Evaluation of cracking behavior of concrete using temperature stress testing machine

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Abstract. At early age, concrete restrained stress can be generated once the deformation is restrained by adjoining members or foundation. Concrete will crack when the tensile stress exceeds its tensile strength. Creep plays an important role on lowering restrained stress and postponing cracking time. This paper presents elaborate descriptions regarding equipment principle, components and main functions of temperature stress testing machine (TSTM) developed by IWHR, as well as a typical case of TSTM application.

1. Research background
Concrete has quite large volume deformation during hardening [1-4]. When deformation and constraint, the two basic elements of stress generation inside a concrete structure, are formed, the concrete will be at risk of cracking. Creep deformation is also a material property dependent on time, which gradually slows down with aging [3]. It can significantly reduce the risk of cracking if the properties of creeping relaxation of concrete under long-term loading are taken into consideration [5-9]. In order to study the stress development and cracking mechanism of concrete under restraint, multiple test methods have been designed, including plate method [10], ring method [11], and crack test frame method [12], which, however, revealed their weaknesses as the research deepens.

Springenschmid designed the first generation of concrete temperature stress test machine (TSTM) in the 1980s, and verified its effectiveness in judging concrete cracking performance through experiment [13]. Bloom and Bentur [14] and Kovler [15] continued to improve the machine, and developed the second generation, as shown in Figure 1.

In 2017, China Institute of Water Resources and Hydropower Research and Development developed a new concrete cracking simulation test machine with improvements in the systems of temperature controls, measurement, and loading, which is able to conduct real temperature stress test of concrete under different restraint, cooling rate, and environmental conditions. This paper aims to introduce the features and main functions of the new concrete cracking simulation test machine.
2. Insufficiency of existing trials and research methods

2.1. Lack of the process of temperature rise—temperature drop of concrete
The process of temperature rise—temperature drop occurs after concreting, affecting the development of concrete hydration (material parameters). The existing specifications require that the constant-temperature environment should be used to maintain standard specimens and measure the parameters of each age, which, however, is inconsistent with the actual state of the concrete. Some scholars also take into consideration the influence of temperature change by means of maturity, which is not accurate enough.

2.2. Lack of concrete material parameters in the early age (casting ~3d)
Since large-volume concrete can not have significant temperature rise of hydration, its overall strength is weaker than that of high-strength/high-performance concrete. Due to the limitations of demoulding and testing equipment conditions, in the current studies on concrete material ratio, the age of compression/elastic test exceeds than 3d, and the age of ultimate tensile test exceeds 7d so as to prevent damage to the test piece during demoulding.

2.3. Lack of real confinement state of concrete
The traditional optimization of concrete proportion only concerns the measurement of material parameters, but not the confinement state, thus unable to reflect the actual working state of concrete. In actual projects, the constraint state of each point of the concrete structure is different, and the large-volume concrete structure is divided into strong-weak-free zones.

2.4. Lack of means of rationality test of concrete quality control
The traditional concrete material design mode fails to reflect the evaluation of temperature history at the component/structural level on crack resistance. Reasonable temperature control process (casting temperature, maximum temperature, target temperature of first cooling, target temperature of secondary cooling, stable temperature, etc.) is important for preventing cracking at early age and controlling the tensile stress at late age.

2.5. Lack of equipment for concrete crack resistance evaluation
There are two commonly used methods for evaluating crack resistance, as shown in Figure 2. The first method is called the ring method, which is applied to the test piece with a small section (particle size less than 20 mm), making it suitable for the mortar test piece; the second is the flat plate method, which can only qualitatively observe the time and distribution of the crack generation with poor data expansion. The most important defect of the above test methods is their incapacity in controlling the temperature of the test piece and considering the most important hydration heat factor of mass
concrete.

Figure 2. Traditional concrete cracking resistance capability evaluation tests

3. TSTM

The TSTM is mainly used in the concrete temperature stress test. It can obtain the development process of the self stress of concrete, and material parameters. It can also simulate the temperature stress and cracking mechanism under the influence of natural factors so as to evaluate the crack resistance of concrete. The photo of TSTM is shown in Figure 3.

Figure 3. Photo of TSTM

3.1. Temperature control system (-20 °C ~ 80 °C)

Temperature control system is mainly made up with heating/cooling equipment and the circulation system. The concrete temperature is indirectly controlled by adjusting the temperature of the circulating medium, as shown in Figure 4.

The temperature control mode of the equipment can meet the requirements of not only the rapid temperature change in the construction of roads and bridges, but also the 0.3°C daily temperature drop of hydraulic concrete structures, which is significant for realizing accurate temperature control simulation of large-volume concrete in the laboratory. Figure 5 shows the temperature history simulation obtained by TSTM.

Figure 4. Temperature controlling system     Figure 5. Measured temperature history
3.2. Displacement control system (accuracy of 1 μm)
The displacement control system is mainly used to measure the deformation of free and constrained specimens, control different confinement levels, and obtain material parameters (elastic modulus, thermal expansion coefficient, etc.). The advantage of the displacement measurement method of this device is in its direct displacement measurement method, which is more reasonable than the indirect one used by the conventional equipment.

3.3. Load measurement system
The load sensor attached to the end of the test machine measures the load of the constrained test piece and monitors the development process of the pressure/pull stress of the concrete. The equipment can satisfy the loading requirement of bidirectional 200 kN tension and pressure with the maximum tensile stress reaching 8.9 MPa.

3.4. Environmental simulation system
The simulation of the boundary of the concrete environment can be realized using the controls inside the environment box of the test machine.

4. Functions

4.1. Test of concrete linear expansion coefficient
Based on the curve of applied temperature and the displacement data of the free test piece measured using LVDT, the linear expansion coefficient of concrete at any age can be obtained, as shown in Figure 6.

4.2. Test of concrete temperature stress
According to the applied constraint degree and the displacement data measured using LVDT, the curve of constraint stress development of concrete under arbitrary constraint can be obtained, as shown in Figure 7.

4.3. Risk assessment of concrete cracking
According to the obtained parameters of cracking temperature and cracking stress, the cracking sensitivity of concrete under any constraint and temperature history can be evaluated, as shown in Figure 8.

5. Engineering applications
The Wudongde Hydropower Station in Jinshajiang is a key construction project in the 13th Five-Year Plan for National Hydropower Development in China. It is 300m high with low-heat cement concrete used in the whole dams, which is the first of its kind both at home and abroad.

The TSTM is used to study the strength development, cracking resistance and mechanism of low-heat cement concrete of Wudongde Dam, thus providing multiple technical support for the temperature control, constraint control, and concrete raw material ratio, ensuring the safe construction
of Wudongde Dam. Figure 8 compares the cracking risks of low-heat cement concrete of Wudongde Dam with different restraint degrees and temperature histories based on the TSTM.

![Figure 8. Effect of restraint degree and temperature history on cracking potential of concrete](image)

Figure 8. Effect of restraint degree and temperature history on cracking potential of concrete

6. Conclusion

Study and relevant test method concerning the whole-process simulation test technology of concrete cracking based on the TSTM provides a new path for applying concrete materials in engineering structure: (1) more realistic reflection of engineering practice (including different degrees of constraint, cooling rates and real temperature stress of concrete under different environmental conditions); (2) directly measurement of the material properties of concrete (including elastic modulus, thermal expansion coefficient, creep, autogenous volume deformation and other basic material mechanical parameters), especially in early age, thus laying a solid foundation for simulation calculation; (3) judgement of concrete performance in different water cooling conditions, constraint modes, curing ages, cooling rates, and humidity, wind speed, temperature drop, thus revealing the actual crack resistance and cracking properties of concrete.

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