Research Progress on Low Temperature Anti-crack Design of Hydraulic Epoxy Mortar Protective Material

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ABSTRACT: Epoxy mortar is an important structure surface protection and repair materials for hydraulic concrete construct, while the design system of epoxy resin mortar crack resistance at low temperature has not been established in the field of water conservancy projects. Therefore, the application of epoxy mortar in the open air is of great blindness, which seriously restricts its application in water conservancy projects. In this study, through the investigation of application problems of epoxy mortar in Xin'An River Hydropower Station surface protection for nearly 60 years, it is shown that the application environment, the failure mechanism of epoxy mortar, constitutive relation and curing shrinkage factors such as are the key factors to construct the system of anti-crack design of hydraulic epoxy mortar. On the basis of the investigation work of epoxy mortar cracking on failure criterion, the viscoelastic constitutive relation, curing shrinkage stress, thin structure stress and so on , it is laid the foundation for epoxy mortar anti-cracking design in the cooling process.

1 INTRODUCTION

Hydraulic engineering concrete buildings will experience surface failure under multiple hydraulic impact incidences or undergoing freeze-thaw damage. Aged and newly built concrete surfaces often require surface protection to ensure the operational safety of hydraulic engineering concrete constructions. Due to good substrate adhesion forces, mechanical properties, penetration resistance and erosion resistance, the epoxy material is a primary protective materials. The erosion resistance capacity of epoxy mortar is about 20 times that of C30 concrete. Compared with materials such as polyurea, epoxy mortar has excellent bed load scouring resistance capacity .

Epoxy mortar has been applied in domestic hydraulic engineering for over 50 years, and a large amount of application works on epoxy mortar research and development have been carried out. These mainly focus on the influences of curing agent property, cure condition and fillers physical properties (such as particle size, type, amount, gradation and moisture content, etc.) on the mechanical properties of cured epoxy mortar such as tensile strength, fracture elongation percentage and bonding strength. On this basis, the domestic hydraulic engineering epoxy mortar research and development has seen great breakthroughs, developing several new epoxy mortars such as the wet epoxy mortar with bonding capacity in wet and underwater environments, elasticity epoxy mortar with large deformation rates in normal temperatures and toughening modification epoxy mortar with higher fracture toughness.

2 APPLICATION OF EPOXY MORTAR

Even so, there is no concrete surface protection material widely suitable for various environmental conditions in hydraulic engineering. At present, the application conditions of hydraulic engineering epoxy mortar can be divided into two categories: One is indoor environments such as tunnel buildings including flood discharging tunnels. The application effect is pronounced in flood discharging tunnels and failure phenomena such as cracking and disengagement occur rarely; the other is outdoor natural environments. The temperature difference variation of epoxy mortar in these kinds of environments is highly varied due to influences from solar radiation, epoxy temperature and rinse effects, so failure phenomena such as cracking and disengagement easily occur. Due to the fragility and higher vitrification temperature of epoxy mortar, it's liable to crack under low temperature conditions. Therefore various failure phenomena often occur, and include protective layer cracking, separation from the basement concrete and even disengagement, necessitating the protect consolidation works of some engineering to be carried out year after year and repeatedly. In these cases, the development of epoxy mortar repairing techniques is seriously restricted.

Completed in 1959, the Xin'anjiang concrete gravity dam is the first dam with overflow on the top of the structure in China, which failed to meet the technical requirements of anti-erosive and anti-abrasive property at a flood-discharge velocity of 25 m/s. Thus, a 2-cm layer of epoxy mortar with a total area greater than 3,600 m^2 was laid on the top of the plant.

Since 1963, common epoxy mortar, elastic epoxy mortar, and highly toughened epoxy mortar have been used successively as protective layer. The study of epoxy materials was still at a preliminary stage when common epoxy mortar has been first applied. A low-molecular amine was used as the curing agent, and it can significantly shrink the epoxy mortar coating and expose it to the outside. Thus, the epoxy coating was more likely to crack with climate and temperature changes. The field investigations on the defects of epoxy mortar materials in 1981, 2003, and 2015 indicate that cracking, warping, bumps, and edge cracking are the main damages occurring in the large-scale application of epoxy-mortar thin-layer structures. In 1981, over 200 cracks that were several meters long and 142 disengaging with a total area of 16.4 m^2 were found with increased surface cracking. In 2003, the density of cracks running through the layers were found to be rather even, usually at 0.23 m/m^2 to 0.51 m/m^2; 6 disengaging ranging from 0.1 m^2 to 0.3 m^2 were found during the digging of epoxy mortar on dam sections #7 and #8, of which dam section #7 showed a larger area of void of approximately 1 m^2 to 2 m^2 at the downstream side of the lower block. Jutao Hao et al. successively studied the large area mortar damage situation of Xin'an River in 1960s many times and carried out detailed investigation and analysis. These studies found that its failure forms were complex. However, the penetrating crack caused by low temperature was the primary failure form.

Great importance was attached to the improvement of the epoxy material in the previous repair. By reducing the elasticity modulus, curing shrinkage, and thermal expansion coefficient, the inner stress of thin layers can be reduced to improve the anti-cracking toughness and deformation, but problems such as cracking and void have not yet been solved completely. Elastic epoxy mortar and highly toughened epoxy mortar were developed to avoid the cracking of common epoxy mortar. An investigation of the performance defects of the elastic epoxy mortar and highly toughened epoxy mortar on the spillway of the plant from August to September in 2015 had been taken, it is indicated that these two types of epoxy mortar have fewer performance defects compared to common epoxy mortar, but cracking, fissure, warping, and bumps still exist.

Low temperature cracking is a significant reason for the failure of epoxy mortar thin layer protective structure and it will affect the integrality and safety of epoxy mortar.

3 DESIGN SPECIFICATIONS AND RESEARCH METHODS

3.1 Relative specifications

The Technical Code for Epoxy Resin Mortar (DL/T 5193-2004) was published and came into effect in 2004 and stipulated various aspects of epoxy mortar materials, including raw material quality, cured material property indexes and on-site construction quality control. However, there is no design method of epoxy mortar thin layer repairing structure in domestic and the relevant protective designs still belong to the empirical design. The Technical Specification for Abrasion and Cavitation Resistance of Concrete in Hydraulic Structures (DL/T5207-2005) only proposes that the ratio between linear expansion coefficient of abrasion resistance protective surface organic material and linear expansion coefficient of basement concrete should be less than 4. The requirement is too simple and insufficient to meet the operational requirements of a thin layer protective structure.

The foreign technical requirements of epoxy mortar are relatively complete, but the content about structure technical requirement is also lacking. In 1995, US National Traffic & Transportation Board jointly issued the Technical Guidance on Bridge Deck Polymer Concrete Thin Layer and proposed technical requirements for epoxy mortar. In addition, property requirements for concrete surface protective coating are proposed in the EN Concrete Surface Protective System (BS EN 1504-2:2004). In foreign standards of epoxy mortar or protective coating, the properties related to low temperature anti-cracking are mainly thermal expansion coefficient, cure shrinkage rate, tensile strength and elongation and compatibility tests which cover the property requirements of relevant materials. Among them, the thermal compatibility test can qualitatively inspect the low temperature anti-crack capacity of materials. This test method is also introduced into domestic Epoxy Resin Mortar Technical Regulations.

3.2 Domestic test method research

The epoxy mortar anti-crack property test is an important anti-crack application index, and main test methods include the ring test, tablet compatibility test and TSRST.

3.2.1 Cirque fracturing test

The cirque fracturing test is a test method which can qualitatively determine anti-cracking and interfacial disengaging resistance capacities of epoxy mortar and it's not a specification-stipulated standard test method. This method adopts the ring test piece. The inner ring of test piece is concrete and the outer ring of test piece is epoxy mortar thin layer with a thickness of 1cm. The inner diameter of concrete ring is 100mm, the outer diameter is 160mm, and the axial thickness is 60mm. The curing time of the test piece is 28d. During the test, put the test piece in the environment of -20℃ for 16h and then put it in the environment of 80℃ for 8h as one cycle. Check whether the epoxy mortar thin layer cracks and whether the interface between the epoxy mortar and concrete cracks in each cycle or not, etc. If the test piece has no crack in 10 to 15 cycles, then the epoxy mortar thin layer meets the anti-crack requirement.

The studies of Jutao Hao (2009) determined the cirque fracturing test method to be a relatively effective way to inspect thin layer structure failure properties which can evaluate the anti-crack capacity of polymer mortar thin layer on a concrete foundation during a temperature declination period and the layered failure resistance capacity during a temperature rising period. The crack stress of epoxy mortar has linear relationships with temperature variation, elasticity modulus and linear expansion coefficient of epoxy mortar.

3.2.2 Compatibility test

The compatibility test is another frequently used test method to qualitatively research the crack capacity and interfacial compatibility of epoxy mortar. The compatibility test method is to pour the epoxy material with 15mm thickness on concrete measuring 300mm×300mm×75mm. The test piece is put inside the refrigerating plant with a temperature of -20℃±2℃ for 24h after curing in normal temperature conditions for 7d. Then the test piece is removed and put in a room temperature condition (23±2℃) for 24h. This process is one cycle. The ASTMD884 standard stipulates that if the bonding interface and material itself have no cracking or fractures after 5 cycles, this kind of epoxy material is deemed to have good anti-crack capacity and can be applied in engineering. In the Epoxy Resin Mortar Technical Regulations, the test does not stop until cracks appear around the concrete or the sample reaches 30 cycles. Wu et al. (2015) proposed the temperature-drop compatibility coefficient on the basis of epoxy mortar compatibility test research.

3.2.3 Thermal stress restrained specimen test

The bitumen concrete pavement has certain similarities with epoxy mortar thin layer in the aspects of structural form and material property. The thermal stress restrained sample test (which is called TSRST) is a typical method to research the low temperature crack failure of bitumen concrete. The TSRST is a relatively common method in the bitumen concrete low temperature crack design application and it is based on the strength theory or deformation theory; this can simulate the stress development and crack failure of bitumen concrete in low temperature restrictive conditions and reflect the frost-break temperature and strength of bitumen concrete.

US Strategic Highway Research Program studies show that the TSRST can correctly simulate the site situation and comprehensively reflect the strength characteristics and stress relaxation characteristics of bitumen concrete. Domestic scholars have carried out many experimental studies on TSRST successively and results show that the thermal stress restrained sample test can truly evaluate the low temperature anti-crack capacity of bitumen mixtures.

The cirque fracturing test and the compatibility test are commonly used methods in the hydraulic epoxy mortar anti-crack capacity evaluation, which can reflect stress accumulation during the curing process of epoxy mortar and the stress development under the temperature variation conditions. They can also reflect the influences of different parameters on epoxy mortar crack. These two methods play a vital role in the processes of comparing the relative anti-crack properties of materials and guiding material research and development, therefore, although the ring test and the compatibility test have been adopted in the epoxy mortar selection of Xin'an River Hydropower Station Plant, they cannot specifically and quantitatively study the anti-crack capacity of material besides temperature and still need improvement.

The actual engineering application conditions are complex and changeable. The TSRST condition still has a great difference with actual engineering condition. Therefore, the TSRST must be cooperatively used with a complete anti-crack analysis model to reasonably predict crack stress and crack strength, and carry out the anti-crack design study of epoxy mortar.

4 ANTI-CRACK DESIGN INDEX RESEARCH

The low temperature crack problem of epoxy mortar thin layer repaired structure and the research contents involve the crack failure mechanism research and low temperature stress model research.

4.1 Mechanical evaluation index of epoxy mortar crack

At present, the property research indexes of epoxy mortar are mainly divided into two methods: One method is the strength theory which is developed by taking the material mechanics and structural mechanics as the assumes that the material is a homogeneous and continuous whole. This method is an important basis to the structural design of concrete materials in engineering practices; another method takes the fracture mechanics as the basis and assumes that there is an inherent defect existing in the material. The various material property parameters such as fracture mechanics are tested. As an important research means, the fracture mechanics is frequently used in the toughening study of epoxy polymer materials, and the toughening effect of polymer material is commonly evaluated by adopting fracture mechanics parameters. The fracture toughness property and anti-crack capacity static load test of ISO13586 are used in foreign and domestic researches to analyze the improvement status of material toughening effect.

Property parameters such as tensile strength and fracture toughness are the important index parameters for evaluating the anti-crack properties of epoxy mortar material. Due to certain complexities of actual engineering, it's hard to determine the specific various parameters of defects in the actual engineering such as size, shape and stress states which lead to crack parameters which laboratory studies cannot apply. Therefore, it has not been widely used in anti-crack designs. At present, the engineering sector often uses some macroscopic average stresses and strains to describe the strength of materials, e.g. all the traditional strength theories consider this as the criteria of crack or fracture, and take it as the theoretical basis of crack design.

4.2 Low temperature crack mechanism and strength model study of epoxy material

The studies of Kelsey et al.(1993) show that failure characteristics of epoxy mortar are related to temperature. When the temperature is lower than the vitrification temperature limit, the failure form is either along the interface between epoxy material and sand aggregate or exhibits epoxy failure itself, which can also present pulverulence upon brittle failure. Studies in epoxy resin strengths under different stress conditions of tension, pressure and torsion carried out by Fiedler et al. (2005) show that the strengths of different stress states present the parabola relationship between octahedral normal stress and octahedral shear stress. The failure form of epoxy mortar has certain relationships with temperature and loading speeds. The studies of Kanchanomai et al. (2005) show that the epoxy resin material has ductile fractures and brittle fractures in low and high loading speeds, respectively.

The anti-crack property of epoxy mortar has certain relationships with temperature and loading speed. The studies of Kelsey and Biswas (1993) show that the tensile strength has linear relationship with temperature variation when the temperature is lower than the vitrification temperature. The studies of Saburo Usami (1999) show that the tensile strength of an epoxy resin test piece with small defects increases along with the decrease of temperature. The studies of C. Kanchanomai (2005) show that when the loading speed of epoxy resin is in the range of 0.1-1000mm/min, the fracture displacement decreases along with the increase of loading speed and stabilizes in higher speed. The values of maximum load, stress cracking factor and strain energy releasing factor are higher and stable in low loading speed and the values are lower and stable in high loading speed. The transition loading speed is 10mm/min. The studies of M. Heidari-Rarani (2014) show that the fracture toughness value and the tensile strength value of polymer concrete decrease along with the increase of average temperature of temperature cycle test. The epoxy mortar used in hydraulic engineering or the vitrification temperature of epoxy resin material is generally higher than the normal temperature. The epoxy mortar material is in the vitreous state under low temperature conditions and its internal crack defect has certain similarities with glassy polymer.

In engineering applications, due to the vitrification temperature of epoxy material being relatively high, it will possess brittle failure properties in low temperature conditions or higher loading speeds. However, the inner stress of epoxy mortar is derived from curing shrinkage stress and temperature stress. In the condition that curing shrinkage residual stress is fixed, the loading speed caused by temperature difference variation is relatively small compared to indoor loading speeds. The failure form and strength criterion in low temperature conditions and low loading speeds still deserve further studies to determine.

4.3 Low temperature stress model study of epoxy material

As the surface protective material of hydraulic engineering structures, epoxy mortar needs to bear the impact of annual variation, day and night variation and water temperature variation. For the epoxy material thin layer structure restrained by basement concrete, its stresses mainly come from the volume variation caused by curing shrinkage and temperature variation, thermal expansion coefficient difference between coating and basement layer and extractum of epoxy components when curing in a humid environment; among them, the temperature stress accumulated due to temperature variation and shrinkage stress generated in the process of curing reaction are significant sources of internal stress. The daily temperature difference could even reach 60℃ in some extreme conditions.

Due to the variation of intermolecular forces, the epoxy mortar will possess volume shrinkage during the curing processes. Different systems have different shrinkage reasons which mainly include curing reaction, solvent evaporation and phase separation and some other chemical combinations. Various methods have been attempted to test the influences of curing shrinkage internal stress and temperature stress on polymer materials such as epoxy resin in domestic and foreign studies.

The epoxy resin is a typical viscous-elastic material and the epoxy mortar material is a mixed material which takes the epoxy resin as base. Its stress and strain capacities are affected by four factors of external force, basement deformation, temperature variation and environmental conditions (illumination, temperature and humidity and biology) . Generally, fix two factors to study the relationship between other two factors and the common tests are stress relaxation test and creep test. The polymer studies generally assume that its behavior meets the linear viscoelastic behavior in the conditions of small strain and low temperature . Saburo Usami et al. (1999) have tested that the creep rate of epoxy resin decreases all along with the increase of glass transition temperature and the decrease of test temperature. The studies of Kelsey and Biswas (1993) show that when the temperature is lower than the vitrification temperature, the modulus of compressibility also increases along with the decrease of temperature. The temperature stress of epoxy mortar is related to temperature and the mechanical relaxation also varies along with temperature. This process belongs to the temperature-varying viscoelastic process.

The epoxy mortar is a viscoelastic plastic material during the curing stage, and the stress-strain after curing is mainly dominated by viscoelasticity. As a surface repaired structure, the stresses of epoxy mortar material in low temperature conditions mainly are curing shrinkage residual stress and temperature stress. The residual stress of curing shrinkage can be measured through testing and the residual stresses of different systems have great differences. The temperature stress is related to temperature difference, linear expansion coefficient, modulus, and stress relaxation. Tests of relevant bituminous and epoxy resin materials have proven that all the linear expansion coefficient, modulus and stress relaxation capacities have a certain correlational relationship with temperature, and the modulus and stress relaxation parameters also have some relationships with loading speed and stress level. Although there are many analytical methods using the viscoelastic model and viscoelastic plasticity model to study the stress-strain characteristics of high polymer materials, relevant tests and model researches targeting at epoxy mortar are still very few at present and models can be used for the low temperature stress-strain analysis of epoxy mortar are still lacking.

5 CONCLUSIONS

The low temperature cracking of epoxy mortar is the main cause for failure of thin layer protective structure, and relevant supporting structure design method specifications and anti-crack research still need improvement.

The low temperature cracking of epoxy mortar mainly occurs in the temperature declination period of winter and the sudden cooling period after flooding in the summer. The current specification is the material qualitative selection targeting at the research and development of material properties. There is no low temperature anti-crack design specification of epoxy mortar thin layer structure, so the anti-crack design of protective thin layer structure cannot be conducted according to environmental conditions.

The ring test and the compatibility test are important methods for the material selection of epoxy mortar thin layer structure which can reflect stress accumulation during the curing process of epoxy mortar and the stress development under conditions of temperature variation. They can also reflect the influences of different parameters on epoxy mortar cracking, but they cannot specifically and quantitatively study the anti-crack capacity of material. The TSRST is an important research method for the anti-crack study of thin layer material, but it must be combined with anti-crack mechanisms and stress models of epoxy mortar to carry out research.

The tensile strength of epoxy mortar is an important index to evaluate the anti-crack capacity of epoxy mortar material. The crack form and the strength model of epoxy mortar are related to various factors such as temperature, strain rate and size. The stress sources mainly include curing shrinkage stress and temperature stress. Because of the characteristics of the material itself, it is necessary to establish the viscoelastic model for the constitutive relationship of the epoxy mortar.

REFERENCES

J. Hao, J. Zhu, Z. Bao, Y. Guan. Crack checking and analysis of epoxy mortar facing on the spillway of Xin'anjiang Power Plant. *Journal of China Institute of Water Resources and Hydropower Research*, 2004, 2(3): 204-207.

Technical Code for Epoxy Resin Mortar, DL/T 5193-2004. Standards of the Power Industry, National Development and Reform Commission, 2004.

Technical specification for abrasion resistant concrete of hydraulic structures DL/T 5207-2005 Standards of the Power Industry, National Development and Reform Commission, 2005.

AASHTO-AGC-ARTBA, Joint Cooperation Committee. Guide specifications for polymer concrete bridge deck overlays[M]. U.S. Dept. of Transportation, Federal Highway Administration, 1995.

Products and systems for the protection and repair of concrete structures —Definitions, requirements, quality control and evaluation of conformity —Part 2: Surface protection systems for concrete, The European Standard EN 1504-2:2004

Jutao Hao, Hao Huang, Shufang Mai. Cirque fracturing test for thin reinforcing structure of polymer mortar[J]. J*ournal of China Institute of Water Resources and Hydropower Research*, 2009, 7(3):199-205.

Wu Junming, Wang Wei. Relationship between different types of epoxy materials and low temperature compatibility of concrete [J]. Highway traffic science and technology: applied technology, 2015 (3)

Monismith C L, Secor G A, Secor K E. Temperature induced stresses and deformations in asphalt concrete[C]// Association of Asphalt Paving Technologists Proceedings. 1965.

ASTMD884 Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay[S]

ISO 13586：2000, Plastics – Determination of Fracture Toughness –Linear Elastic Fracture Mechanics Approach (2000).

Kelsey, R. and Biswas, M. (1993). Thermomechanical Properties of Epoxy Mortars." ASCE Journal Materials in Civil Engineering, 5(2)：187–197.

Fiedler, B., Hobbiebrunken, T., Hojo, M., Schulte, K. Influence of stress state and temperature on the strength of epoxy resins, http ： //www.icf11.com/proceeding/EXTENDED/3825.pdf. 11th International Conference on Fracture, Turin, Italy, March 20-25, 2005.

C. Kanchanomai, S. Rattananon, M. Soni, Effects of loading rate on fracture behavior and mechanism of thermoset epoxy resin, Polymer Testing, Volume 24, Issue 7, October 2005, 886-892

Saburo Usami a, H. Ejima b, T. Suzuki a, K. Asano Cryogenic small-flaw strength and creep deformation of epoxy resins Cryogenics 39 (1999) 729-738.

M. Heidari-Rarani, M.R.M. Aliha, M.M. Shokrieh, M.R. Ayatollahi, Mechanical durability of an optimized polymer concrete under various thermal cyclic loadings – An experimental study Construction and Building Materials 64 (2014) 308–315.

Joshua V. Brien, Kamyar C. Mahboub, Influence of polymer type on adhesion performance of a blended cement mortar. International Journal of Adhesion and Adhesives, Volume 43, June 2013, Pages 7-13.

Knudsen, O. Ø., Bjørgum, A., Frydenberg, T., and Johnsen. R. (2006). “Development of internal stress in organic coatings during curing and exposure.” 61st Annual Conference & Exposition, Corrosion NAC Expo 2006：1-10.

Askheim, E., Nokeleby, J.O. Why do paints crack? Ballast tank coating study focusing on brittleness and loss of flexibility. *Protective Coating Europe*, 2001(3)：49-55.