results of corrosion depth of calculation by Eq.2 are listed in Table 14.

4.5 Corrosion depth prediction

According to the empirical formula Eq. 2 for cement paste corrosion depth prediction mentioned previously, the depth is predicted to be 22.2mm for 50 years (18250 days) in simulating severely corrosive environment as Eq. 3. The standard deviation of the results was calculated to be 10.0.

[3] $$h_{50\,years} = 0.0198 \times 18250^{0.7159} = 22.2mm$$

It was found that corrosion rate decrease along with the concrete age increasing. So the depth predicted through linear extrapolation method will be greater than the actual depth. It is thought to be safe when the depth predicted through linear extrapolation as design index.

The concrete corrosive depths predicted through linear extrapolation are listed in Table17 for 50 years (18250 days) in simulating severely corrosive environment. The standard deviation of the results was calculated to be 5.8.

Table17: Corrosion depth predicted for concrete

Concrete type	Prediction method $h_{50year} = h_{56\text{day}} + (h_{56\text{day}} - h_{28\text{day}}) \times \frac{(18250-56)}{56-28}$
C45(SCE)	26.1mm
C80(TP)	26.1 mm
Concrete type	Prediction method $h_{50year} = h_{28\text{day}} + (h_{28day} - h_{14\text{day}}) \times \frac{(18250-28)}{28-14}$
C35(CSP / SCE)	26.2 mm
C35(CSP / MCE)	39.1 mm
C45(MCE)	26.2 mm

It is known that the characteristic corrosion depth predicted is normally based upon a 5% quantile in the lower tail of the distribution function for resistance with 95% confidence. Detailed results of the characteristic corrosion depth predicted are listed in Table 18.

Table18: Characteristic corrosion depth predicted for cement paste and concrete

Items		Prediction of depth for 50 years	standard deviation	Depth at the 95% confidence level
Cement paste		22.2	10.0	22.2+1.645×10.0=38.65mm
Concrete type	C45(SCE)	26.1mm	5.8	26.1+1.645×5.8=35.64mm
	C80(TP)	26.1 mm	5.8	
	C35(CSP / SCE)	26.2 mm	5.8	26.2+1.645×5.8=35.74mm
	C35(CSP / MCE)	39.1 mm	5.8	39.1+1.645×5.8=48.64mm
	C45(MCE)	26.2 mm	5.8	26.2+1.645×5.8=35.74mm

According to Table17, after 50 years in simulating severely corrosive environment concrete corrosion depth is predicted to be 35mm approximately at the 95% confidence level. So corrosion allowance supposes to be 35mm. Generally the diameter of the lengthways reinforcing bars supposes to be 25mm and construction error supposes to be 10mm based on the most disadvantageous situation. The concrete cover thickness is calculated to be 70mm by accumulation the corrosion allowance 35mm, lengthways reinforcing bars 25mm and construction error 10mm.

5. Conclusions

According to environmental characteristics where the proposed new structure of HengYi Power Plant is located, indexes reflecting durability of concrete are proposed (listed in Table 1 and 2). Mix proportion of acid resistant concrete is proposed (listed in Table 9). Tests are conducted with specimens prepared according to the proposed mixture proportions. From the tests results presented in this paper, the following concluding remarks and recommendations can be drawn:

1.Anti-permeability test is carried out. From the results presented in Table 10, it is concluded that concrete made according to the mix proportion listed in Table 9 shows good performance in compaction degree.

2.Concrete electric flux is measured. As can be seen from Table 12, the values of charge passed through the concrete samples made according to the mix proportion listed in Table 9 are smaller than 1000. It indicates that chloride ion penetrability of the samples are very low.

3.Sulfate corrosion test is performed. The average expansion rate of the specimens presented in Table 16 is smaller than 0.4%. It means the resistance of sulfate attacks qualified according to Chinese standard.

4.Acid corrosion test is conducted as well. The corrosion depths of cement are measured at 21, 35 and 49 days respectively, while the corrosion depths of concrete are measured at 14, 28 and 56 days respectively. The corrosion depths of cement for 50 years are predicted to be 22.2 mm according to the empirical formula Eq.2, while The corrosion depths of concrete for 50 years are predicted to be 35mm approximately through linear extrapolation.

5.The concrete cover thickness in this project is recommended to be 70mm by accumulation the corrosion allowance 35mm, lengthways reinforcing bars 25mm and construction error 10mm. It is suggested that when calculating the bearing capacity of the concrete foundation, effective sectional area is thought to be original sectional area deducting the area formed by corrosion allowance 35mm.

References

ASTM C 1202-97. 1997. Standard test method for electrical indication of concrete ability to resist chloride ion penetration. *Annual book of ASTM standards*, V. 04.02.

ASTM C 1202-05. 1997. Standard test method for electrical indication of concrete’s ability to resist chloride ion penetration. *Annual book of ASTM standards*, V. 04.02.

Byung Hwan Oh, Seung Yup Jang. 2004. Prediction of diffusivity of concrete based on simple analytic equations. *Cement and concrete research*, 34:463-480.

Lampo, R. 1996. Federal interest gives recycled plastic lumber a leg up. *ASTM Standardization News*, 26-31.

Paulo J.M. monteiro, Kimberly E. Kurtis. 2003. Time to failure for concrete exposed to severe sulfate attack. *Cement and concrete research*, 33: 987-993.

Shannand, M.J. and Shaia, H.A. 2003. Sulfate resistance of high-performance concrete, *Cement and Concrete Composite*. 25: 363-370.

Youzhi Wang, Xiaowei Wen, Yuanyuan Sun. 2008. Experimental study on CFRP impermeability. 2008 international symposium on information science and engineering, *IEEE Conference Publications*, Shanghai, China, 1: 178-182.