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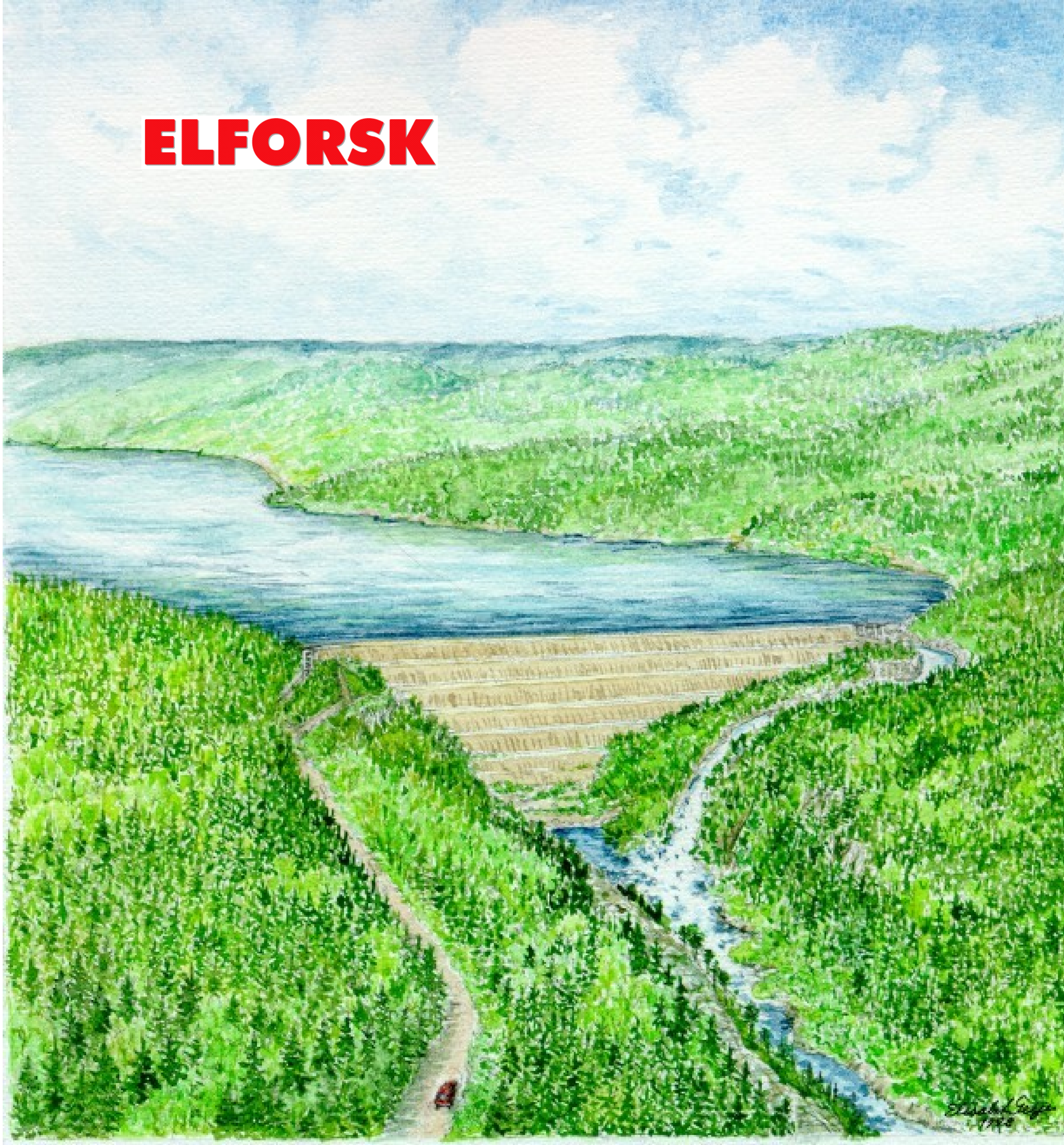

DAMMSÄKERHET

Non-dispersible underwater concrete and maintaining technology of erosion damage – Chinese experiences

Rapport 09:76

Non-dispersible underwater concrete and maintaining technology of erosion damage – Chinese experiences

Elforsk report 09:76

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Förord

Denna rapport är ett delresultat inom ”Elforsks ramprogram dammsäkerhet”. Målen för programmet är att långsiktigt stödja branschens policy, dvs att:

- Sannolikheten för dammbrott där människoliv kan vara hotade skall hållas på en så låg nivå att detta hot såvitt möjligt elimineras.
- Konsekvenserna i händelse av dammbrott skall genom god planering såvitt möjligt reduceras.
- Dammsäkerheten skall hållas på en god internationell nivå.

Prioriterade områden är teknisk säkerhet, operativ säkerhet och beredskap samt riskanalys.

Ramprogrammet Dammsäkerhet har en styrgrupp bestående av: Jonas Birkedahl – Fotum, Malte Cederström - Vattenfall Vattenkraft, Lars Hammar - Vattenfall Vattenkraft, Anders Isander – E.ON, Martin Johansson – Skellefteå Kraft, Gunnar Sjödin – Vattenregleringsföretagen, Rolf Steiner - Fortum samt Cristian Andersson – Elforsk. Adjungerade till gruppen är också Maria Bartsch och Olle Mill - Svenska Kraftnät.

Stockholm augusti 2009

Cristian Andersson

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Summary

In the past decades, the development of hydropower has been developing rapidly in China. The use of new concrete materials and construction methods are successful and experiences of construction accumulate.

This report includes two parts - non-dispersible underwater concrete and abrasion destruction repairing technology. In the first part, it discusses new material, mix design, characters of mixture and placing method of non-dispersible underwater concrete. In the second part, repairing technologies are introduced for abrasion damages of flood discharge structure. Several kinds of concrete used are discussed, such as low shrinkage silicon concrete, iron ore aggregate silicon concrete, diabase cast stone aggregate concrete, steel fibre silicon concrete, multiple gel material anti-scouring concrete, polyurea anti-scouring material, “sea island structure” epoxy anti-scouring material etc.). At the end of this report, good engineering examples are given to show the use of the methods.

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1 Non-Dispersible Underwater Concreting

The non-dispersible underwater concrete is the concrete which can be self-levelling, self-compacting and non-dispersible underwater.

There is a lot underwater placing concrete during the underwater engineering, but it is impossible to place the concrete by directly pouring the mixture of cement concrete because the concreting and shaping technology can't be performed when the mixture passes through the water level, the cement and aggregate will be separated, though there demands the double conduit method to reach underwater concrete pouring, embedding the conduits into the concrete and also guaranteeing the depth of the conduits. This method will cause the cement slurry loss and will let cement strength decrease when the cement's surface contacts the water. According to some literatures there will be 50% strength loss of surface concrete, so scavenging 15～45cm underwater low-strength surface concrete or 15cm extra concrete on each side is very necessary, but it will cause some waste.

These methods have been widely used for a long time, but there still exist problems like the low strength of the concrete's surface. Therefore Germany started to study on the properties of concrete to improve concrete quality in 1970s and applied it to the engineering in 1974. They gave the definition of non-dispersible underwater concrete (NDC for short). Japan introduced this advanced technology from West Germany in 1980 and applied it to the engineering in 1981. Britain and USA also gave research and application on this technology. China introduced this technology from Japan in 1985 and successfully developed the first underwater anti-washout flocculating agents UWB-1, and then developed anti-washout flocculating agents PN by the construction scientific department of Ministry of Communications. Nanjing Hydraulic Research Institute (NHRI) developed NNDC-2 type underwater anti-washout flocculating agents; China Institute of Water Resources and Hydropower Research (IWHR) developed NDC-IA type underwater anti-washout flocculating agents; Huadong scientific institute developed the NDC-A and NDC-B. There had been 20 years for the application of non-dispersible underwater concrete in China; it was widely used in bridge, wharf, port and hydraulic engineering.

Besides the non-dispersible underwater concrete, there are polymer underwater concretes like underwater polyester resin concrete and underwater epoxy concrete, which are generally used for reinforcement and strengthening of underwater concrete.

1.1 Non-dispersible underwater cement concrete

1.1.1 Non-dispersible underwater concrete raw material

Non-dispersible underwater concrete raw material mingled anti dispersion agent and coarse aggregate (Particle Size less than 20mm), others just like the normal concrete.

Cement

Non-dispersible underwater concrete chooses the normal Portland cement or early strength Portland cement, moderate heat Portland cement etc.

Aggregate

Fine aggregate should be the medium sand (fineness modulus between 2.4～3.0); coarse aggregate should be the first gradation and the biggest aggregate diameter is 20mm.

Anti dispersion agent

1. Classification of anti dispersion agent

   Anti dispersion agent includes polyacrylamide flocculants and cellulose types.

   The polyacrylamide flocculants are:

UWB-1, UWB-2	Engineering and Technology Academic Institution of PetroChina Company Ltd.
PN	Ministry of Communications
NDC-IA	Beijing KHL-IWHR Co. Ltd， of China Institute of Water Resources and Hydropower Research

   The cellulose type is:

NNDC-2	NHRI

2. Anti dispersion agent quality requirements

   Anti dispersion agent performance requirements:

- bleeding rate(%)		<0.5
- Air content(%)		<4.5
- slump(mm)	30s	230±20
	2min	230±20
slump loss	30min	<30mm

- collapse expand degree	30s	450±20	
	2min	450±20	
- anti-washout property	cement running off(%)		<1.5
	Suspension particles (mg/L)		<150
	pH		<12
- setting time(h)	initial setting	≥5	
	final setting	≤30	
- aqueous vapor (%)	7d	>60	
	28d	<70	

1.1.2 Mix Proportion of non-dispersible underwater concrete

1. It must mix with anti dispersion agent and aggregates with maximum diameter less than 20mm in the non-dispersible underwater concrete.

2. The cement dosage of non-dispersible underwater concrete is higher than that of regular concrete, normally above 350kg/m^3; sand ratio is 38%~42%.

3. The Fluidity of non-dispersible underwater concrete should use collapse expand degree or diffusion degree to express, but not slump. They choose the collapse expand degree depending on construction method; underwater slideway construction requires a collapse expand degree of 30~40cm, conduit construction 35~45cm and pump concrete between 45~55cm.

4. The water cement ratio should be chosen according to the requirement of strength and durability.

5. The design of mix proportion should use the compressive strength value of concrete moulded and cured under water. The results of strength tests are not suitable which will be done in normal environment and standard curing measure.

1.1.3 Performance

Performance of concrete mixture

1. Anti-washout property

The anti-washout property can be told by cement loss; suspension content and pH value, and sometimes use the transparency. The results of anti-washout property are shown in Table 1.1.From this table, we can tell the cement loss amount between 0.3%~0.7% when there mix with anti dispersion agent, and the other amount is 5.1% on the contrary.

Table 1.1 Anti-washout property.

Admixture	Water Cement ratio	Cement content (kg/m^3)	slump flow (cm)	Transparency (%)	Cement loss (%)	pH
/	0.51	418	46.0	24	5.1	/
wooden-calcium	0.41	465	44.5	5	4.2	11.8
NNDC-2	0.52	433	48.5	87	0.7	10.7
NNDC-2	0.52	433	45.0	91	0.3	/

2. Fluidity

Non-dispersible underwater concrete has good fluidity. Its normal slump is 23~26cm, and collapse expand degree between 48~60cm. But its slump will be reduced when the concrete has anti-dispersion and self-compacting (shown on Table 1.2).

Table 1.2 Non-dispersible underwater concrete by mixture NNDC-2 change of fluidity.

Time (min)	0	30	60	90	120
slump (cm)	21.5	21.0	18.0	15.0	16.0
CED (cm)	39.0	39.0	35.0	27.5	28.5
slump flow (cm)	47.5	44.0	34.5	34.0	32.2

3. Water retention

There has water retention ingredient in underwater anti-washout flocculating agents. It aims to improve the concrete's water retention performance. The bleeding rate is very small (shown on Table 1.3), and bleeding and laitance phenomenon rarely occur.

Table 1.3 Bleeding rate (%).

category	time(min)										
	0	20	45	66	87	110	140	170	200	230	260
regular	0	1.28	2.61	3.51	4.30	5.49	6.42	7.05	7.36	7.36	7.36
Non-dispersible underwater concrete	0	0	0	0	0	0	0	0	0	0	0

4. Setting time

Concrete setting time can be prolonged by mixing underwater anti-washout flocculating agents. The more the dosage is, the longer time is. The setting time normally can be prolonged to 5~15 hours by mixing anti dispersion agent of cellulose type.

Performance of hardened concrete

1. Compressive strength

Aqueous vapour strength ratio is compressive strength of non-dispersible underwater concrete specimen shaped in water to that of moulded in the air. Underwater anti-washout flocculating agent quality requirement is: 7d aqueous vapour strength ratio >60%, 28d aqueous vapour strength ratio >70%.

Test results are shown in Table 1.4. We can tell the 28d aqueous vapour strength ratio between 0.74~0.77.

Table 1.4 Aqueous vapor strength ratio

age	Concrete amount (kg/m^3)								
	436			501			550		
	water	air	strength ratio	water	air	strength ratio	water	air	strength ratio
7d	21.1	24.9	0.85	21.5	26.8	0.74	23.8	27.8	0.86
28d	26.7	35.3	0.75	34.9	46.9	0.74	39.1	50.3	0.77

Note: Compressive Strength unit is MPa.

The aqueous vapour strength ratios of non-dispersible underwater concrete and common concrete are shown on Table 1.5[2]. We can tell the 28d common concrete aqueous vapour strength ratio is 0.34, 28d NDC aqueous vapour strength ratio between 0.84~0.90, much higher than that of common concrete.

Table 1.5 28d aqueous vapour strength ratio of two concrete

Category	water	air	strength ratio
Common concrete	13.1	38.4	0.34
NDC	26.8	31.8	0.84
	34.0	37.8	0.90

Note: Compressive Strength unit is MPa.

The different curing temperature has different impact on the NDC compressive strength, shown in Table 1.6[1]. Concrete cured in water at 10℃ has a Compressive Strength accounting for 81%~93% of that at 20℃.

Table 1.6 the impact of different curing temperature on the NDC compressive strength

Curing condition	Age (d)			
	7	28	90	180
20°C water	22.8	30.7	35.5	39.5
10°C water	18.4	28.4	30.7	35.5
R_{10}/ R_{20}	0.81	0.93	0.88	0.90

Note: Compressive Strength unit is MPa.

2. Bond strength

The tensile bond strength of non-dispersible underwater concrete and common concrete underwater is shown in Table 1.7.

Table 1.7 Bond strength, splitting tensile strength and aqueous vapour strength ratio

Category	tensile bond strength (MPa)			splitting tensile strength (MPa)		
	water	air	strength ratio	water	air	strength ratio
Common concrete	0.6	2.2	0.27	0.8	2.8	0.28
NDC	1.7	2.1	0.81	3.0	3.4	0.88

3. Bonding stress between concrete and steel

The results of common concrete moulded under water and bonding strength between non-dispersible underwater concrete and steel were shown in Table 1.8[2].

Table 1.8 Results of bonding stress between concrete and steel

Category	water cement ratio	Cement (kg/m^3)	Compressive Strength (MPa)	bonding stress between concrete and steel (MPa)
Common concrete	0.55	400	36.4	1.82
NDC	0.55	400	33.8	6.91

4. Permeability

The test results of permeability of non-dispersible underwater concrete in water and air are shown in Table 1.9[1].

Table 1.9 Test results of permeability of non-dispersible underwater concrete mix with PN

<table>
<tr><th>Category</th><th>Forming</th><th>PN (%)</th><th>slump flow (cm)</th><th>Maximum water pressure (MPa)</th><th>average permeability (mm)</th><th>anti-permeability grade</th></tr>
<tr><td rowspan="2">NDC</td><td>Air</td><td rowspan="2">3.3</td><td>44 - 49</td><td>2.2</td><td>29</td><td>>W22</td></tr>
<tr><td>Water</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">NDC</td><td>Air</td><td rowspan="2">2.8</td><td rowspan="2">49 - 50</td><td rowspan="2">1.9</td><td>43</td><td>>W19</td></tr>
<tr><td>Water</td><td>14.5</td><td>>W19</td></tr>
<tr><td>Common concrete</td><td>air</td><td>/</td><td>45 - 48</td><td>2.2</td><td>76</td><td>>W22</td></tr>
</table>

1.1.4 Construction of non-dispersible underwater concrete

1. Anti-dispersion agent should be stored indoor and dries to prevent consolidation and spoilage; storing time should not be too long.

2. Concrete Mixing
   The non-dispersible underwater concrete is ropy. Basically we use forced action mixer; if we use gravity mixer, there will need more time or increase the target strength. Mixers of both types have strength influence on non-dispersible underwater concrete, which are shown in Table 1.10[1]. The concrete strength of gravity mixer is lower than that of forced action mixer.

Table 1.10 Different type impact to NDC strength

mixer	slump flow (cm)	Transparency (%)	7dCompressive Strength (MPa)		28dCompressive Strength (MPa)	
			air	water	air	water
Forced type	44.5	76	17.6	13.6	33.1	26.4
Gravity type	45.0	28	17.1	10.5	34.4	18.6

Normally, 2~3min is needed for forced action mixer and 3~6min for setting type.

3. Transportation
   Transportation of NDC could use truck mixer, pumping, hoist bucket, chute or wheelbarrow; it depends on the distance.

4. Concrete pouring
   Pouring NDC concrete normally uses conduit, pumping and bottom opening vessel. All these methods should guarantee that free falling distance of NDC in the water can't exceed 50cm, normally it between 30~50cm.
   Pouring NDC concrete should be in static water. The velocity is 0.3~0.5m/s, and loss on cement amount should be less. Measures like embedding conduit into concrete or useing steel plate on the concrete surface should be taken when the velocity above 0.5m/s.

5. Concrete curing
   After the pouring of NDC concrete, there need measures to prevent cement slurry loss resulting from dynamic water and wave flow.

1.2 Polymers Underwater Concrete

Polymer underwater concrete is also called resin concrete because it uses resin as the cementing material. Its study started at Japan, Germany and Soviet Union in 1950's. The polymer underwater concrete includes epoxy resin, unsaturated polyester resin, furan resin and urea-formaldehyde resin, etc. The unsaturated polyester resin has a much lower price and it is much easier to control its solidification time.

Polymer concrete is made up of organic binder (resin), filler, and coarse and fine aggregate etc., and sometimes also mixes short fiber, shrinkage reducing agent, coupling agent, flame retardant and antioxidant for improving the performance.

Regular concrete solidification thanks to the hydration of cement and water, while the polymer concrete’s cementing material basically is resin, so it needs appropriate curing agent or curing accelerator.

Fillers of Polymer concrete mixture aims to decrease resin to lower the cost, at same time to enhance the compressive strength, bond strength and abrasion resistance of polymer concrete as well as to increase thermal conductivity index and linear expansion index and reduce shrinkage ratio, etc. The filler normally is quartz powder, talcum powder, cement, etc.; its fineness normally should be about 200 meshes and is dry.

Polymer concrete’s aggregates can be river sand, gravel etc. Their Moisture Content should be lower than 0.5% and the maximum particle size less than 20mm.

Compared with normal concrete, the polymer concrete’s tensile strength, compressive strength, bending strength and bond strength are much higher. Its anti-scouring and anti-wearing, anti-freezing, anti-permeability durability is also much better than the regular.

There have two types of polymer underwater concrete: underwater epoxy resin concrete and polyester resin concrete.

Underwater epoxy resin concrete needs underwater curing agent for the solidification of epoxy resin, and polyester resin concrete needs modified polyester resin used as cementing material.

Both of these two polymer underwater concretes are used for reinforcement and strengthening of the underwater concrete.

1.2.1 963 Underwater Epoxy Concrete

The 963 Underwater epoxy resins were developed and produced by east china investigation and design institute of state power corporation. Concrete with this underwater epoxy resin is not dispersing in the water. It doesn’t need the conduit during the construction. It could be placed directly in the water and doesn’t need vibration. It could be self-levelling and self-compacting. Underwater epoxy resins concrete’s performance was shown in Table 1.11. Results of its 30d compressive strength, tensile strength, flexural strength and bond strength are 81.4MPa, 17.4MPa, 23.0MPa and 3.0MPa, respectively.

Each strength result is very high, but the disadvantage is that it can not rapidly solidify when the temperature is low.

Table 1.11 Performance of two types of underwater polymer concrete

Underwater concrete	Curing time	Low temperature adaptability (about 5°C)	compressive strength (MPa)		tensile strength (MPa)		flexural strength (MPa)		bond strength (MPa)	
			7d	30d	7d	30d	7d	30d	7d	30d
963 Underwater epoxy concrete	Hours	Couldn't rapidly curing	19.7	81.4	12.6	17.4	10.7	23.0	1.4	3.0
PBM concrete	Minutes	Could rapidly curing	47.6	78.3	6.3	8.3	15.1	20.2	2.2	2.9

1.2.2 Underwater polyester resin concrete (PBM)

Underwater polyester resin concrete is made up of modified polyester resin, accelerator, initiator, cement filler and sandstone aggregate, among which modified polyester resin was developed and produced by east china investigation and design institute. The underwater polyester resin concrete does not disperse in the water; it doesn't need the conduit during the construction. It could be placed directly in the water and doesn't need vibration; it could be self-levelling and self-compacting.

The performance of underwater polyester resin concrete and underwater epoxy concrete is shown in Table 1.11. Form this table we can tell the underwater polyester resin concrete's curing time is much shorter, and it can be curing in several minutes. Its low temperature resistance is good, and the 30d compressive strength, tensile strength, flexural strength and bond strength are 78.3MPa, 8.3MPa, 20.2MPa, 2.9MPa, respectively. But its 7d compressive strength, 7d and 30d tensile strength are lower than that of the underwater epoxy resins concrete. From the engineering viewpoint the various strength of underwater polyester resin concrete is enough, especially the cost is lower than the others, and its curing is much easier to control, so the reinforcement and strengthening working normally choose the underwater polyester resin concrete.

The main characteristic of polymer underwater concrete:

1. The underwater polyester concrete could rapidly cure under the water and the curing time could be adjusted from in several hours;

2. The non-dispersible concrete has no segregation and doesn't need the conduit for underwater placing;

3. It doesn't need vibrating and can be self-levelling and self-compacting;

4. Various kinds of strength are high, such as 30d compressive strength of 70MPa, tensile strength of 8MPa, flexural strength of 20MPa and bond strength of 2.5MPa.

5. It could be thin-layer pouring and repaired under the water.

1.2.3 Construction technology of polymer underwater concrete

1. Transportation of concrete
   Transport of polymer underwater concrete uses the hoister to send the buckets containing concrete to the appointed site that is 0.4m to the underwater lift surface.

2. Concrete placement
   when the buckets are 0.4m to the underwater lift surface, the diver opens the buckets to place the concrete and then flat it by hand or let it self-levelling.

3. Concrete curing
   after the placement, PBM concrete should be cured in static water for at least 1.5h, and underwater epoxy concrete for at least 2.5h.

2 Non-Dispersed Concrete - Engineering Examples

2.1 Underwater non-dispersed concrete construction at right bank of Three Gorges dock project

The right bank of Three Gorges dock is mainly used for the rolling transport of underground station generator and transformer of the right bank. This dock is a inclined funicular dock, and the incline length is 138.7m. Above the 66m height there is ordinarily concrete with a thickness of 28cm, and below the 66m height is underwater non-dispersed concrete with a thickness of 120cm and a total amount of 1600m^3.

The designed strength grade of underwater non-dispersed concrete is of C30, slump of 20~24cm, maximum aggregate diameter of 40mm and cement of 42.5 ordinary Portland cement.

(1). Mixture ratio of underwater non-dispersed concrete

The mixture ratio submitted by Construction unit is shown on Table 2.1. The 28d strengths of concrete moulded under water are 30.2, 31.9, 31.7 MPa, a little higher than the designed strength. This means that the strength is not favourable.

Table 2.1 The mixture ratio of underwater non-dispersed concrete

Ratio	Water cement ratio	cement type	Sand ratio (%)	UWB-II mixing amount (%)	Material dosage, kg/m^3					
					Cement	Water	Sand	Gravel stone	Medium stone	UWB-II
Design	0.43	ordinary portland cement 42.5	40	2.5	472	203	654	589	392	11.8
Construction	0.40	Medium heat	40	2.5	510	204	672	576	384	12.75

Note: the particle size of gravel stone is 5~20mm, and medium stone is 20~40mm.

We decided to drop the water cement ratio to 0.40 and increase the cement amount to 510 kg/m^3. We moulded the underwater concrete specimen in

March 2006 and cured them in the Yangtze river. The 7d compressive strength is 29.6MPa and the 28d compressive strength is 37.0MPa; both of them can meet the design requirement.

(2). Construction

Mixing: We used 42.5 ordinary Portland cement and small mixer during the mix proportion design stage, but in the field construction small mixer can not meet the placement intensity requirement, so it was decided to produce concrete in the 84 mixer system. However, there only had 42.5 medium heat cement in this system but no 42.5 ordinary Portland cement. Therefore, during the construction we actually adopted 42.5 medium heat cement as long as the medium heat cement and UMB-ant segregating agent were compatible with each other.

Transportation: we used the concrete truck mixer to send the concrete to the hopper of concrete pump, and then pump it to the placement spot.

Placement: we used the pump pressure to send concrete, and the conduit outlet was buried in the concrete. When we used the normal concrete conduit method, the construction quality can be well guaranteed and aqueous vapour ratio of compressive strength was rather large, making the strength loss small.

(3). On-site sampling inspection of concrete strength

The compressive strength specimen were sampled on site and moulded underwater, and then cured in curing room and the Yangtze River, respectively. Test results of ompressive strength are shown in Table 2.2. From this table we can tell the 28d compressive strength varying between 35.0 and 55.2MPa, meeting the design requirements.

Table 2.2 On-site sampling inspection of concrete intensity

Date	sampling unit	28d compressive strength, (MPa)	Note
2006.4.25	supervision unit	38.1	In curing room
2006.4.25	supervision unit	41.2	In Yangtze river
2006.4.25	supervision unit	55.2	In curing room
2006.4.28	supervision unit	42.4	In Yangtze river
2006.4.28	supervision unit	54.7	In curing room
2006.4.30	supervision unit	42.2	In curing room
2006.4.30	construction unit	35.0	In curing room

2006.4.30	construction unit	35.3	In curing room

2.2 Treatment on the scouring pool at Plunge pool of Manwan hydropower plant

Manwan hydropower plant is located at the middle of lancang river, Yunnan Province. The dam is a concrete gravity dam with a maximum height of 132m. The dam uses the powerhouse overflow type to make the overflow part and powerhouse part be together because the riverbed is rather narrow. Because the Manwan reservoir capacity is small, the reservoir does not have the regulating ability. It is a runoff hydroelectric station which needs to flow discharge frequently except dry season.

The spillway uses front plant trajectory energy dissipation, the scour pool location is near the powerhouse and the riverbed anti-rush ability is low. Because Manwanhydropower plant has the characteristics of frequent flow discharge, large flow, long flow duration and huge flood discharge, we set the plunge pool to protect the riverbed. The plunge pool is 140m long and 120m wide with a bottom plate of 3m thick, which is covered by C40 abrasion resistance concrete with a thickness of 0.50m.

2.3 Abrasion situation of plunge pool and cause analysis

In June 1993, Manwan's first generator unit started to operate. In December 2000, we found in the inspection that the abrasion area was 2000m^2 and the depth was from 20 cm to 30cm and even from 70cm to 110cm of the worse part. The reasons are listed as follows:

1. There had a large number of rocks, logs and steel bars in the plunge pool; reflux made the stuff hit and abrade the bottom plate.
2. The operation mode of flow discharge was not in accordance with the regulations, which made the downstream water depth lower and let the water jets abrade the bottom plate directly.
3. On the bottom plate surface, the C40 concrete with a thickness of 50cm had a low strength and no silica fume was used in the concrete, which brought about its poor abrasion resistance.
4. The hydropower plant is of runoff flow type and the reservoir doesn't have the ability to regulate its capacity, which results in the frequent flow discharge. Frequent flow discharge and wasted items in the

plunge pool abrade the bottom plate, causing fatigue failure of bottom plate concrete.

It is difficult to repair the plunge pool underwater because abrasion area is big. Also we can't repair the pool with the generators stopped for 24 hours. Therefore, the pool has been repaired for several times, and the reparation in 2003 are as follows:

We did the comprehensive underwater check in Nov. 2002, just before the seasonal flood in 2003, and found that the abrasion of the bottom plate was much worse. It already formed a big area scour pool and gully with a depth of 10~80cm, uncovering the buried steel.

We took the reinforcement processing to the three big scour pools before the seasonal flood in 2003; Qingdao Pacific engineering company took charge of the underwater construction. The construction was as follows:

1. The cleaning of underwater parts needing reinforcement.
   We cleaned the gravels and logs in the three scour pools and used the high-pressure water jet to flush the base surface before concrete placement.

2. Cutting and chisel work.
   We did the underwater cutting and chisel work to the position with a abrasion depth less than 10cm to guarantee that the reparation concrete at the margin of the scour pool had a thickness more than 10cm.

3. The layout of anchor bar.
   The anchor bar was ϕ25 rebar, the boring depth was 50cm and the aperture was 42mm; anchor agent was PBM-3 resin cement mortar.

4. Underwater layout of anti-crack steel meshwork
   Anti-crack steel meshwork was welded on the ground and laid under water; the steel bar was ϕ12 rebar and the spacing was 30cm; each meshwork was 2.5×1.3m and the overlap width of adjacent meshwork was 20~30cm.

5. The underwater repair material.
   The mix proportion (kg/0.25m^3) of underwater polyester resin concrete is shown in the table below (Table 2.3).

Table 2.3 Mix proportion (kg/0.25m^3) of underwater polyester resin concrete

cement	coarse aggregate	Medium sand	PBM-3A	PBM-3B	accelerator	initiator

60	221	232	76	7.6	665ml	509ml

The cement was 52.5R ordinary Portland cement, the sand was the medium sand and the maximum particle size of coarse aggregate was 25mm. The mix proportion (kg/0.25m^3) of underwater non-dispersed concrete (NDC) is shown in the table below (Table 2.4).

Table 2.4 Mix proportion (kg/0.25m^3) of underwater non-dispersed concrete

cement	water	silicon powder	Medium sand	coarse aggregate	UWB	adjustable solidification agent
150	47	5	140	215	4.13	0.50

The variety of cement, sand and coarse aggregate were as same as that of PBM concrete.

6. The environment of underwater work and construction time limit.
   The underwater construction was during the time when the hydro plant was switched off. The depth of water was 16m, the temperature of water was about 12°C and the weather temperature was about 15°C. The construction was from 9 Jan, 2003 to 8 April, about 90 days in total and about 64 days for the underwater work.

7. The underwater reparation area.
   There have three big area scour pools need to repair.

   No.1 scour pool: about 33m in length, 5m in width and an area about 165m^2; the deepest part of this scour was 70cm.

   No.2 scour pool: about 18m in length, 2.6~3.5m in width and an area about 60m^2.

   No.3 scour pool: about 15m in length, 16m in width and an area about 250m^2.

   The No.1 and No.2 scour pool were repaired with the use of underwater polyester resin concrete and the project quantity was 111.5m^3; the No.3 scour pool was repaired with the use of underwater non-dispersion concrete for reinforcement and strengthening and its project quantity was 168.5m^3.

8. Underwater concrete construction
   the concrete mixer used two forced action mixers whose capacity was

350L and the power was 5.5kw. The PBM concrete used the air drying coarse and fine aggregate. We set the PBM resin to A and B units and adjusted the ratio 3~4 hours before placement, and then put the PBM resin and coarse and fine aggregates together to mix with each other for about 3 minutes. Then the mixture was put into the bucket whose capacity was $0.5m^3$. Following the hoister we sent it to the appointed placement spot. The diver opened the bucket outlet when the bucket outlet was about 40cm away from the lift surface. Then the diver flattened the concrete. Because the PBM concrete had excellent self-levelling and non-dispersion underwater properties, it didn't even need the diver flatten the concrete by hands. It took 6~9 minutes for each bucket of mixture to be processed from mixing to being flattened.

The mixing, transportation and underwater placement of underwater non-dispersion concrete (NDC) was as same as that of PBM concrete. But the self-levelling and non-dispersion characteristic of PBM concrete was better than that of the NDC, so the NDC concrete needed the diver flatten homogeneous and filled the whole scour pool gradually.

The PBM curing time was not less than 1.5 hours after the placement and the NDC curing time was not less than 2.5 hours, also put the steel plate on the surface to prevent the erosion of the concrete surface.

With the help of the diver and the underwater video, we found the PBM concrete and the NDC concrete surface was very uniform. There was no leakage and crack, also the placement surface was little higher than the peripheral concrete.

9. The on site spot-checking results of concrete intensity
   We extracted 15 group specimen of compressive strength on site; six of them were PBM specimen and nine of them were NDC specimen. The PBM concrete 83d~90d compressive strength between 57.8 and 75.0MPa , the NDC concrete 54d~65d compressive strength between 47.1 and 64.1MPa , both of them were meet the C40 scale requirement, 28d was 40MPa.

3 Repairing Concrete Erosion of Flood Discharge Structures

3.1 Introduction

Hydraulic flood discharging structures include spillway dam, flood spillway, discharge tunnel, sediment tunnel, diversion tunnel, bottom diversion outlet and sediment flushing outlet, etc. Concrete surface of these structures are very susceptible to erosion. This report concerns two kinds of erosion, abrasion erosion and cavitations erosion. The former can be flushing abrasion resulting from suspended load (silt and sand) carried by high-velocity flow, or impact abrasion caused by waterborne bed load, rock, pebble, etc.

Abrasion erosion and cavitation erosion are attributed to different mechanisms. The abrasion erosion damage results from the mechanical abrasive effects of high-velocity water-carrying silt, sand, gravel and rocks flushing over a concrete surface. The suspended load carried by high-velocity flow has such effects as abrasion, cutting and impinging on overflow concrete surface, and the rate of erosion is dependent on a number of factors including the velocity of the water, flow shape, anti-abrasion strength of the concrete, as well as the quantity, size, shape and hardness of particles being transported. The movement of waterborne bed load is in the form of gliding, rolling and flopping, causing sliding friction and impact on the overflow concrete surfaces; the rate of erosion is related to the velocity and shape of the flow, the quantity, size and movement manners of the bed load, the anti-abrasion strength of the concrete, as well as the period of overflow, etc.

Cavitation erosion caused by high-velocity flow is a very complicated process. Generally, the high-velocity water flowing on the structural parts with shape changes or irregular surfaces can trigger the formation of vortices and offsets in flow boundaries, resulting in local pressure drops. The cavities form where the local pressure drops to a value that will cause the water to vaporize at the prevailing fluid temperature, which can cause the interruption of water flow continuity. Once the cavities carried by water flow reach high-pressure areas, they will collapse immediately under the compression of surrounding water body, and then produce large instantaneous impact forces. If the local stresses caused by impact forces exceed the cohesion forces of concrete, the scaling deterioration (that is, cavitation damage) will occur on concrete overflowing section. Cavitation damages have great adverse effect on hydraulic structures. Cavitation is not bound to happen, however, the abrasion erosion of overflowing surfaces resulting from high-velocity flow is inevitable. If the overflowing surface shape can be optimized, or the smoothness of the surfaces can be ensured, or anti-cavitation materials can be adopted in the construction, the cavitation erosion should be avoided.

Both abrasion erosion and cavitation erosion can occur to field structures. The concrete surface irregularities due to abrasion erosion can often be the origin of cavitation erosion.

There are various kinds of repairing materials, on which researches are carried out to increase such properties of concrete as abrasion resistance, impact resistance, cavitation resistance, anti-cracking property and frost resistance. Eight kinds of abrasion-resistant materials are introduced as follows.

Low-shrinkage silica fume concrete;

Silica fume concrete made with iron ore aggregates;

Concrete made with dolerite cast stone;

Steel fiber-reinforced high-strength concrete;

Steel fiber-reinforced silica fume concrete;

Anti-abrasion concrete with multi-component cementitious power;

Anti-abrasion polyurea materials;

Anti-abrasion materials with "sea island structure" epoxy alloy.

3.2 Repairing materials for abrasion erosion

3.2.1 Low-shrinkage silica fume concrete

High-strength silica fume concrete is usually employed as anti-abrasion materials thanks to its excellent abrasion resistance. However, the fact that silica fume concrete usually has large shrinkage can easily result in cracking. Thus measures should be taken to lower the shrinkage of silica fume concrete, and consequently reduce cracking and improve abrasion resistance.

Silica fume concrete has much larger dry shrinkage and autogeneous shrinkage than ordinary concrete, which is one of the reasons for the extremely high possibility of its cracking. Large shrinkage is not particular to silica fume concrete, but a common fault of high-strength concrete with low w/c ratio. Abrasion-resistant silica fume concrete generally has a w/c ratio lower than 0.35, which can obviously increase the concrete autogenenous shrinkage due to such little water dosage. Dry shrinkage attributes to the surface evaporation of water inside concrete. The capillary water losses on surface layer can cause the formation of surface tension, which can bring about tensile forces on capillary pore walls, and consequently resulting in the macroscopic shrinkage of concrete. Autogeneous concrete shrinkage ascribes to the surface tension resulting from the rapid hydration of cementitious materials and the subsequent capillary water losses of concrete. The low w/c ratio of high-strength concrete makes it possible for hydration products to block the passages of capillary pores during early hydration period, impede the curing water transport from outside to inside, and consequently cause the capillary water losses and autogeneous shrinkage.

Measures to lower shrinkage of high-strength silica fume concrete

The mechanisms of both dry shrinkage and autogeneous shrinkage of high-strength silica fume concrete fall on the surface tension of concrete capillary pores, and thus measures that can reduce the surface tension of capillary pore solutions are helpful to lower shrinkages. The addition of shrinkage-reducing agent is one of these measures, which can play two roles. Firstly, it can reduce the surface tension of concrete capillary pores, so as to lower the dry shrinkage and autogeneous shrinkage; on the other hand, it can give rise to volume expansion under the condition of water losses, compensating part of the shrinkage.

Shrinkage-reducing agent of KH-21 type, an independently developed product, was employed in the research. It has a main organic component of polyalcohol ether type that is easy to dissolve in water.

The test results showed that, mortar with 2% KH-21 shrinkage-reducing agent had a 90d dry shrinkage lower than reference mortar by 40%. This indicated that shrinkage-reducing agent can obviously lower the dry shrinkage of cement mortar and concrete.

Properties of high-strength silica fume concrete with shrinkage-reducing agent

The concrete mixing proportion used in the study was: cementitious materials—280kg/m^3, silica fume dosage—5%, water—105 kg/m^3, KH-21 shrinkage-reducing agent—2%, superplasticizer—0.8%. Aggregate with a maximum particle size of 40mm was used in the concrete, and the slump of the concrete was designed to be 6-8cm. The test results of concrete with and without (control concrete) shrinkage-reducing agent were as follows.

(1) Dry shrinkage

Test results of dry shrinkage were listed in Table 3.1. It can be concluded that the dry shrinkage of concrete with shrinkage-reducing agent was much lower than that of control concrete, and shrinkage-reducing agent with a dosage of 2% can reduce the dry shrinkage by more than 40%.

Table 3.1 Dry shrinkage and autogenous volume deformation of high-strength silica fume concrete with shrinkage-reducing agent

Test items	Concrete type	Duration (d)										
		1	3	5	7	15	28	60	90	120	150	180
Dry shrinkage (10^{-6})	Control concrete	9	34	50	76	106	126	154	166	182	196	213
	Concrete with shrinkage reducing agent	5	17	29	48	78	80	100	110	120	128	140
Autogenous volume deformation (10^{-6})	Control concrete	-18	-14	-16	-19	-22	-25	-24	-23	-24	-24	-25
	Concrete with shrinkage reducing agent	-5	7	10	10	10	12	18	19	22	21	22

(2) Autogenous volume deformation

Autogenous volume deformation is defined as a concrete volume change resulting from the hydration of cementitious materials under the condition of constant temperature and no moisture transfer to the environment. It is usually a shrinkage deformation. The autogenous volume deformation of concrete with 2% shrinkage-reducing agent and control concrete are also listed in Table 3.1. The results show that the autogenous volume deformation of control concrete is shrinkage, with a 180d shrinkage of 25×10-6, while the autogenous volume deformation of concrete with 2% shrinkage-reducing agent was expansion deformation, with an 180d expansion deformation of 22×10^{-6}. Therefore, the employment of 2% shrinkage-reducing agent can not only reduce the dry shrinkage of concrete, but also transform the autogenous volume deformation from shrinkage type to expansion type, which is greatly favourable for concrete anti-cracking performance.

(3) Concrete mechanical properties

Test results of mechanical properties such as compressive strength, axial tensile strength and compressive elastic modulus are listed in Table 3.2. It can be seen from the table that the concrete with shrinkage-reducing agent has an almost same compressive strength with control concrete, which shows that the shrinkage-reducing agent has a very small effect on compressive strength. At the same time, the concrete with 2% shrinkage-reducing agent has a lower axial tensile strength than and approximately the same compressive elastic modulus with control concrete.

Table 3.2 Test results of mechanical and deformation properties of high-strength silica fume concrete with shrinkage-reducing agent

Concrete type	Compressive strength (MPa)			Axial tensile strength (MPa)			Compressive elastic modulus (Gpa)			Ultimate tension (10^{-6})		
	7d	28d	90d	7d	28d	90d	7d	28d	90d	7d	28d	90d
Control concrete	52.3	62.4	71.6	4.34	4.58	4.72	43.1	46.0	48.9	112	106	107
Concrete with 2% shrinkage reducing agent	53.6	66.2	70.5	3.95	3.92	4.13	41.9	44.7	49.7	107	97	97

Note: The concrete has a w/c of 0.29, cementitious material of 360 kg/m^3 and a silica fume dosage of 5%.

(4) Ultimate tension deformation

The test results of ultimate tension deformation are listed in Table 3.2. The results demonstrate that the ultimate tension deformation of concrete with 2% shrinkage-reducing agent is lower than that of control concrete.

Anti-cracking performance of silica fume concrete with shrinkage-reducing agent

The shrinkage-reducing agent is so employed to reduce the concrete dry shrinkage, self-shrinkage and autogeous volumetric shrinkage deformation. It can be concluded from the above test results that, the use of shrinkage-reducing agent can reduce the concrete dry shrinkage by more than 40% and transform the autogenous volume deformation from shrinkage type to expansion type. Although concrete with 2% shrinkage-reducing agent has lower tensile strength and ultimate tension deformation, the shrinkage-reducing agent can obviously reduce concrete shrinkage. Therefore, its use in concrete can greatly improve the anti-cracking performance of concrete.

3.2.2 Silica fume concrete with ironstone aggregate

Concrete is a multi-phase material composed of cementitous materials, water, aggregates, mineral admixtures as well as chemical admixtures. There are two main properties determining its anti-cracking performance; one is the anti-cracking performance of component materials themselves, and the other is the binding strength between component materials. The latter property can be characterized by concrete strength, while the former can be improved by employing hard aggregate thanks to the fact that aggregates can account for about 70% in mass of all the concrete component materials. Ironstone, as a material with hard texture, high density and excellent anti-abrasion property, can be used in concrete to improve its anti-abrasion performance.

Properties of ironstone aggregate

The main chemical components of ironstone are ferric oxide (Fe_2O_3, 69.53%) and silicon dioxide (SiO_2, 24.59%). Test results of its physical properties are listed in Table 3.3.

Table 3.3 Test results of ironstone aggregate properties

Aggregate type	Modulus of fineness	Specific gravity on S.S.D basis (kg/m^3)	Water absorption ratio on S.S.D basis (%)	Consolidating coefficient (%)	Crushing index (%)
Ironstone coarse aggregate	-	4070	1.00	-	7.2
River pebble aggregate	-	2800	1.30	-	9.9
Ironstone fine aggregate	3.97	4180	1.52	6.5	-
River sand	2.84	2680	2.04	12.9	-

It can be seen from Table 3.3 that:

(1) The specific gravity on S.S.D basis of ironstone aggregate is higher than that of common aggregates (natural aggregates) by 40%;

(2) The water absorption ratio on S.S.S basis of ironstone aggregate is lower than that of common aggregates by 25% or so, which demonstrates that ironstone aggregate has a favourable density;

(3) Both of the crushing index and consolidating coefficient of ironstone are lower than that of common aggregates. Therefore, it can be concluded that ironstone has the properties of high specific gravity on S.S.D basis, low water absorption ratio on S.S.D basis and small crushing index, which are helpful to improve concrete density, strength and anti-abrasion performance.

Properties of ironstone silica fume concrete

Ironstone coarse and fine aggregates are used to mix silica fume concrete that has a w/c ratio of 0.28, a cement amount of 482kg/m^3, a silica fume replacement ratio of 10% and a sand ratio of 42%. Also, ironstone fine aggregate and river pebble coarse aggregate are used in concrete with the same mixing proportion parameters. The maximum aggregate size of both concrete is 20mm. The test results are shown in Table 3.4.

Table 3.4 Mixing proportions of ironstone silica fume concrete

Mixing proportion No.	w/c	cement (kg/m^3)	Silica fume (%)	Admixture (%)	Sand ratio (%)	Aggregate		Maximum aggregate size (mm)
						Fine	Coarse	
GH	0.28	482	10	1.3	42	Ironstone	River pebble	20
A	0.28	482	10	1.3	42	Ironstone	Ironstone	20

Test results for 28d compressive strength, elastic modulus, bonding strength, anti-abrasion strength and frost resistance of ironstone silica fume concrete are listed in Table 3.5.

Table 3.5 Test results of ironstone silica fume concrete properties

Mixing proportion No.	Compressive strength (MPa)	Elastic modulus (GPa)	Bonding strength (MPa)	Anti-abrasion strength h/(kg/m^2)	Frost resistance grade	Note
GH	74.0	43.0	2.50	0.31/100	>F400	Ironstone sand and river pebble coarse aggregate
A	90.5	52.0	2.65	0.83/267	>F400	Ironstone fine and coarse aggregate

Note: The test age is 28d.

It can be concluded from Table 3.5 that:
The compressive strength of ironstone silica fume concrete can be 90.5MPa.

The ironstone silica fume concrete has a very high elastic modulus that reaches 52.0GPa.

The bonding strength of ironstone silica fume concrete can be 2.65MPa, higher than that of ordinary concrete (0.6-1.2MPa) by one time.
The anti-abrasion strength of silica fume concrete with ironstone fine and coarse aggregate is higher than that of silica fume concrete with ironstone sand and pebble aggregate by 1.67 times.

The ironstone silica fume concrete has a rather high frost resistance that can reach F400 frost resistance grade.

3.2.3 Dolerite cast stone concrete

Dolerite cast stone is a kind of commercial slabs made of dolerite stone through such processes as material proportioning, melting, molding, crystallizing and annealing. Thanks to the re-crystallization of dolerite under certain temperature during in certain period, the cast stone has a better mechanical property than natural stone. Dolerite cast stone has an excellent impact resistance and abrasion resistance, resulting in its usual employment as anti-abrasion lining protection material. Dolerite cast stone has been widely used in metallurgy, mine and coal industry. From 1971 it begun to be used in anti-abrasion parts of hydraulic projects. The most typical project is Sanmen Gorge Project on Yellow River, in which the dolerite cast stone was used in desilting bottom hole as abrasion resistance layers.

Dolerite cast stone slab, despite of excellent abrasion resistance, is also brittle when heated by waterborne bed load (pebble and rock), which makes it easy to lose bonding with other materials and then to be carried by water flow. This fact consequently results in the failure of playing its anti-abrasion performance. To overcome this disadvantage, dolerite cast stone is crushed into coarse and fine aggregates and then used in high strength concrete. This method not only can play the excellent abrasion resistance of dolerite cast stone, but also can avoid the problem of cast stone slabs uncovered by water flow or heated into pieces and carried away by waterborne bed load. This problem usually happens to slabs used as anti-abrasion lining protect materials.

Mechanical properties of dolerite cast stone, limestone, granite and biotite quartzite diorite as well as the test results of relative anti-abrasion strength of concrete are listed in Table 3.6.

Table 3.6 Test results of the mechanical properties of coarse aggregate rock and the relative anti-abrasion strength of concrete

Rock type of coarse aggregate	Limestone	Granite	Biotite quartzite diorite	Dolerite cast stone
Compressive strength of rock (MPa)	143.3	190.6	118.2	-
Impact toughness of rock ($N.cm/cm^2$)	43.4	103.8	-	120.2
Relative anti-abrasion strength of concrete *	1.00	1.73	2.33	3.04

* The concretes used the same mixing proportions, cement and aggregates, and the maximum aggregate size was 40mm.

Table 3.6 shows that concretes with different aggregates have nearly the same compressive strength, but the anti-abrasion strength are obviously different from each other and the anti-abrasion strength of dolerite cast stone concrete is almost twice as high as that of granite concrete.

The test results of anti-abrasion strength and the relationship between anti-abrasion strength and abrasion time for dolerite cast stone concrete and granite concrete indicate that two kinds of concretes have nearly the same anti-abrasion strength at the beginning of the abrasion test. This attributes to the fact that only the cement mortar is abraded in the beginning and cement mortar in different concretes has the same mechanical properties. With the process of abrasion continued, the coarse aggregates of concrete are gradually exposed. The dolerite cast stone has a better abrasion resistance than granite; therefore dolerite cast stone concrete are more resistant to abrasion.

Concrete with cast stone aggregate (mortar) had an excellent performance in project application. For example, two kinds of aggregates, dolerite cast stone and local aggregate were used in anti-abrasion concrete for sluice bottom board of Shimian Stage II hydropower station on Nanya River, Sichuan Province. In flood season there was quantity of waterborne bed load (pebble, gravel) carried by water flow, which had a serious abrasion to sluice bottom board. The laboratory tests indicated that the anti-abrasion strength of concrete with dolerite cast stone aggregate was 3.3 times that of concrete with local aggregate. After the abrasion for a flood season, the abrasion depth of concrete with dolerite cast stone aggregate was 1.07cm, while that of concrete with local concrete was 4.83cm, 4.5 times that of concrete of dolerite cast stone aggregate.

The No. 6 desilting bottom hole of Sanmen Gorge Plant on Yellow River employed dolerite cast stone slabs as anti-abrasion lining protection materials from 1971 to 1973. The abrasion of the slabs was slight, but part of slabs was torn off and washed away by water flow. In 1984, dolerite cast stone mortar was used in the reparation, and at the same time high strength mortar and high strength concrete were prepared for comparison. From 1984 to 1990, the bottom hole operated for more than 10000 hours, with a total overflow of 11.3 billion m^3 and a total flow of sand of 0.7 billion ton. The ratio of silica with Morse hardness is higher than 7 among all the sand minerals is 90.0-92.2%, and most of sand particles are multi-angular or sharp-angled. In flood season the water flow carrying sand had a velocity of 14-18m/s and a maximum velocity of 20m/s. The bottom hole operated under the above water flow conditions until 1990 when the examination was carried out in dry season. The examination showed that the high strength mortar and high strength concrete were abraded very seriously, and needed repairing again. On the other hand, the abrasion of dolerite cast stone concrete was rather slight and the structure had a level surface, which proved the satisfactory anti-abrasion effect of cast stone mortar.

In 1986, concrete and mortar with dolerite cast stone aggregate with were used for the reparation of sluice bottom slab of Erjiang river of Gezhouba project. The reparation area was 10000 m^2. After five years of operation, it was found in the examinations that the abrasion depth of cast stone mortar was 3-12mm, with an annual average abrasion depth of 0.6-2.4mm, which made the Gezhouba power plant satisfactory with the reparation effect. In addition, the cost of cast stone mortar was only one ninth of that of epoxy mortar. It had also the properties of excellent construction performance, quick construction speed and easy control on construction quality.

In conclusion, crushed dolerite cast stone used as coarse and fine aggregates can prepare concrete with excellent abrasion resistance. This kind of concrete has a similar thermal property and construction process as ordinary concrete. When employed as anti-abrasion materials, concrete with dolerite cast stone aggregate not only can play the excellent abrasion resistance of cast stone, but also can solve the problem of cast stone slabs that can be easily torn off and carried away by water flow. The project practices have proved its satisfactory performance.

3.2.4 Steel-Fiber Reinforced High-strength Concrete

Ordinary concrete has the disadvantage of poor impact resistance. The use of steel fiber in concrete not only can improve the impact resistance of ordinary concrete, but also can increase its anti-cracking performance.

Classification and size of steel fiber

The classification of steel fiber is as follows: Classification and size of steel fiber.

According to the production techniques, it can be classified into cut steel wire, sheared plate, melt extracted steel and milled steel ingot.

According to material textures, it can be classified into carbon steel, low alloy steel and stainless steel.

According to the shape, it can be classified into flat-straight bar and profiled bar, while profiled bar can be subdivided into indented steel, corrugated steel, hook-terminated steel, large capitiform steel and irregular pocked steel.

According to the strength grade, it can be divided into Grade 380 (tensile strength: 380-600MPa), Grade 600 (tensile strength: 600-1000MPa) and Grade 1000 (tensile strength higher than 1000MPa).

The following is the size of steel fiber:

(1) The length or nominal length should be 20-60mm;
(2) The diameter of equivalent diameter should be 0.3-0.9mm;
(3) The ratio of length to diameter of steel fiber should be 30-80.

Properties of steel fiber reinforced concrete

(1) The sand ratio of steel fiber reinforced concrete is usually 45-50%, higher than that of ordinary concrete; the more the steel fiber added into concrete, the larger sand ratio.

(2) The water amount for unit concrete of steel fiber reinforced concrete is higher than that of ordinary concrete, increasing with the dosage of steel fiber.

(3) Steel fiber can increase the toughness of concrete by 10-20times. High toughness is one of the advantages of steel fiber reinforced concrete.

(4) The impact resistance of steel fiber concrete is favourable. The number of impact times for initial cracking of steel fiber concrete can be increased by 12-14 times, the number of impact times by 11-13 times and impact toughness by 10-14 times when compared with ordinary concrete. This is due to the fact that the steel fiber completely changes the smashing break forms under effect of impact load, and it can continue to bear the impact load after initial cracking, and as well the cracking resulting from impact develops slowly. All these factors are helpful to improve the impact resistance of steel fiber reinforced concrete.

(5) Steel fiber reinforced concrete has an outstanding performance f limiting shrinkage and resisting cracks. The shrinkage ratio of steel fiber reinforced concrete can be reduced by 50% or so when compared with concrete without steel fiber, and its shrinkage stabilization occurrence is earlier, which attributes to the limit to concrete shrinkage resulting from large ratio of length to diameter of and big spaces between steel fibers.

(6) The durability of steel fiber reinforced concrete is improved. The addition of steel fiber can reduce the amount and width of concrete cracks, and consequently increase concrete resistance to chemical attack. In addition, crack stopping effect of steel fiber not only can improve the pore structures of concrete, but also can effectively restrain the expansion stress resulting from freezing. These two effects can combine together to promote and supplement each other, producing a dual-effect double effect of crack stopping buffering. Therefore, the deterioration degree resulting from freezing can be reduced, correspondingly improving the frost resistance of concrete.

3.2.5 Steel fiber silica fume concrete

The abrasion resistance and cavitation resistance of silica fume concrete is outstanding while the shrinkage deformation is large, which is not favourable for its anti-cracking performance. Therefore, steel fiber was added to silica fume concrete to improve its anti-cracking performance and impact resistance.

The mixing proportions of steel fiber silica fume concrete, silica fume concrete and ordinary concrete are listed in Table 3.7. The dosage of steel fiber and silica fume is 0.5% and 10%, respectively. The concretes are all has a cementitious material amount of 510kg/m^3, a w/c of 0.25 and a maximum aggregate size of 40mm.

Table 3.7 Mixing proportions of steel fiber concrete

Mixing No.	Concrete type	w/c	Binder (kg/m^3)	Silica fume (%)	Steel fiber(%)	Note
A	Ordinary concrete	0.25	510	0	0	Maximum aggregate size of 40mm, superplasticizer
B	Silica fume concrete	0.25	510	10	0	
C	Steel fiber silica fume concrete	0.25	510	10	0.5	

Mechanical properties of steel fiber silica fume concrete

The test results of compressive strength, splitting tensile strength, axial tensile strength for steel fiber silica fume concrete, silica fume concrete and ordinary concrete are listed in Table 3.8. The table can indicated that:

(1) The compressive strength of steel fiber silica fume concrete is higher than that of ordinary concrete by 16-23%, and higher than that of silica fume as well.

(2) The splitting tensile strength of steel fiber silica fume concrete is higher than that of ordinary concrete and silica fume concrete by 66% and 15%, respectively.

(3) The axial tensile strength of steel fiber silica fume concrete is higher than that of ordinary concrete and silica fume concrete by 29% and 20%, respectively.

Table 3.8 Test results of mechanical properties of steel fiber silica fume concrete

Mixing proportion No.	Concrete type Ordinary concrete	Compressive strength (MPa)			28d splitting tensile strength (MPa)	28d axial tensile strength (MPa)
		7d	28d	90d		
A	Silica fume concrete	59.9/100	70.6/100	81.4/100	3.11/100	3.79/100
B	Concrete type	69.3/116	76.3/108	88.6/109	4.48/144	4.06/107
C	Steel fiber silica fume concrete	70.0/117	81.9/116	100.2/123	5.16/166	4.90/129

Deformation properties of steel fiber reinforced silica fume concrete

The test results of ultimate tension deformation and dry shrinkage deformation of steel fiber reinforced silica fume concrete are shown in Table 3.9, which can give the information that:

(1) The ultimate tension deformation of steel fiber reinforced silica fume concrete is larger than ordinary concrete and silica fume concrete by 19% and 10%, respectively.

(2) The dry shrinkage deformation of steel fiber reinforced silica fume concrete is higher than ordinary concrete by 27%.

Table 3.9 Test results of deformation properties of steel fiber reinforced silica fume concrete

Mixing proportion No.	Concrete type	Ultimate tension deformation (10^{-6})	Dry shrinkage (10^{-6})
A	Ordinary concrete	135/100	215/100
B	Silica fume concrete	146/109	-
C	Steel fiber silica fume concrete	160/119	272/127

Impact resistance of steel fiber reinforced silica fume concrete

The impact resistance tests of steel fiber reinforced silica fume concrete and silica fume concrete were carried out on impact apparatus of dropping hammer type. Concrete beam samples with sizes of 75×100×400mm and 100×100×500mm and span of 300mm were used in the experiments. When the drop hammer impacted the center of the beam, the number of impact times was recorded until the beams were destroyed.

The impact energy can be calculated by the following equation:

$$u=9.81GHN$$

Where u= impact energy (J)
G= the weight of the drop hammer (kg)
H= the impact height (mm)
N= impact times

The impact test results of steel fiber reinforced silica fume concrete and silica fume concrete are listed in Table 3.10. It can be seen from the table that the impact energy of steel fiber reinforced silica fume concrete is higher than silica fume concrete by more than 75%.

Table 3.10 The impact test results of steel fiber reinforced silica fume concrete

Concrete type	Section size of samples (mm)	G (kg)	H (mm)	N (times)	Impact energy (J)	Ratio
Silica fume concrete	75×100	2	150	4.5	13.2	1.00
Steel reinforced silica fume concrete				8.0	23.5	1.78
Silica fume concrete	100×100	10	100	2.0	19.6	1.00
Steel reinforced silica fume concrete				3.0	34.3	1.75

Abrasion resistance of steel fiber reinforced silica fume concrete

The silt carrying water flow erosion apparatus was used to carry out the abrasion tests of steel fiber reinforced silica fume concrete, silica fume concrete and ordinary concrete that had an age of 28d. The test results are shown in Table 3.11, from which it can be seen that the abrasion resistance of steel fiber reinforced silica fume concrete is superior to that of silica fume concrete.

Table 3.11 Test results of abrasion resistance of steel fiber reinforced silica fume concrete

Concrete type	Abrasion time: 2h		Abrasion time: 3h	
	Weight loss (g)	ratio	Weight loss (g)	ratio
Ordinary concrete	10	1.00	280	1.00
Silica fume concrete	3	0.30	261	0.93
Steel fiber reinforced silica fume concrete	2	0.20	233	0.83

3.2.6 Anti-abrasion concrete with multi-component cementitious materials

When fine mineral admixtures with different particle distribution and activity were mixed into cement, a kind of multi-component cementitous powders can be obtained. Multi-component cementitious materials have the properties of compacted pileup effect and synergistic cementitious effect.

High-strength silica fume concrete or high-strength fly ash concrete was usually adopted as anti-abrasion concrete, which was a dual-component system consisting of cement and silica fume, or cement and Class I fly ash, respectively. Multi-component cementitious material is a tri-component system consisting of cement, fly ash and blastfurnace slag. The compacted pileup effect of dual-component system was not as favorable as expected, while multi-component cementitious material has a satisfactory compacted pileup effect and synergistic cementitious effect, and can regulate the hydration process, hydration heat release process and the strength development process of each component. These properties of multi-component cementitious material are beneficial to overcome such shortcomings of silica fume as low development speed of early-age strength, concentrated hydration heat release and large shrinkage, taking full advantage of later strength development.

Properties of multi-component material mortar

(1) Outstanding compacted pileup effect

With Environmental Scanning Electric Microscope (ESEM), it can be detected that, the silica fume mortar (10% silica fume) has a large number of pores bigger than 5μm, which is due to the unmatchable effect between silica fume particles (average size of 0.5-1.0μm) and cement particles (average size of 30-40μm). Therefore, only the powders smaller than 5μm that mixed with cement can produce compacted pileup effect. According to compacted pileup theoretic model, the fine silica fume particles can fill into the spaces between cement particles to form compacted pileup structures. However, it can be seen from ESEM pictures that quite a quantity of ultra-fine silica fume particles are absorbed to the surface of cement particles, and silica fumes filled in the spaces between cement particles are existing in the form of flocculation as well. Thus the compacted pileup effect of dual-component system consisting of cement and silica fume is not obvious.

The ESEM pictures of multi-component system of fly ash, slag and cement shows that, due to its reasonable particle gradation and the adjustment and filling up effect of fine mineral admixtures, the porosity of this system is obviously reduced, forming a compacted pileup structure. Therefore, multi-component cementitious materials have a distinct compacted pileup effect.

(2) Moderate hydration heat release process in early age

The test results of hydration heat of multi-component material, silica fume cement (with 10% silica fume) and cement are listed in Table 3.12. It can be concluded that, the hydration heat release process of cement and silica fume cement is rapid in early age, and the hydration heat of silica fume cement is higher than that of cement at the age of 5d. On the other hand, the increase speed of hydration heat of multi-component material is rather slow with a 1d hydration heat of 107 kJ/kg, much lower than silica fume cement (with an 1d hydration heat of 184kJ/kg).

Table 3.12 Test results of hydration heat of different cementitious materials

Cementitious material	Hydration heat (kJ/kg)							
	0.5d	1d	2d	3d	4d	5d	6d	7d
Cement	162	216	239	249	254	258	261	263
Silica fume cement*	119	184	218	234	247	257	264	270
Multi-component cementitious material**	56	107	144	165	184	197	205	211

* 10% silica fume + 90% cement
** 50% cement + 30% slag + 20% fly ash

Properties of concrete with multi-component cementitious material

Properties of anti-abrasion concrete with multi-component cementitious material and high-strength silica fume concrete were compacted. The mixing proportions used in the test are shown in Table 3.13.

Table 3.13 Mixing proportions of anti-abrasion concrete with multi-component cementitious material

No.	w/c	Multi-component cementitious material (%)	Superplasticizer (%)	Material amount (kg/m^3)				
				cement	Multi-component powder	Sand	Coarse aggregate	Superplasti-cizer
Control concrete	0.35	10	1.0	278	31	760	1366	3.09
C1	0.33	32	0.8	223	104	751	1351	2.62
C2	0.35	30	0.8	216	93	760	1366	2.47
C3	0.30	44	1.0	202	158	737	1325	3.60

The tests indicated that the concrete with multi-component cementitious powder had following properties.

(1) Favorable workability of concrete mix

The control concrete with silica fume is very viscous, resulting poor workability and difficult construction practice, while concrete with multi-component cementitious powder has excellent workability and is easy to be placed.

(2) High strength increase ratio at later age

The strength results of multi-component cementitious powder concrete and control concrete are listed in Table 3.14. It can be seen that the 90d compressive strength and axial tensile strength of control concrete are higher than its 28d strength by 5% and 6%, respectively; while the 90d compressive strength and axial tensile strength of multi-component cementitious powder concrete are higher than its 28d strength by 11.7-12.7% and 12.2-15.4%, respectively.

Table 3.14 Test results of abrasion concrete with multi-component cementitious material

No.	Compressive strength (MPa)		Axial tensile strength (MPa)		Ultimate tension (10^{-6})		Dry shrinkage (10^{-6})		Autogenous volumetric deformation (10^{-6})		
	28d	90d	28d	90d	28d	90d	28d	90d	28d	90d	180d
comparison	74.8/100	78.7/105	4.17/100	4.42/106	188/100	191/102	317/100	390/100	-49	-100	-106
C1	58.2/100	70.2/121	3.57/100	4.36/122	172/100	186/108	173/55	288/74	-9	-18	-20
C2	58.2/100	74.2/127	3.03/100	3.71/122	143/100	163/114	183/58	298/76	-	-	-
C3	64.9/100	75.8/117	2.83/100	4.35/154	132/100	187/142	181/57	260/67	-	-	-

(3) Large increase of ultimate tension deformation at later age

The test results of ultimate tension deformation of multi-component cementitious powder concrete and control concrete are shown in Table 3.14. The test results indicate that the 90d ultimate tension deformation of control concrete is higher than its 28d ultimate tension strength by 2%, while the 90d ultimate tension deformation of multi-component cementitious powder concrete is higher than its 28d ultimate tension strength by 8-42%.

(4) Small dry shrinkage

The test results of dry shrinkage deformation of multi-component cementitious powder concrete and control concrete are shown in Table 3.14. The test results indicate that the 28d and 90d dry shrinkage of multi-component cementitious powder concrete accounts to 55-58% and 67-76% of that of control concrete, respectively.

(5) Small autogenous volumetric shrinkage deformation

The test results of autogenous volumetric shrinkage deformation of multi-component cementitious powder concrete and control concrete are also shown in Table 3.14. It can be seen from the test results that, the autogenous volumetric shrinkage deformation of multi-component cementitious powder concrete and control concrete at the age of 180d is 20×10^{-6} and 106×10^{-6}, respectively. The autogenous volumetric shrinkage deformation of multi-component cementitious powder concrete is much smaller than that of silica fume concrete, which is beneficial to its abrasion resistance.

(6) Similar anti-abrasion strength of multi-component cementitious powder concrete and silica fume concrete

The anti-abrasion strength tests of multi-component cementitious powder concrete and silica fume concrete were carried out on high-speed silt carrying water flow erosion apparatus. The speed of water flow is 40m/s, and the section of concrete cirque samples is 100×100mm. The test results are in Table 3.15, which indicates that, the anti-abrasion concrete with multi-component cementitious powder and control concrete has nearly the same 28d anti-abrasion strength.

Table 3.15 Test results of anti-abrasion strength of multi-component cementitious powder concrete

No.	w/c	28d average abrasion ratio (g/h·m^2)	28d average anti-abrasion strength (h/(g/cn^2)
Control concrete	0.35	0.287	3.48
C1	0.33	0.285	3.51
C2	0.35	0.342	2.92
C3	0.30	0.281	3.56

3.2.7 Polyurea anti-abrasion protective materials

Polyurea is a kind of double component material, of which component A refers to MDI based isocyanate quasi-prepolymer, and component B consists of amine-terminated polyether, liquid amine chain extender, colour filler and promoter. The mixing ratio of component A to B is usually 1:1.

Properties of polyurea materials

(1) Excellent abrasion resistance

Abrasion resistance of several samples was compared. These samples included sample sprayed with polyurea on its abraded inner surface, limestone silica fume concrete with a 28d compressive strength of 66.5MPa and granite silica fume concrete with a 28d compressive strength of 65.6MPa, of which the later two kinds of concrete had a maximum aggregate size of 40mm. The tests were carried out on silt carrying water flow erosion apparatus. All the samples have an external diameter of 500mm, an internal diameter of 300mm and a height of 100mm. The water flow speed and the sand content percentage of the water were 40m/s and 10%, respectively.

Every sample was abraded twice, with 30 min for each time. The anti-abrasion test results of polyurea coating are presented in Table 3.16. It can be concluded that the wearing rate of polyurea coating is 0.027 $g/cm^2 \cdot h$, much lower than that of high-strength silica fume concrete (0.104-0.440 $g/cm^2 \cdot h$) that has a maximum aggregate size of 40mm. The test results adequately indicate that the abrasion resistance of polyurea coating is favourably outstanding, about 5-10 times higher than that of high-strength silica fume concrete.

Table 3.16 Anti-abrasion test results of polyurea coating and high-strength silica fume concrete

Anti-abrasion materials	Wearing rate ($g/cm^2 \cdot h$)	Abrasion condition of samples
Polyurea coating	0.027	Only several superficial scratches on the coating surface
C60 silica fume concrete (with limestone aggregate)	0.440	Many chipped grains on the inner surface of the sample
C60 silica fume concrete (with granite aggregate)	0.104	Many chipped grains on the inner surface of the sample

(2) Favorable bonding between polyurea coating and wet concrete surface

For concrete with wet surface, interfacial agent is required to be brushed. The bonding strength between interfacial agent and wet concrete and the bonding strength between interfacial agent and polyurea coating is larger than 3.5MPa and 1.5MPa, respectively. Therefore, the bonding strength between these three materials is larger than 1.5MPa if polyurea coating is sprayed after brushing interfacial agent on wet concrete. This means that the bonding between polyurea coating and wet concrete is satisfactory.

(3) Outstanding anti-aging performance of polyurea materials

Artificial aging tests on aromatic polyurea materials were carried out less than 50°C for 3871 hrs. The results of tensile strength, tearing strength and elongation ratio of polyurea materials are listed in Table 3.17. It can be seen that after aging tests, the tensile strength is nearly unchanged and the tearing strength is somewhat increased while the elongation ratio is slightly decreased, which fully indicate that polyurea materials have outstanding anti-aging performance.

Table 3.17 Test results of aging tests of polyurea materials

Aging tests	Tensile strength (MPa)	Tearing strength (kN/m)	Elongation ratio (%)
Before	13.5	76.4	137
After	13.5	84.4	110

(4) Nice low-temperature performance

The test results of low –temperature performance of aliphatic and aromatic polyurea materials are shown in Table 3.18. It can be concluded that the tensile strength and tearing strength of aliphatic polyurea under low temperature is higher than that in normal temperature (25°C), and only the low-temperature elongation ratio is somewhat reduced. Aromatic polyurea has nearly the same low temperature properties with aliphatic polyurea.

Table 3.18 Test results of low temperature of polyurea materials

Properties tested	Aliphatic		Aromatic	
	25℃	-20℃	25℃	-20℃
Tensile strength (MPa)	8.9	11.4	12.3	14.1
Elongation ratio (%)	420	350	180	130
Tearing strength (kN/m)	43.9	105	67.7	102
Hardness	35	-	51	-

(5) Favorable corrosion resistance

Polyurea materials have favourable corrosion resistance. They can well resistance the corrosion of strong corrosion media except such acids as dimethyl amino methane, methylene chloride, hydrofluoric acid, concentrated nitric acid, concentrated sulphuric acid and concentrated phosphoric acid.

Spraying construction of polyurea

(1) Spraying equipment

In the middle of 1990s, GUSMER Company in USA developed second generation spraying equipment titled H-3500, and launched a new generation of spraying host unit of H-20/35. The spraying guns produced by this company include such type of GX-7-100, GX-7-400 and GX-8.

(2) Spraying pressure

Component A and component B of polyurea can react with each other very rapidly after mixed. The performance of polyurea is related to spraying pressure and the higher the spraying pressure, the better the performance (Table 3.19). On the other hand, high spraying pressure can result in fine atomising effect and consequently reduce coarse spraying surface and the phenomena of orange skin, but give rise to severer backwashing.

Table 3.19 Test results of effect of spraying pressures on the performance of polyurea

Properties tested	Spraying pressure (MPa)					
	6.3	7.0	7.7	9.8	12.6	14.0
Tensile strength (MPa)	7.9	9.8	12.0	12.6	14.5	12.9
Tearing strength (kN/m)	50.9	59.6	68.4	70.2	72.8	78.1
Elongation ratio (%)	14.4	40.1	71.5	87.8	158.0	151.0
Shore Hardness	45	45	50	56	54	58

Note: The spraying temperature is 71℃.

(3) Spraying temperature

The performance of polyurea can be improved with the increase of both spraying pressure and spraying temperature. Under the spraying pressure of 14MPa, the test results of effect of spraying temperature on the performance of polyurea are listed in Table 3.20. It can be seen from the table that the tensile strength, tearing strength and the elongation ratio of polyurea rise with the increase of spraying temperature.

Table 3.20 Test results of effect of spraying pressures on the performance of polyurea

Properties tested	Spraying temperature (℃)					
	38	49	54	60	66	71
Tensile strength (MPa)	11.8	10.0	10.1	11.8	13.1	12.7
Tearing strength (kN/m)	48.2	49.1	61.4	64.9	66.7	68.4
Elongation ratio (%)	16.3	41.8	67.7	76.4	126.0	150.0
Shore Hardness	42	47	54	56	53	53

(4) Construction performance

Component A and component B of polyurea can react with each other very rapidly, forming a gel in 5-10s and reaching walking strength in 1min. Then the spraying of upper layer can be carried out.

Complete set of spraying equipment has the properties of large output, easy and continuous construction manners. It takes only 30 min for spraying an area of 100m2 (thickness of 1.5-2.0mm), having very high construction efficiency.

Spraying process is not affected by environment temperature ad relative humidity, but special heat preservation boxes are needed to keep the temperature of component A and component B higher than 21℃ before entering pumps. On the other hand, the temperature of concrete surface should be higher than dew-point temperature by 3℃.

(5) Construction techniques

The construction techniques of polyurea spraying include concrete substrate treatment, spraying and edge scaling.

Substrate treatment: Grinding mill or high-pressure water guns can be employed to removal of the dust, scruff and other filth on concrete substrate. After concrete surface is dry, joint materials should be used for surface levelling and sealing. Until the solidification of levelling materials, grinding wheels will be used to smooth the surface

Spraying polyurea: A layer of priming paint should be brushed before the spraying of polyurea. Then polyurea layer should be sprayed in 12-36 hours after the brushing of priming paint. The spraying layer should have homogenous thickness and the intervals between two neighbouring layers should be less than 3 hours.

Edge scaling: Edge scaling should be executed in 24 hours after spraying polyurea, which means sealing the ends of spraying layers by sealant guns. For structure parts abraded by high-velocity water flow, grooves should be cut along the periphery of the polyurea, and then sealed by elastic epoxy mortar.

3.2.8 Anti-abrasion epoxy alloy materials with "island structure"

Epoxy resin materials have better anti-abrasion performance when compared with high-strength cement concrete, but they also have the properties of large brittleness and easy to give rise to cracks, which limit their application in projects. For a long time, research work was engaged in improving the brittleness of epoxy materials and trying to increase their toughness. Epoxy alloy materials are made by adding toughening agents into epoxy resin to make epoxy and toughening agent mix and dissolve with each other and then forming a homogenous phase. During the process of solidification, the toughening agent accumulates to form spherical particles that act as disperse phase in the continuous phase formed by cross-linking network of epoxy resin. The particle size of disperse phase is usually smaller than several microns with a microcosmic topography of "island structure", and consequently this kind of materials was called epoxy alloy materials with "island structure".

The disperse particles of "island structure" are elastic bodies with low modulus, with a main effect of inducing yield deformation and plastic deformation of epoxy resin matrix and consequently largely reduce the fracture toughness of the material. The addition of toughening agents can increase the molecular weight and reduce the cross-linking density of cured resin, which is the main reason for the great increase of toughness.

Under the effect of impact, abrasion and cutting forces resulting from high-velocity water flow carrying silts, toughening agent particles in the epoxy alloy materials with "island structure" can consume energy in the process of cracking, and the "island structure" can inspire such energy consuming processes as orientation, tension, deformation, cavitation and cracking of the network of epoxy resin particles, which are helpful to avoid destroying and increase the anti-abrasion resistance of the materials.

Fracture toughness and elastic modulus of epoxy alloy materials

The mixing proportions of materials used in fracture toughness and elastic modulus tests are listed in Table 3.21.

Table 3.21 Mixing proportions of epoxy ally materials

Mixing No.	Epoxy resin	Solidifying agent	Toughening agent	Internal releasing agent
HD_2-0	100	10-15	0	0
HD_2-0-Si	100	10-15	0	1~3
HD_2-40	100	10-15	40	1~3
HD_2-80	100	10-15	80	1~3
HD_2-120	100	10-15	120	1~3

Material numbered HD2-0 is a ordinary epoxy resin material without toughening agent and internal releasing agent and HD2-0-Si without toughening agent but with internal releasing agent, while materials with the other mixing numbers are epoxy alloy materials with toughening agent and internal releasing agent.

The test results of fracture toughness and elastic modulus of epoxy alloy materials are listed in Table 3.22.

Table 3.22 Test results of fracture toughness and elastic modulus of epoxy alloy materials

Mixing No.	Fracture toughness (J/m^2)	Elastic modulus (MPa)	Note
HD_2-0	126	4388	The testing temperature: 21°C Loading speed of elastic modulus test: 2mm/min
HD_2-0-Si	615	3837	
HD_2-40	1185	2693	
HD_2-80	2497	1864	
HD_2-120	2519	1816	

Table 3.22 indicates that the fracture toughness of epoxy alloy materials is 10-20 times higher than that of epoxy materials without toughening agent, while the elastic modulus of epoxy alloy materials is lower than that of epoxy materials by 2 times. The higher the toughening agent dosage, the larger the fracture toughness and the lower the elastic modulus of epoxy alloy materials.

Abrasion resistance of epoxy alloy

The mixing proportions of epoxy alloy mortar used in anti-abrasion tests are shown in Table 3.23. There is 20% polysulfide rubber added in epoxy alloy mortar without toughening agent, and the filler is a mixture of silica powder and silica sand whose dosage is 500-700% of epoxy resin in quality.

Table 3.23 Mixing proportions of epoxy alloy mortar

Mixing No.	Epoxy resin	Solidifying agent	Toughening agent	Polysulfide rubber	Internal releasing agent	Filler
EP-15	100	10-15	0	20	1~4	500~700
HD-40	100	10-15	40	-	1~4	500~700
HD-80	100	10-15	80	-	1~4	500~700
HD-120	100	10-15	120	-	1~4	500~700

Each group of mortar samples was abraded for 3 times under the water flow with a velocity of 40m/s and a waterborne silt content of 7.5%, and 15 minutes for each time. The abrasion area of the samples was 100 cm^2. The comparison between the abrasion resistance of epoxy alloy mortar with "island structure" and that of epoxy mortar without toughening agent are presented in Table 3.24. From the table, it can be concluded that the anti-abrasion strength of epoxy mortar is higher than that of C70 concrete, while the anti-abrasion resistance of epoxy alloy mortar is higher than that of epoxy mortar. Epoxy alloy mortar with a toughening agent dosage of 80% and 120% has a much higher abrasion resistance than that with a toughening agent dosage of 40%. The abrasion resistance of epoxy alloy mortar with a toughening agent dosage of 80% is higher than that of epoxy mortar without toughening agent by more than 30%.

Table 3.24 Test results of abrasion resistance of epoxy alloy mortar

Mixing No.	Toughening agent (%)	Average anti-abrasion strength (g/cm^2)	Note
C70 concrete	-	1.84	Silt content carried by water flow: 7.5%; Velocity of water flow: 40m/s; Each group of samples was abraded for 45 min.
EP-15	-	2.43	
HD-40	40	2.91	
HD-80	80	3.55	
HD-120	120	3.56	

Bonding strength of epoxy alloy mortar with concrete

The bonding strength of HD-80 mortar with 80% toughening agent and EP-15 mortar without toughening mortar with dry, saturated surface dry and wet concrete surface was tested. The test results were shown in Table 3.25. The test results indicate that the bonding strength of epoxy alloy mortar with 80% toughening agent is nearly the same with that of epoxy mortar without toughening agent.

Table 3.25 The test results of bonding strength of epoxy alloy mortar and epoxy mortar

Mixing No.	Age	Surface state of concrete	Tensile bonding strength (MPa)	Fracture conditions
EP-15	28	Dry	6.28	Cement mortar
		Saturated surface dry	3.59	Interface
		wet	2.83	Interface
HD-80	28	Dry	6.17	Cement mortar
		Saturated surface dry	3.85	Part of mortar
		wet	2.16	Interface

Strength and ultimate tension deformation of epoxy alloy mortar

Epoxy alloy mortar samples with a size of 40×40×40mm and were employed in the compressive strength tests, while dumbbell-shaped samples in the tensile strength tests. The test results of strength and ultimate tension deformation are shown in Table 3.26. It can be concluded that the compressive strength, tensile strength and ultimate tension deformation of epoxy alloy mortar with 80% toughening agent is nearly the same as that of epoxy mortar without toughening agent. The compressive strength, tensile strength and ultimate tension deformation is higher than 100MPa, 20MPa and 1700×10^{-6}, respectively.

Table 3.26 Test results of mechanical properties and deformation performance of epoxy alloy mortar

Mixing No.	Compressive strength (MPa)			Tensile Strength (MPa)			Ultimate tension (10^{-6})	Linear expansion index (10^{-6})
	7d	14d	28d	7d	14d	28d		
EP-15	-	-	103.5	15.9	-	18.3	1650	35.5
HD-80	105.0	110.0	104.2	22.3	20.8	21.5	1702	37.9

In conclusion, when toughening agent is added into epoxy mortar with amine solidifying agent, a kind of epoxy alloy materials with "island structure" will be formed. Their morphology under scanning electric microscope indicates that there are two phases in the materials, with epoxy resin as the continuous phase and tinny spherical toughening agent as disperse phase. The fracture toughness and abrasion resistance of epoxy alloy materials with island structure is obviously increased when compared with that of epoxy materials.

4 Abrasion Failure Reparation Techniques

The processes of abrasion failure reparation techniques include substrate treatment, treatment of adjoining faces between old and new concrete, placement and backfill of reparation materials and curing. The reparation of abrasion failure is not as easy as it seemed, and it is difficult to get satisfactory reparation effect. The reparation work not only requires the designers and builders to have rich project reparation practical experience and know about the properties of reparation materials, but also asks meticulous construction to ensure project quality.

4.1 Substrate treatment

Substrate treatment requires a complete removal of abraded concrete so as to ensure the favourable combination of reparation material and old concrete. It is recommended that round saw be used to cut grooves to mark the concrete being removed, so as to form regular edges on old concrete. Then manual tools, light-duty tools or heavy-duty tools will be chosen depending on actual conditions to remove the damaged concrete marked. The thickness of the concrete cut off should be uniform, and weak sections should be avoided. The cutting of the peripheral should be vertical to concrete surfaces to form a convex polygon that has an inclination of two neighbouring sidelines larger than 90.

4.2 Treatment of adjoining faces between old and new concrete

After substrate treatment, high-pressure water will be used to completely rinse the surfaces, or dust collection equipment will be employed to clean up the scruff and dusts to get a clean surface. If cement based reparation materials will be used, the old concrete should be saturated but without open water on the surface. On the other hand, if resin reparation materials will be used, try to make the old concrete surface dry or reach the humidity required by reparation materials.

To ensure a fine combination between new and old concrete, interface treatment agent should be brushed on old concrete surface or steel bars should be buried. If the reparation layer is thinner than 10cm, under the condition that the old materials are cement based ones such as cement concrete/mortar and polymer cement concrete/mortar, a layer of cement paste and polymer cement paste or interface agent should be brushed on old concrete to act as bonding layer, respectively; on the other hand, under the condition that the old materials are resin based ones, the resin based liquid can be employed as bonding layers. What requires serious regards is that whatever kind of materials is employed as bonding layers, reparation materials should be placed in allowed time before the solidification or dryness of bonding layers. If the reparation layer having a large area is thicker than 10cm, a layer of cement mortar is usually placed to be employed as bonding layer, and sometimes steel bars are buried in new concrete to increase the bonding strength between new and old concrete and improve the anti-cracking performance and durability of reparation materials.

4.3 Placement and backfill of reparation materials

Placement and backfill of reparation materials should be carried out layer by layer, and the upper layer should be cast after the placement of lower layer finished but before its initial setting or full solidification. If the construction between upper and lower layer is delayed, then the roughening of the lower layer is required and the construction of upper layer can be carried out only after brushing or setting new bonding layer. The thickness of mortar reparation materials should be 1-2cm, while the thickness of concrete reparation materials should be set to satisfy the need of adequate vibration.

4.4 Curing

Thanks to the high strength development speed of cement based reparation materials, wet curing at early age should be reinforced to avoid the damage of bonding surface of reparation materials and old materials before it gets enough resistance. Excessive evaporation at early age can easily result in dry shrinkage cracking, peeling and shedding or surface quality decrease, which is rather harmful to thin layer repairing. Frost action at early age can give rise to severe damage to inner structure of repairing materials and consequently lead to irreversible quality decrease. Therefore, heat preservation curing is required.

Resin based repairing materials are with the properties of short solidification time and rapid strength development rate. Therefore they usually need no curing after solidification except the condition of sudden drop of environment temperature, under which heat preservation is needed.

5 Concrete Reparation - Engineering Examples

5.1 Repairing in overflow surface of Yunfeng dam

5.1.1 Engineering situation

The Yunfeng hydropower station is located at the middle river of Yalu River, Jilin province. It is a project confounded by China and North Korea. The dam design and construction is completed by North Korea and the hydropower plant's design and construction is carried out by China. Its operation is also managed by China. The slotted gravity dam height is 113.75m, the length is 828m, and is composed by retaining dam and overflow dam. There have 21 part dams in this overflow dam, the width of spill port is 11m and the pier thickness is 4m.

The dam placement began in 1960 and was finished in 1966. The construction of concrete overflow dam was divided into two periods, the surface of overflow dam with a depth of 1m was second-stage concrete, the requirement of concrete design due to C20W8F150 and without admixture. The area of overflow surface is 33500m^2; part of this concrete, about 22.3% of whole overflow area, was placed by vacuum template construction method. But it doesn't reach the vacuum process effect due to the lower vacuum degree.

5.1.2 Damage situation of overflow surface

There were six times of flow discharges from 1966 to 1986 after the completion of Yunfeng dam and 50% of overflow parts had never been discharge. We carried out investigation on concrete situation of the overflow dam in March 1980 and found that the demolished area was up to 11000m^2. Denudation depth and area was shown on Table 5.1

Table 5.1 Denudation situation of Yunfeng overflow surface

Denudation depth (cm)	0~10	10~20	20~30	>30
Demolish area (m^2)	9779	888	68	23
Ratio (%)	30.00	2.65	0.20	0.03

From Table 5.1, we can tell that denudation depth of most part of overflow dam is about 10cm, several parts in the transverse joints and longitudinal joints about 40~45cm. In the survey of 1985 we found that the denudation area and depth were enlarged; there had laminated scaling, uncovered stones and loose concrete in the concrete surface, with the demolish area up to 40% of the whole area.

There also had denudation destroy at the overflow parts that hadn't even operated for water discharge, and the phenomena was like the parts having ever discharged water. The different was that the parts having discharged water had been suffer the erosive action, making the denudation depth deeper.

5.1.3 Cause analysis of denudation destroy

The main reasons of denudation destroy were as follows.

The dam was located at cold area and the cycle time of freeze-thaw was much more than regular. The lowest air temperature of Yunfeng dam area was –41°C and the average of lowest air temperature was -13.6°C. The overflow dam part was faced to the south, solar radiation made the temperature raise 6°C and it made the cycle time of freeze-thaw to 135 times, the most depth was 1.0m.

The design index of overflow surface concrete was lower. The regular design index of overflow abrasion-resistant concrete was C20F150, the C20 compressive strength index was lower and the frost resistant grade of F150 was lower too.

The concrete construction of surface's quality was bad, the sand fineness was 2.09, there had no classification of 5~40mm coarse aggregate; concrete water consumption not controlled strictly, water cement ratio variations was large, made the slump of concrete have big fluctuation; the vibrating was not compacting, the phenomena of less vibration was severe; the vacuum work was not enough; there had no insulation measures for the winter construction, the concrete durability was lower because the early age frost. The compressive strength varied only between 11.0 and 13.0MPa on these 20cm thickness concrete samples. The deep concrete sample's compressive strength was higher than 20MPa. The old concrete strength would over 23.0MPa after the dig on a wide area.

Snowmelt and leakage of sluice sealant, all these made the saturated water of overflow surface concrete, it would make the freeze-thaw damage happened in the cold area.

It would have hydraulic abrasion when the dam discharges water.

5.1.4 Repairing and strengthening of overflow part surface

Depend on the test of compute and on site sample we could tell the 50cm depth of concrete surface wasn't infected by the variation of temperature. The positive and negative temperature's alternating wasn't beyond 10 times, the lowest temperature was about -5°C and it didn't make the capillary porosity frozen, we confirmed the repairing thickness was 50cm because there had no leakage in this dam and it could meet the construction requirement.

The concrete repairing design was C30F300 three-graded concrete, its mix proportion was shown on Table 5.2.

Table 5.2 Concrete mix proportion of overflow surface

Design requirement	water cement ratio	sand ratio (%)	Slump (cm)	material dosage (kg/m^3)							
				water	cement	sand	gravel stone	Medium stone	Large stone	wooden-calcium	SJ-1
C30F300	0.37	27.0	4~5	99	268	552	446	446	594	0.54	0.027

Note: diameter of gravel stone 5~20mm, medium stone 20~40mm, large stone 40~80mm

The reparation construction firstly was excavated the freeze-thaw and weathering concrete by silent blasting agents and the excavation depth was 30cm, then placement 50cm thickness concrete on it, there were mesh reinforcement in the reparation layer, the diameter of steel was between ϕ16 and ϕ19, crossbar spacing was 30cm, there still had ϕ22 rebar burying which the spacing was 60cm, buried depth was 1.5m, anchored by mortar.

After the installation of mesh reinforcement, we had the thoroughly cleaning to the datum plane and dig out the loose concrete before the placement, then we washed it by high-pressure water jet. The reparation construction used steel sliding mode placement. The work began in 1986 and in 1987 the placement was completed. There were totally 21 overflow dam parts in the reparation. The compressive strength and the frost resistance all met the design requirements.

5.2 Reparation in right middle water outlet bottom plate of Lijiaxia arch dam

5.2.1 Engineering situation

Lijiaxia hydropower plant was located at upriver of yellow river, Qinghai province. Its main purpose was for power generation, irrigation and supply water. The main buildings had concrete hyperbolic arch dam, post dam double row powerhouse and bottom middle hole water outlet. The maximum discharge was 5640 m^3/s and the maximum velocity was 42.5m/s.

The project was located at Tibetan plateau which was the typically continental climate. The winter was long and the summer was cool, the temperature difference was huge and the solar radiation was strong. The lowest air temperature was -19.8°C, and the highest air temperature was 34.5°C, the average temperature was 7.8°C, the maximum of wind speed was 16m/s, the average precipitation was only 331mm and the evaporation was 1881mm.

May 2003, we checked the bottom hole and the middle hole of water outlet and found there had crack phenomena on the C60 silica fume concrete surface, erosion phenomena also happened, then we decided made the reinforcement treatment to the bottom plate.

5.2.2 Technical requirements of repair material

The repair material use the first grade high strength concrete, the performance index was as follows.

Compressive strength	≥50MPa
Tensile strength	≥5MPa
Bond strength	≥3MPa
Ultimate elongation	$\geq 1.4\times10^{-6}$
Drying shrinkage	$<(300\sim400)\times10^{-6}$
Frost resistant grade	≥F300
Seepage resistance grade	≥W8

5.2.3 Mix proportion design of abrasion resistance concrete

This project's abrasion resistance material was used multiple cementing material abrasion resistance concrete, this was a new type abrasion resistance concrete that had significantly advantage than the usual silica fume concrete, firstly the early strength was lower than the silica fume concrete but the later strength was growth rapidly, this would avoid the crack by the temperature variation, secondly, the lower cohesiveness made the easygoing of construction, at last the shrinkage reducing agent made the volume slight expansion and the anti-cracking was obvious increased.

The mix proportion of new type abrasion resistance concrete and silica fume concrete were shown on Table 5.3, the test results of concrete performance was shown on Table 5.4.

Table 5.3 Mix proportion of new type abrasion resistance concrete

kind of concrete	water-binder ratio	sand ratio (%)	Admixture amount (%)	water-reducer(%)	air-entraining agent (1/million)	material dosage (kg/m^3)			
						water	glue	sand	stone
High silica fume concrete	0.35	38	10	0.5	1.4	126	370	744	1214
new type abrasion resistance concrete	0.33	38	25	0.5	1.0	126	380	737	1205

Table 5.4 Test results of concrete performance

kind of concrete	compressive strength (Mpa)			axial tensile strength (MPa)	ultimate elongation (10-6)	abrasion rate (kg/h·m2	anti-permeability grade	Antifreeze grade	drying shrinkage (10-6)	
	7d	28d	90d	28d	28d	28d	28d	28d	28d	90d
High silica fume concrete	58.7	71.1	74.7	4.66	119	2.87	>W12	>F300	317	390
new type abrasion resistance concrete	48.1	65.9	69.9	4.66	113	2.85	>W12	>F300	190	288

The new and old concrete's interface employed the Z shape interfacial agent; bond strength of moisture and drying interface was 3.43Mpa, 3.21Mpa. Destruction also occurred in the concrete.

In case to increase the plastic contraction deformation of the early time and also to increase the crack phenomena, we had mixed the polyacrylonitrile fiber 1kg/m^3 during the construction, the new type abrasion resistance concrete was shown on Table 5.5.

Table 5.5 Mix proportion of new type abrasion resistance concrete

water-binder ratio	Sand ratio (%)	Admixture quantity(%)	the amount of admixture (%)			material damage usage (kg/m^3)				
			Effective water reducing agent	shrinkage reducing agent	air-entraining agent	water	glue	sand	stone	acrylic fiber
0.33	38	25	0.5	1.0	1.2/	138	418	816	1130	1.0

5.2.4 Construction technology

Foundation base processing

The principle of foundation base processing decreased the damage of bond interface and also decreased the pollution, and increased the clean degree and roughness.

The first step of foundation base processing was trimmed the roughen and then used the high-pressure water jet to wash and make the bare of fresh concrete.

Layout of inserted reinforcement

To insert reinforcement was for the enhancing bond force of new and old concrete. The layout used the quincunx formation and the spacing was 1.0m, the inserted steel bar was ϕ18, and the anchor with the anchor agent. We used the high pressure water jet wash the base surface after the inserted reinforcement, and then covered it by plastics cloth to prevent the pollution.

Brushing the interfacial agent

We used the brush to brush the interfacial agent, the brush should be thinner and even, it should not have missing brush thick brush drainage and there shouldn’t have sedimentary, the interfacial agent should be onsite mix and should be prevented excess the quantity.

Concrete mixing

The concrete mixing used the 350L forced action mixer, firstly put the sandstone aggregate, cementing material and fibre together then add the water, water reducing agent, shrinkage reducing agent after 15 sec of dry-mixed, the slump should between 1~3cm after the 3 minutes mixture.

Transportation and placement of concrete

We loaded the concrete to the wheelbarrow after mixing, and then used the hoister lift the concrete to the designate location. The placement had two layers and for each layer we used the plate vibrator for 15~20 sec. For the corner place we used the insertion vibrator. Finally we used the hand vibrator to mud extracting trowel finish and trowel.

Concrete curing

After the placement we covered the concrete surface by plastic cloth, and also covered the plastic by a layer straw mat, we sprinkled water to prevent the drying of the concrete surface.

5.3 Spraying anti-abrasion polyurea layers on reinforced concrete snail shell of Ni'erji dam

Project introduction

The Ni'erji hydraulic project, 189 km from Qiqiha'er city, was located in Nahe City, to the left of the main Nenjiang rivier at the boundary of Heilongjiang Province and Inner Mongolia Municipality. The controlled basin area upper to the dam site was 660, 000 km^2, accounting to 66% of Nenjiang basin area. The project was composed of a main dam, secondary dam, spillway, power house and diversion tunnel for irrigation, etc, with a total reservoir capacity and an installed capacity of 8.61 billion m^3 and 250, 000kW, respectively. To fulfil the requirements of permeability and abrasion resistance of reinforced concrete snail shell, anti-abrasion polyurea layers with an area of 2800 m^2 were sprayed on the concrete.

Anti-abrasion layers

Anti-abrasion layers were polyurea materials made from isocyanate (component A), amide (component B), chain extender and promoter, etc. The mixing ratio of component A to component B is 1:1.

Construction technique

The construction processes of polyurea materials included substrate treatment, spraying of anti-abrasion layers and edge scaling, etc.

Substrate treatment

Grinding mill or high-pressure water guns could be employed to removal of the dust, scruff and other filth on concrete surface. After concrete surface was dry, joint materials should be used for surface levelling and sealing. Until the solidification of levelling materials, grinding wheels will be used to smooth the surface, and then interface agent will be sprayed or brushed.

Spraying of polyurea materials

After the dryness of interface agent for substrate treatment, polyurea layers could be sprayed. The spraying of polyurea should be carried out in 24 hours after the spray of interface agent; otherwise, a new layer of interface agent should be brushed again. Before spraying polyurea, high-pressured dry air should be sprayed to blow off the surface dust. The spraying should be carried out for 2-3 times with a homogenous spray layer thickness of not less than 2mm.

Edge scaling

Before the spraying process of polyurea, a rectangle groove with a size of 3×5cm should be cut at the joints and peripheries, in which epoxy mortar was applied for edge scaling. Before the spraying process of polyurea, a rectangle groove with a size of 3×5cm should be cut at the joints and peripheries, in which epoxy mortar was applied for edge scaling.

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