# Comprehensive Evaluation of Crack Resistance for Dam Concrete Based on Temperature Stress Testing Machine

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***ABSTRACT.*** *In order to comprehensively evaluate the crack resistance, a temperature stress testing machine is used to investigate the anti-crack ability of dam concrete. Wet sieved dam concretes have been tested in semi-adiabatic conditions. The full development process of the mechanical, thermal and deformation properties of concrete during early age is monitored and testing time can be shortened dramatically by the temperature stress testing machine. With comparing with single parameters tested by standard methods and the testing data from similar research, it is concluded that cracking temperature is reasonably adopted as direct evaluating index to effectively contrast the anti-crack ability of different concrete. The coefficient of linear expansion, which reflects the combined effect of autogenous shrinkage and thermal deformation, tested by TSTM is more useful for temperature stress analysis than the thermal coefficient tested by standard method. This testing method has broad prospect in the mix proportion optimization and crack resistance evaluation of dam concrete.*

## 1. INTRODUCTION

Concrete cracking of the large-scale water conservancy structures is always the hot topic and difficult problem. Concrete structures of hydropower projects, which are represented by Jinping 305m high arch dam, the highest arch dam in the world, propose higher demand on the crack resistance of concrete. How to objectively evaluate the crack resistance is an urgent problem to be solved for the engineering and technical personnel . The disadvantages of generally used crack resistance evaluation index, such as ultimate tensile strain value and adiabatic temperature rise, have been recognized. However, there is no standard test for cracking evaluation due to the retrained shrinkage. The most commonly used ring test and plate test can be informative with respect to the comparative resistance of different concretes. Plate test is suitable to simulate the thin-walled structures and the concrete structures with large exposure area. Ring test is appropriate to evaluate the influence of drying shrinkage and autogenous shrinkage during early ages. The defects of these two methods are that they can not simulate the temperature development process, restraint degree can not be varied, the stress development can not be monitored, the maximum size of aggregate is limited and the discrete data make analysis difficult, etc. A suitable testing method for comprehensively evaluating the crack resistance of dam concrete is urgently needed.

The first application of temperature stress testing machine (TSTM) for evaluating crack resistance of dam concrete is in Austria during 1983-1985. The TSTM was firstly invented to compare the crack resistance of concretes with different cements for the 186m high Zillergrundl dam. But there is no other report for its application on dam concrete research except literatures [1,2,3]. The objective reasons of this phenomenon are that the cementitious materials content of dam concrete is lower than that of normal concrete, the flowability of dam concrete is bad for its bigger aggregate size(maximum size is 120mm or 150mm), and it is hard to vibrate and compact. The absolute values of stress and deformation of dam concrete are lower than those of high strength concrete and high performance concrete. Therefore, advanced measuring and controlling ability and high accuracy for the manufacture of frame members and components are required. With the development of high range water reducer, the renovation of the technology of measuring and controlling and the improvement of the machining precision, it is well-timed for TSTM to be used to evaluate the crack resistance of dam concrete at present stage.

In this paper, TSTM was employed to evaluate the crack resistance of dam concretes including two kind aggregate combinations.

## 2. BRIEF INTRODUCTION OF TSTM

Based on cracking frame, TSTM was invented at the Building Materials Institute at TU-Munich by E.Gierlinger and R.Springenschmid in 1984 [3]. Kolver developed the closed loop instrumented restraining system in 1999 [4], as shown in Fig 1. There are free specimen and retrained specimen. The cross-head of free specimen moves without any restrain. The restrained specimen has two crossheads, one is rigidly fixed on the frame, and another is movable. The movable cross head is connected to step motor and can be positioned by the motor with a precision of about 5μm. The position of movable crosshead is controlled by a computer. The restrained degree of approximately 100% can be reached. The restraining force which is produced as a result of the crosshead control is measured continuously by a load cell. Stress measurements begin immediately after concrete casting. The temperature of the mould can be varied by a thermostat. With circulating system the restrained specimen and the free specimen share the same temperature history. The displacement of the movable crosshead of the concrete due to expansion or contraction is measured by a system which is independent from temperature changes. A LVDT or non-touched laser sensor is used to for precise measurement. During the test, the data of temperature, stress and displacement are recorded automatically. The TSTM used for this research is shown in Fig 2.

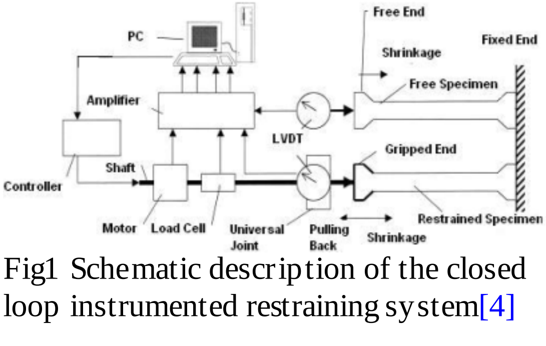

Fig1 Schematic description of the closed loop instrumented restraining system[4]

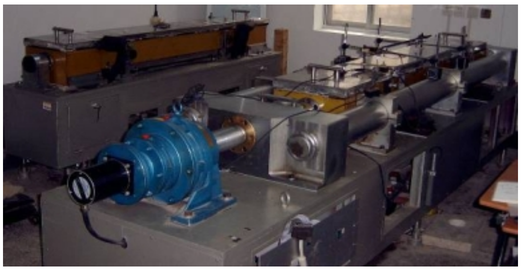

Fig 2 The TSTM used in this research

## 3. RAW MATERIALS AND MIX PROPORTIONS

Materials：P·MH 42.5 moderate heat cement，Class F fly ash， high range water reducer and air entrainment were used.

Fine aggregate is manmade sand, i.e. sand stonesand and marble sand. Table 1 shows the properties of fine aggregate.

Table 1 The physical properties of fine aggregate

| Type of fine aggregate | Fineness modulus | Content of stone powder（%） | Specific gravity（g/cm3） | Water Absorption（%） |
|---|---|---|---|---|
| Sandstone | 2.96 | 16.3 | 2.74 | 1.8 |
| Marble | 2.05 | 25.0 | 2.72 | 1.5 |

Coarse aggregate is manmade crushed sandstone. Table 2 shows specific gravity and water absorption of coarse aggregate. The content of flaky and elongated particles is less than 3.6% and the crushing index is not over 6.3%.

Table 2 The physical properties of coarse aggregate

| Size of aggregate（mm） | Specific gravity（g/cm3） | Water Absorption（%） |
|---|---|---|
| 5～20 | 2.72 | 0.8 |
| 20～40 | 2.74 | 0.5 |
| 40～80 | 2.74 | 0.4 |
| 80～150 | 2.74 | 0.2 |

Table 3 shows the mix proportions. Sand ratio and content of chemical admixtures were adjusted to control the slump in range of 3cm and 5cm.

Table 3 Mix proportions of concrete

| Series | Mix proportion（kg/m$^3$） | | | | | | | | | | Type of aggregate | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Cement | Fly ash | Sand | Coarse aggregate | | | | Water reducer | Air entrainment | Fine aggregate | Coarse aggregate |
| | | | | | 5～20mm | 20～40mm | 40～80mm | 80～150mm | | | | |
| SM | 84 | 155 | 66 | 386 | 421 | 452 | 469 | 419 | 1.1 | 0.133 | Sand stone | Marble |
| SS | 84 | 155 | 66 | 472 | 335 | 452 | 469 | 419 | 1.99 | 0.176 | Sand stone | Sand stone |

## 4. RESULTS AND DISCUSSIONS

A 2000mm long concrete beam of cross section 150mm×150mm is cast horizontally. The measuring system has an initial length of 1500mm. The sensitivity of temperature sensor is 0.1 ℃, and that of displacement sensor is 0.1μm. After 120s mixing, the coarse aggregate whose size is greater than 40mm is sieved. Then the fresh concrete was cast in formwork of the testing machine through vibrating and compacting. Copper tubes were embedded to place the temperature sensors. When the surface was finished, one layer of plastic sheeting was covered and then the top formwork was placed. The following step was to settle the sensors. The free water can not escape from the surface because the specimen is sealed by the plastic sheeting and formworks, so the drying shrinkage will not appear. The deformation of the concrete specimen includes autogenous shrinkage and thermal deformation. During the testing process the temperature of the laboratory was kept at 20±2℃, the influence of the deformation of the machine frame was minimized. The specimen was under semi-adiabatic condition, the temperature difference between concrete specimen and the circulating medium is less than 0.5℃. When the temperature reaches its maximum, it is kept at this point for 48 hours. Afterwards, the specimen temperature is reduced by 1～5℃/h. With further cooling tensile stresses occur until finally the beam specimen ruptures in a transverse fashion. Fig 3 and Fig 4 show the temperature and stress development process of the restrained specimen respectively. Fig 5 demonstrates the deformation of free specimen.

Table 4 shows key parameters of SM/SS. The maximum temperature and cracking temperature were almost the same；the maximum compressive stress during heating and maximum tensile stress at the time of cracking of SM is greater than that of SS，but the deformation of free specimen of SM is less than that of SS ( more than 20%). The difference of cracking temperature of these two concretes was 37.5℃. It was the most remarkable distinction of these two concretes.

The content of the cementitious materials and water binder ratio of the two mix proportions are same, so the difference of the maximum temperature of SM/SS is not noticeable. Comparing the thermal parameters of SM/SS (as shown in Table 5), the specific heat of SM is greater than SS. However, the thermal conductivity and thermal diffusivity of SM is less than that of SS. This difference is caused by the thermal properties of different aggregate. Li [ 5 ] investigated the effect of aggregate combinations on the thermal properties of dam concrete by using the same aggregate as we adopted in this paper, the results shows that when replacing the sandstone fine aggregate with marble sand the adiabatic temperature rise can be decreased 0.6℃. The maximum temperature rise difference of SM/SS is 0.7℃. So TSTM can sensitively reflect the effect of aggregate on the thermal properties of concrete.

To keep the maturity of two series concretes, after 125h the cooling rate of SM has changed from 1℃/h o 2.5～5.0℃/h. If the cooling rate is kept at 1℃/h, the age of SM at cracking will be prolonged and the cooling rate reduces the stress relaxation of SM.

Table 4 Key parameters of concrete SM/SS

| Series | SM | SS |
|---|---|---|
| Maximum temperature rise (℃) | 35.3 | 36 |
| Cracking temperature (℃) | -9.3 | 28.2 |
| Maximum compressive stress during heating (MPa) | 0.94 | 0.76 |
| Maximum tensile stress at the time of cracking (MPa) | -1.15 | -1.05 |
| Age at cracking (h) | 168 | 163 |
| Maximum deformation of free specimen ($\times10^{-6}$) | 349 | 425 |

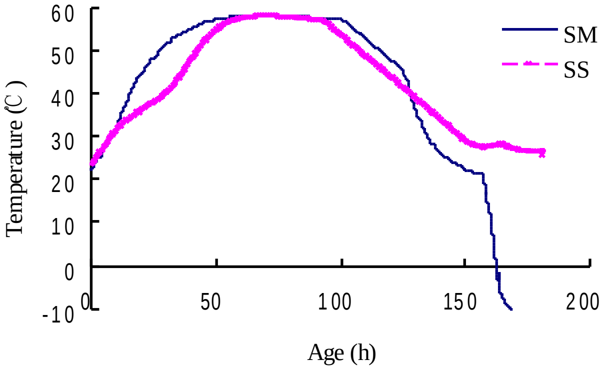

Fig3 Temperature versus age of SM/SS for restrained specimen

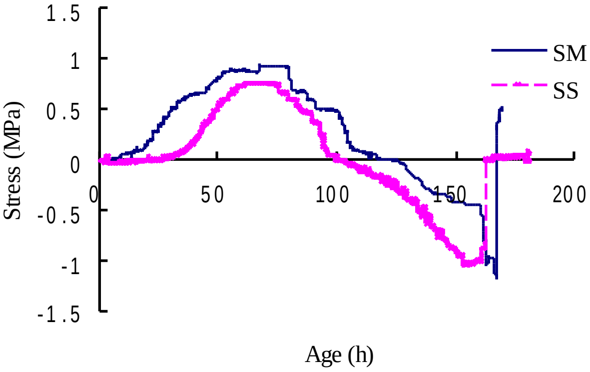

Fig4 Stress versus age of SM/SS for restrained specimen

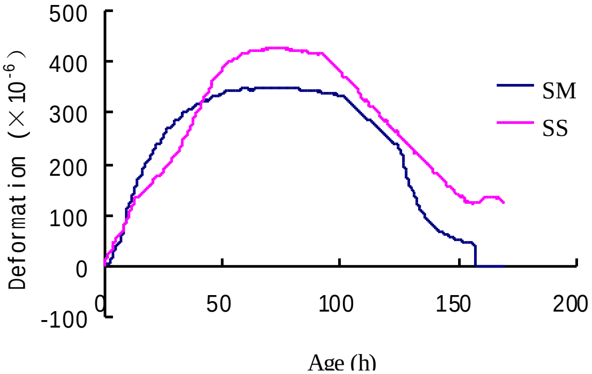

Fig 5 Deformation versus age of SM/SS for free specimen

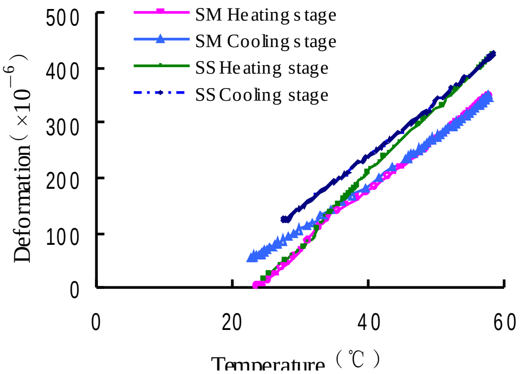

Fig 6 The relationship of deformation and temperature history of free specimen

Table 5 Thermal parameter of concrete SM/SS

| Series | coefficient of thermal expansion (×10$^{-6}$/℃) | specific heat (kJ/kg·℃) | thermal conductivity (kJ/m·h·℃) | thermal diffusivity (m$^2$/h) |
|---|---|---|---|---|
| SM | 8.1 | 1.008 | 9.187 | 0.003798 |
| SS | 9.7 | 0.892 | 9.598 | 0.004483 |

Due to the thermal coefficient and toughness of aggregate, the thermal coefficients of SM/SS have remarkable distinction. By fitting the relationship between deformation of free specimen and temperature rise, the coefficients of linear expansion of heating stage and cooling stage are acquired: for SM during heating stage $\alpha=10.0\times10^{-6}$/℃,during cooling stage $\alpha=8.5\times10^{-6}$/℃; for SS during heating stage $\alpha=12.2\times10^{-6}$/℃, during cooling stage $\alpha=9.9\times10^{-6}$/℃. Generally the coefficient of SM is lower than that of SS, which is similar to the result of standard test (as shown in Table 5). But the absolute value acquired by TSTM test is higher than that of standard test. This is because the coefficient of linear expansion reflects the effect of temperature on autogenous deformation and thermal deformation .At early ages, the thermal coefficient decrease sharply from $20\times10^{-6}$/℃ to $10\times10^{-6}$/℃ [6]. The autogenous deformation of concrete also increases rapidly at early ages [7]. The TSTM test comprehensively reflects the difference of linear expansion coefficients between the heating stage and the cooling stage. Since the thermal deformation and autogenous shrinkage happen simultaneously for inner dam concrete, the coefficient of linear expansion tested by TSTM is more useful for temperature stress analysis than the thermal coefficient tested by standard method.

### *4.1 Discussion on the evaluating index of concrete crack resistance with TSTM test method*

The maximum temperature is not suitable to evaluate the anti-crack ability of concrete although adiabatic temperature test is commonly performed. Springenchmid [1] studied the influence of cement varieties on the crack resistance with same mix proportion by TSTM, the results shows that the maximum temperature can not characterized the anti-crack ability of concrete (Fig 7). Take concrete with cement B for example, its maximum temperature is the second highest one, i.e.44℃, only 1℃ lower than the that of concrete with cement A. But when cracking temperature is considering, concrete with cement B has the lowest temperature, only 3.5 ℃.

The maximum compressive stress during heating is not suitable to act as the evaluating index, neither. Before concrete reaching its maximum temperature, the compressive stress has begun to relax. The degree of stress relaxation during the period of 48 hours with constant temperature is quite different. It changes with materials and concrete mix proportion. Springenchmid [1] investigated the degree of relaxation ranged from 0.11 to 0.50 for 7 concretes with different mix proportions. Shoppel [2] studied the degree of relaxation changed from 0.20 to 0.40 for 4 concretes.

When using the maximum tensile stress at the time of cracking to evaluate the anti-crack ability, its unreasonableness is evident. Different concrete endures different tensile stress because the deformation and Young's modulus are not developed in the same way. The ratio of maximum tensile stress and tensile strength is more rational [8], but it requires the uniaxial tensile strength of the concrete ,which shares same temperature history with TSTM specimens.

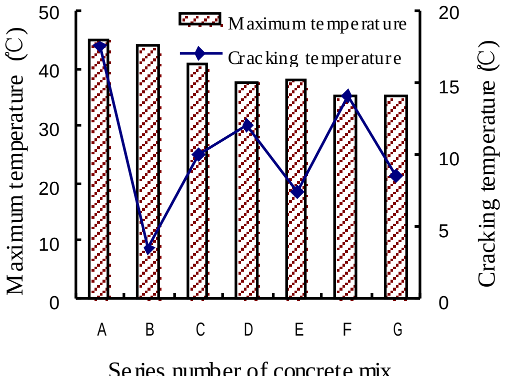

Fig 7. The maximum temperature and cracking temperature of concrete

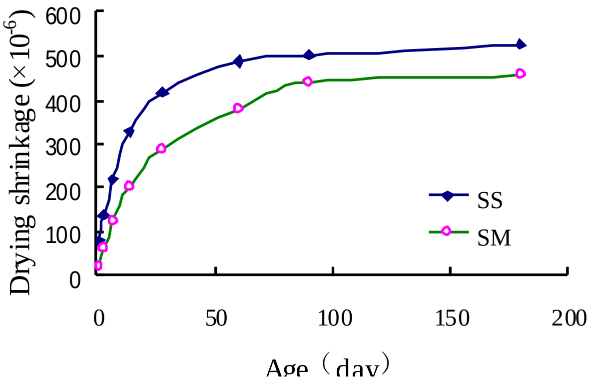

Fig 8 Drying shrinkage of SM/SS

As far as TSTM test is concerned, it is reasonable to use cracking temperature as index to evaluate the crack resistance of concrete. Cracking temperature depends on temperature rise due to heat of hydration, compressive stress during heating, tensile stress during cooling, degree of stress relaxation, Young's modulus, tensile strain capacity, coefficient of linear expansion and autogenous deformation. Cracking temperature determined by experiment is not a material constant [1]. RILEM TC119-

TCE3 " Testing of the cracking tendency of concrete at early ages using the cracking frame test " using cracking temperature as the index to evaluate the anti-crack ability of concrete. Springenchmid [1], Zhang [9] and Brettenbucher [10] also used this parameter to compare the crack resistance of concretes, and it is consistent with the practical behaviors of anti-crack ability of in-site concrete.

### *4.2 Discussion on the consistency of using cracking temperature and single parameters to evaluate crack resistance*

Single parameters tested by standard test method have always been used to compare the crack resistance of concrete. Table 6 shows compressive and splitting tensile strength of SM/SS. Fig 8 gives the drying shrinkage test results. The grading of aggregate and bond between coarse aggregate and mortar influence the mechanical properties. For SM/SS, they share the same coarse aggregate, so the difference of drying shrinkage of concrete is induced by the mortar. Tensile strength and drying shrinkage used to be acted as the parameter to compare the cracking tendency of SM/SS. From above mentioned results, SM has lower cracking tendency than SS. Li [5] studied the influence of aggregate combinations on crack resistance of Jinping Arch Dam. The results show that the cracking tendency of concrete with combined aggregate is lower than that of concrete with aggregate of sandstone. By using cracking temperature as the index to evaluate the crack resistance of concrete, the same result can be obtained as mentioned before.

Table 6 Compressive strength and splitting tensile strength of SM/SS

| Series | Compressive strength （MPa） | | | | Splitting tensile strength（MPa） | | |
|---|---|---|---|---|---|---|---|
| | 7d | 28d | 90d | 180d | 28d | 90d | 180d |
| SM | 25.5 | 37.9 | 44.5 | 48.7 | 2.38 | 3.72 | 4.04 |
| SS | 20.7 | 26.4 | 39.2 | 43.3 | 2.60 | 3.41 | 3.62 |

TSTM test is one reliable method for evaluating crack resistance of dam concrete. Comparing with single parameters tested by standard method, TSTM test reflects the full development process of properties of mechanical, thermal and deformation at early age. The evaluation results will be more objective. TSTM test can be finished within 200 hours. The standard tests have to last 90~180 days or even longer. The testing time and the workload can be remarkably reduced. TSTM has broad prospect in the mix proportion optimization and crack resistance evaluation of dam concrete.

With TSTM test, tensile creep, Young's modulus and fracture energy can also be achieved. With further improvement of our TSTM, these functions can be realized in near future.

## 5. CONCLUSIONS

1）SM has lower crack tendency than SS.

2）TSTM test is one reliable method for evaluating crack resistance of dam concrete.

3）Coefficient of linear expansion tested by TSTM is more useful for temperature stress analysis than the thermal coefficient tested by standard method.

4）As far as TSTM test is concerned, cracking temperature can act as the comprehensively index for evaluating crack resistance of concrete. The similar evaluating results can be obtained by using cracking temperature and single parameters.

5）TSTM test reflects the complete development process of properties of mechanical, thermal and deformation at early ages. The evaluating results will be more objective.

6）TSTM test remarkably reduced testing time and workload. TSTM has broad prospect in the mix proportion optimization and crack resistance evaluation of dam concrete.

## ACKNOWLEDGEMENT

This work was supported by National Nature Science Foundation of China (Grant No.50539040) and Special Fund for Public Sectors by the Ministry of Water Resources of China (Grant No.200701014).

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