Application progress of scour-abrasion resistant materials of hydraulic concrete

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Abstract. As the concrete surfaces of the sluice structure in the water conservancy and hydropower engineering would often suffer from the erosion of high speed sandy flow or water flow with bed load, there will often appear different degrees of wear and cavitations damages after a certain time of operation. Therefore, it is especially important to use the materials with high performance in resisting erosion and abrasion. Based on analyzing the abrasion damage mechanism and form of concrete, this paper mainly summarizes the research and application of scour-abrasion resistant materials, introduces the new development of scour-abrasion resistant materials, and finally provides an effective way of solving the impact of high silt-laden water erosion.

1. Introduction
Concrete structures are widespread in water conservancy projects. However, many concrete buildings have suffered diseases because of poor quality of construction and management, and long-term operation in harsh environments and other factors. For water discharge structures of water conservancy and hydropower projects, the scouring impact and cavitation damage are the most common diseases. Especially when the water flow velocity is large and is brought with sand and gravel, such damages will be more serious. Scoured by high-speed water flow, and under the combined effects of freeze-thaw, flushing, cavitation and water erosion, the concrete of the water discharge structures will be damaged to varying degrees after years of operation, thereby directly affecting the safe operation of the project, reducing the service life and the maintenance will be costly. To solve this problem, scholars at home and abroad have done many researches on the impact resistance and wear protection technology of the water discharge structure concrete. In addition to scientifically performing hydraulic and hydraulic design on the surface characteristics of the building, it is particularly necessary to adopt superior materials and reasonable construction methods to protect and repair the water discharge buildings.

2. Mechanism and form of hydraulic concrete erosion failure
The sand and gravel carried by the high-speed water flow have a certain kinetic energy. When the water flows over the concrete surface, part of the energy will be transferred to the concrete material, causing the material particles to peel off. This kind of damage is related to many factors, such as sand and gravel characteristics, water flow velocity, concrete surface shape, material strength and hardness.
There are three main forms of high-speed water flow damage to water discharge structures: scouring erosion, cavitation erosion, and hydraulic erosion. Both scouring erosion and cavitation erosion occur on the concrete surface of the water discharge area, and scouring can even induce cavitation erosion. Factors that impede the moving of high-speed water flow, such as staggering, unevenness, residual roots, and the structure itself, may cause cavitation erosion on the surface of the concrete. Cavitation erosion speed is very fast, and its damage to the concrete is often more serious than other factors. The forms of scouring erosion can be divided into bedload damage and suspended load damage. It is inevitable that the surface of the water drainage building will be buffeted by the high-speed water flow containing bedload and suspended load mass. The damage speed of suspended load is slower than bedload masses, but the damage will become increasingly serious over time, and as the unevenness of the concrete surface increases, the influence of water flow conditions will be deteriorated, inducing cavitation erosion. Under the double effect of scouring and cavitation erosion, the damage to the drainage building is accelerated, and when it develops to a certain degree, large-scale hydraulic erosion damage will occur.

3. Overview of anti-impact and wear-resistant materials in the hydropower industry

Due to the erosion of suspended load and bedload sediment, in most water conservancy projects, the damaged area of concrete structure eroded need to be regularly maintained after a certain operation period to ensure the safe operation of the project. At present, many studies worldwide have devoted to the research and application of anti-abrasive materials to improve the anti-abrasive performance of hydraulic discharge structures. There are many varieties of anti-abrasive concrete repair materials on the market, which mainly can be divided into two types of inorganic materials and organic materials. In the field of inorganic materials, it is mainly to research and develop anti-abrasive concrete technology; as for organic materials, it is mainly to study the performance of polymer materials.

3.1. Polypropylene fiber concrete

Polypropylene fiber concrete was originally used in US military projects to enhance the solidity of concrete. In the past more than ten years, the United States and Canada have widely used ready-mixed concrete with low blending rate synthetic fibers (polypropylene monofilament, polypropylene membrane split fiber and nylon fiber, etc.) in concrete engineering. Compared with ordinary concrete, the brittleness index and elastic modulus of polypropylene fiber concrete is lower, and the ultimate tensile deformation is larger. These characteristics are conducive to improving the ductility of concrete, enhancing the deformation performance of concrete, thereby effectively restraining the expansion of concrete cracks, improving the concrete performance of anti-abrasive, impermeability and frost resisting, so as to ensure the quality of concrete pouring, making polypropylene fiber concrete be widely used in water conservancy engineering. Polypropylene fiber concrete material was used and performed well in the second-phase project of Ningbo Baixi Reservoir and the restoration project of the spillway of Bajiazui Reservoir in Gansu.

3.2. Silica fume concrete

Silica fume concrete is the concrete mixed with tiny particles in ordinary concrete, so that the ordinary concrete’s anti-abrasive and anti-cavitation degree can be improved. Since the average particle size of the silicon fume is 0.1 ~ 0.15 μm, which is 50~100 times smaller than the cement particle, and its density is 2.2~2.5 g/cm³. The filling effect of silicon fume can greatly improve the performance and the durability of concrete. The incorporation of silica fume can improve the pore structure of cement and the interface structure between cement stone and aggregate, and enhance the interface adhesion of cement stone and aggregate, so that the coarse aggregate is hard to be destroyed when it is worn. Silica fume high performance concrete has good anti-abrasive and anti-cavitation properties, and is generally recognized by domestic and foreign engineering circles. It have been widely used in projects such as the Danish Great Belt Strait Project, the Dahuofang Water Transmission Tunnel Energy Dissipation Pond, the Longyangxia Bottom Hole, the reverse arc section of the Panjiakou dam overflow surface,
the bottom hole of the discharge and sand conveyance of the Baishi Reservoir, the Gejiangba Erjiang sluice gate and so on.

3.3. Steel fiber concrete
The most important feature of steel fiber concrete is its excellent energy absorption characteristics, impact resistance and blast resistance. Steel fiber concrete is made by evenly dispersing steel fibers in the concrete mixture, which can improve the tensile strength, flexural strength, crack resistance, toughness, and impact resistance of the concrete. When the volume content of the steel fiber is 2%, the toughness of steel fiber concrete is 40 ~ 200 times that of plain concrete, and the capacity of steel fiber concrete to absorb energy is large. Its dynamic strength under explosive impact and tensile and compressive load is 5 ~ 10 times greater than that of plain concrete. What’s more, it has strong cavitation resistance, its compressive strength can reach more than 70 MPa, the erosion resistance reaches 0.66 h·m²/kg, and the cavitation resistance reaches 4.00 h·m²/kg.

3.4. HF anti-abrasive concrete
HF high-strength wear-resistant fly ash concrete (referred to as HF concrete) is a new type of anti-impact and wear-resistant material developed after silica powder concrete. It is made of HF admixture, high-quality fly ash, sand and gravel aggregate and cement that meet the requirements etc., and is carried out through the mix proportion test and the engineering design according to the regulation method, and pouring according to the regulated craft process. HF concrete improves the direct binding ability of cementitious materials and aggregates, so as to make the concrete form a relatively homogeneous material body, which is not easy to occur concentrated stress and damage. Due to its enhanced strength and erosion resistance, under cavitation and scouring erosion, the entire surface is basically uniformly worn to form a relatively smooth surface, and there will be no regeneration unevenness caused by cavitation damage owing to the exposure of cementitious materials and mortars when they are worn off. Therefore, this material has the characteristics of small shrinkage, good workability, small temperature rises of hydration heat, strong impact resistance, wear resistance and cavitation resistance. After more than ten years of research and engineering application, it has been gradually improved, optimized, and perfected, and become a new type of professional hydraulic cover concrete. HF anti-abrasive concrete was used in the surface protection project of the Ertan Spillway Tunnel in 2002 with good results.

3.5. Epoxy mortar
Epoxy mortar’s cavitation resistance performance is 6 ~ 8 times that of C40 concrete and 20 times that of C30 concrete, which is an ideal material for anti-erosion protection and repair in water conservancy and hydropower projects. Since the 1960s, China has been engaged in the research of epoxy resin in the protection material against impact and wear and the damage repair material of the thin layer of impact and wear at the high-speed water discharge site of hydropower projects. The first project to use epoxy mortar to repair was the repair project of Xin’an river overflow surface. Since then, the modification research of epoxy material has never been stopped. Mai Shufang of the Chinese Academy of Water Sciences studied the anti-abrasive protective material, “island structure” epoxy resin alloy, to improve the fracture toughness of the “island structure” epoxy mortar and make it more suitable for hydraulic structures with high requirements for erosion resistance and crack resistance, or as a partial repair for concrete surfaces. Zhang Tao conducted a modification study on epoxy resin mortar. By changing the epoxy resin synthesis process and selecting the curing agent, the viscosity of the epoxy resin was greatly reduced and the flexibility was increased under the premise of unchanged other basic properties, and made the epoxy mortar and foundation concrete firmly adhere, not easy to crack brittlely, and has good durability, which improves the construction performance. The research and development of epoxy materials make it widely used in hundreds of large and medium-sized water conservancy and hydropower projects at home and abroad.
In the process of engineering application, compared with general concrete, although the performance of the above-mentioned concrete anti-impact and wear-resistant materials is significantly improved, there are still many problems. Polypropylene fiber concrete is easy to uneven mixing and agglomerate, and has no obvious effect on improving the shrinkage cracks and temperature cracks of concrete. Silica fume concrete has problems such as poor work performance, construction difficulties, early dry shrinkage, and severe cracks. Steel fiber concrete is difficult to mix evenly, and has poor workability and poor construction performance. HF anti-abrasive concrete also has problems such as poor workability. Due to the current technical development level of raw materials such as epoxy resins and curing agents, the development of epoxy mortar materials in the field of water conservancy and hydropower engineering is limited in a certain extent. From the perspective of application, epoxy resin itself needs to be further improved in improving fracture toughness and crack resistance, as well as in the aspects of convenience, speed and ease of construction, adaptability to water or wet concrete surface and high adhesion strength.

4. New progress of anti-impact and wear-resistant materials

Traditional hydraulic concrete impact and wear resistant materials all have their respective application limitations. In order to better solve or alleviate the problems of scouring erosion and cavitation damage of overflow buildings, researches are currently being conducted from two aspects: on the one hand, the strength and related properties of concrete materials are continuously improved; on the other hand, the anti-impact and wear technology of the new polymer composite material is adopted, and the high strength and toughness of the polymer material is used to resist the impact and erosion of the high-speed sand-bearing water flow. High-strength anti-abrasive concrete often adopts a small water-cement ratio, and generally incorporates admixtures with small fineness, resulting this kind of concrete is viscous, and has low water bleeding, and the problems of plastic shrinkage and drying loss make the concrete construction more difficult, and cannot obtain an easy construction process and quality assurance system, which is difficult to achieve the effect of the laboratory and the surface flatness required by the design in the project, and limits the application of high-strength concrete. Due to the excellent mechanical properties, impact resistance and wear resistance of polymer composite materials such as polyurea and epoxy, they have gradually become a new method to solve the problems of wear and cavitation in water conservancy and hydropower facilities, especially water discharge structures.

4.1. High elasticity repair mortar

High elastic repair mortar is a new type of thin layer repair material for concrete defects, which can effectively solve the problems of concrete wear, erosion, and cracking, and has features of strong impermeability, high strength, good anti-abrasive effect, and large elongation. The addition of polyurea as a cementing material improves the inherent quality of the mortar, greatly improves the tensile properties, elasticity, and impact resistance of the mortar, thereby improving the durability of the mortar. Research by the Chinese Academy of Water Sciences shows: (1) The bonding strength between the high elastic repair mortar and concrete is high, which can reach more than 3MPa, and the good bonding performance can ensure that the mortar will not be lifted when resisting high-speed water flow; (2) The high elastic repair mortar has good stretching deformability; (3) High elasticity repair mortar has low temperature flexibility and toughness. Under environment of - 40 °C, the high elasticity mortar elongation rate can still reach more than 10%, which has certain applicability in cold areas. (4) The high elasticity repair mortar material has good elasticity, the elastic modulus is 16–50 MPa, which is about 1000 times lower than that of ordinary mortar, and its elongation rate is 10% ~30% (which varies according to the ratio). After compression 50%, it still can be restored to its original state, so it has good crack resistance and ability to adapt to deformation, which is not available in the traditional mortar repair materials in the past. This feature makes it obvious in the repair of thin concrete layers. This technology has been applied in the lining joint test project of the Yellow River Crossing Tunnel in Henan and the repairing project of the overflow surface of Xin’an River Power Station, which has a broad prospect of market application.
4.2. High toughness epoxy protective coating

The high toughness epoxy protective coating material uses an epoxy/polyurethane hybrid system to internally plasticize the cold-curing epoxy resin. Through the molecular structure design, it uses different segment curing agents for curing. Through its synergistic effect, it shows certain toughness and elongation for breaking. The main characteristics of high toughness epoxy protective coating: (1) Tensile strength can reach 17 MPa, and elongation for breaking can reach 6%; (2) Impact toughness can reach 2.9 kJ•m⁻²; (3) Yellow River Crossing, bonding strength can be up to 3.76 MPa, bonding with wet mortar can be up to 3.35 MPa; (4) The material does not crack or vacant under -40 °C environment, indicating that the low temperature crack resistance is good; (5) The erosion resistance in high-speed (40 m/s) silt (20%) water flow is 2.65 h•m²/kg, which is more than 10 times that of C60 concrete. This technology has been successfully applied in many project, such as the maintenance of Beijing-Shijiazhuang section of South-to-North Water Transfer Emergency Water Supply Project (Beijing segment), the anti-seepage treatment of the pressure regulating well and the water diversion tunnel of the pressure pipeline of Songshan estuary hydropower station in Yunnan province, the anti-impact wear protection of concrete on overflow surface of Fuchun River hydropower station in Zhejiang province, the dam panel protection of Jilin tai hydropower station, Xinjiang, and all of them have obtained a good effect.

5. Conclusion

Due to the coupling effect of water flow, sand and gravel and various factors in the natural environment, the normal use and safe operation of hydraulic discharge structures are difficult. To ensure the safe and stable operation of hydraulic discharge structures, the material selection and application of the key parts washed by water flow and sediment are very important. Through the research and engineering practice in recent years, it has been proved that, under the condition that the traditional materials can not completely solve the problem of water discharge structures erosion, we can use high polymer material to improve the toughness of hydraulic concrete anti-impact wear-resistant material, improve the ability of resistance to temperature and humidity changes, and improve the bonding force between the material and the base concrete, taking “Overcoming firmness by gentleness” as a new method, so as to provide an effective way to solve the impact and erosion problem of high speed sand-bearing water flow, which will become a new trend in the anti-impact and wear-resistant protection of water conservancy and hydropower industry.

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References

[1] Maiti A K, Mukhopadhyay N, Raman R. Effect of adding WC powder to the feedstock of WC–Co–Cr based HVOF coating and its impact on erosion and abrasion resistance[J]. Surface and Coatings Technology, 2007, 201(18): 7781-7788.

[2] Sundararajan G. The differential effect of the hardness of metallic materials on their erosion and abrasion resistance[J]. Wear, 1993, 162: 773-781.

[3] Ping L, Jing L, Mingliang M, et al. Research on Seawater Corrosion Resistance of Spray Polyurea Protective Coating[J]. MS&E, 2018, 436(1): 012017.

[4] ZHANG Y, SI Y, ZHANG J, et al. Compression Tests of Plain Chloroprene Rubber Bearings of Highway Bridge under Acid Corrosion Condition[J]. Journal of Shenyang Jianzhu University (Natural Science), 2013, 4.

[5] Weibo H, Xiao H, Fei X. Research progress of protection technologies for scour-abrasion resistance of hydraulic concrete[J]. Journal of Water Resources and Hydropower Engineering, 2014, 45(2): 61-63.