Experimental study on mechanical properties of concrete under sub-high temperature cycles

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Abstract. Nuclear power plant containment, large storage tank, industrial cooling tower and some industrial plants under high temperature will be subjected to the sub-high temperature cycles from normal temperature to ~200 ℃. To explore the durability of the structural concrete, this paper carried out the experimental research on the mechanical properties of concrete under the cyclic environment of normal temperature to sub-high temperature (below 200 ℃). The uniaxial compression test of different strength concrete was carried out. The axial compressive strength grade ranged from 20 MPa to 70 MPa, and the changes in the appearance feature of concrete with different strengths after different number of times of sub-high temperature cycles were recorded. The evolution rules of mechanical parameters such as Young’s Modulus, peak strength, peak strain, and Poisson’s ratio under temperature cycles are obtained through uniaxial compression tests. The influence of sub-high temperature cycle on the macroscopic mechanical properties of concrete was studied. Moreover, the prediction formulas of mechanical parameters such as strength, peak strain, and Young’s modulus under different number of sub-high temperature cycles were established according to the test data.

1. Introduction
Concrete material is widely applied in the energy engineering structures such as containment of nuclear power plants, large storage tank structures. Therefore, it is essential for the serviceability of concrete structures in special temperature environment to study the influence mechanism of thermal cycling on the mechanical properties of concrete. The studies on concrete in high temperature mainly focus on the following aspects [1-6]: 1) the residual strength of different types of concrete at different temperatures; 2) the appearance feature, stress-strain relation, the transient thermal strain and deformation of concrete in high temperature; 3) the non-uniform thermal field induced by rising temperature and the thermal performance of different phases in concrete; 4) the physical or chemical changes in concrete on the meso-scale or micro-scale under different temperatures etc. It has been studied that high temperature or temperature cycling will influence the mechanical properties of concrete, and the performance of concrete will decrease as the number of loops of temperature cycling increases [7-11]. Concrete properties vary significantly with temperature and also depend on the composition and characteristics of concrete batch mix as well as heating rate and other environmental conditions [12-15]. As concrete is in a complex environment, the evolution of mechanical properties of concrete in some specific temperature conditions has rarely been studied. Based on this, the characteristic and reduction laws of mechanical properties of concrete in sub-high temperature cycling...
are studied in this paper, and it is promising to be of reference value for the design of special concrete structures.

2. Experimental part
Three batches of concrete prism specimens with different strengths are designed targeting at the strength from 20 MPa to 70 MPa. With different loops of sub-high temperature cycling, the uniaxial compression test was conducted afterwards. The influence of sub-high temperature cycling on the macro-scale mechanical properties of concrete are studied in a macroscopic way. And by combining large amount of test data, the prediction formula of mechanical properties of concrete with different strengths is fitted.

2.1. The design of the specimens and the material properties
The size of the specimens is 100 mm×100 mm×300 mm [16]. the specimens were casted in three batches: Test A (70 MPa), Test B (20 MPa), and Test C (50 MPa) with the number of specimens being 25, 44, and 25 respectively. The mixing proportion of the three batches is shown in Table 1. All of them use common high-early-strength portland cement with mark 42.5R in accordance with the CN standard [17]. The plasticizer was used as water reducer. The granite aggregates with 10~20 mm in diameter are applied in Test A as coarse aggregate. And the granite aggregates with 5~10 mm in diameter are applied in Test B and C. The common quartz sand is used as the fine aggregate [11]. In the mix procedure, the mixers were applied with respect to the mixing proportion listed in Table 1, and vibrators were used in the casting procedure to make sure that the concrete is evenly vibrated. The molds were removed after 48 hours and the specimens were cured for 28 days before the sub-high temperature cycling [9, 11].

Table 1. The design of concrete mix proportion.

| Concrete mix proportion | Water (kg/m³) | Cement (kg/m³) | Coarse aggregate (kg/m³) | Fine aggregate (kg/m³) | Water reducing agent (ml/m³) | Water cement ratio |
|-------------------------|--------------|----------------|--------------------------|------------------------|-----------------------------|-------------------|
| Test A                  | 192.6        | 440            | 978.6                    | 838.7                  | 1200                        | 0.44              |
| Test B                  | 218          | 440            | 985                      | 862                    | 1200                        | 0.5               |
| Test C                  | 206.8        | 440            | 966.5                    | 846                    | 1200                        | 0.47              |

2.2. Method for sub-high temperature cycling
After 28 days of curing of specimens, the sub-high temperature cycling was conducted by applying the Muffle furnace to raise the temperature and the natural cooling to reduce the temperature. According to the number of designed loops, the sub-high temperature cycling is simulated in the above procedure, and the typical heating and cooling profile is shown in Figure 1. The rate of temperature rising is 2 ℃/min, the constant-temperature time is 5 hours, and the number of loops is 0 to 50. The highest temperature of Test A is 200 ℃, and that of Test B and C is 150 ℃. The specimens were heated from the room temperature up to 200 ℃ in duration of 90 min or to 150 ℃ in 65 min. Then they were kept at the maximum temperature circumstances for 5 hours. After that, the Muffle furnace was opened for natural cooling in the laboratory atmosphere for 12 hours, following with the next cycle [11, 18]. For convenience, all the specimens were labeled by the number of batches and temperature loops. For instance, A1 represents the specimen in Test A that was tested in temperature cycling for the first loop.

2.3. Test and measurement equipment
After all the batches of specimens were finished in the temperature cycling procedure, the fore-testing preparation was carried out including:
1) Sticking strain gauge. Sticking of the strain gauge is to measure the Poisson’s ratio of the specimen, and in the meanwhile, to make sure that the specimen is in the state of uniaxial compression. Eight strain gauges were stuck on the side surface of the specimens, as shown in Figure 2.

2) Flattening the surface of specimens with plaster. In order to guarantee that the specimens are in perfect vertical state, the flattening work was conducted.

3) Installing the displacement meter. Hoops were installed to clamp the displacement meters (LVDT). The gauge length of the LVDT is 100 mm, and the model of LVDT is TML CDP-5 with 5 mm in range and 1 μm in accuracy. The installation location of the LVDT is shown in Figure 3.

4) The test was conducted. The MATEST 5000 kN test machine was used in the compression test, and displacement control was applied in the loading procedure with a loading rate at 0.18 mm/min. The JM3841 dynamic-static data collector was used to synchronously collect the data from LCDT, strain gauges and force sensors with the sampling rate at 1 Hz.

3. Test results and analysis

3.1. The influence of sub-high temperature cycling on the appearance feature of concrete

1) The change law in the appearance feature of concrete

The changes in the appearance feature of concrete after different number of loops of sub-high temperature cycling were recorded in the test. The change in appearance feature of high strength concrete in Test A at 50 loops of sub-high temperature cycling is shown in Figure 4. It is found that the surface of the specimen after 28 days of curing is relatively smooth with fewer holes, and micropores appeared after 1 loop of sub-high temperature cycling. As the loops of sub-high temperature cycling increase, the number of micropores increases. Microscopic cracks that are visible to the naked eye developed on the surface of specimens after 20 loops and the cracks were extended and new cracks were generated as the loops increased. The micropores are formed by the evaporation of free water in concrete, while the cracks are formed because there is difference in the coefficient of thermal expansion in different phases of concrete, and the sub-high temperature cycling induces the difference in the thermal expansion inside the specimen and causes thermal stress which then generates cracks. Comparatively, the change in the appearance feature of Test B and Test C after 50 loops of sub-high temperature cycling was not obvious, and no visible cracks appeared. Visible
microscopic cracks developed during the sub-high temperature cycling. The pre-set maximum temperature of Test A is the highest, which accelerates the evaporation of the free water and the hydration process, resulting in more micropores generated.

Figure 4. The appearance feature of specimens in Test A.

2) The mass loss of specimens

The mass loss of the specimens before and after the sub-high temperature cycling is recorded. As the mass loss of different batches of concrete is rare after the sub-high temperature cycling, and the mass loss of concrete below 200 °C is mainly caused by the evaporation of free water, which differs for each batch of specimens, only the mass loss with 50 loops of sub-high temperature cycling in Test B is taken as an example to study the influence of temperature cycling on mass loss. The mass loss of the normal specimen that is in the environment of laboratory without temperature cycling was also measured at the same time with the above three batches of specimen after each loop of sub-high temperature cycling. The mass loss of concrete is graphically shown in Figure 5 with fitted curves in exponential form of second order. It is seen that the mass of normal specimen keeps reducing after 28 days of curing, and reaches a stable state at the 13th loop. Overall, the total loss of mass compared with the original specimen after 28 days of curing is around 0.5%. However, for the specimens after 1 loop of sub-high temperature cycling, the mass loss is different from the normal specimen. Compared with the state after 28 days of curing, the mass loss of the specimen after 1st loop of sub-high temperature cycling is 2.75%, and the mass loss tends to stabilize after 3 loops, with a total loss of mass ~3%.

3.2. The macro-scale failure

It was set up that the test machine for uniaxial compression test of prisms would stop in the unloading procedure when the load reaches 10% of the peak loading. The failure state of concrete at the 10% peak loading is recorded after the test. The failure modes of the specimens at different loops of temperature cycling in Test C are listed in Figure 6. Cracks started to appear from the surface that was in contact with the test machine, and more microscopic cracks developed at the peak loading, finally the cracks on the top and bottom surfaces penetrated through the whole specimen to form a macro-scale crack with specimen failed. It is concluded that the failure of concrete is mainly in the types of shear type, cone type and split type, etc. The shear type is mainly caused by the clinodiagonal penetration crack between the top and bottom surfaces. The cone type is induced by the large friction between the surfaces of specimen and the test machine, which results in the difficulty for the ending surface to expand freely. The split type is caused by the large vertical penetration crack in the specimen. The failure mode of concrete is related to the distribution of aggregate or whether it is strictly uniaxially compressed, etc.

The failure mode of specimens without sub-high temperature cycling treatment is mainly in shear type, while the failure mode of specimens after sub-high temperature cycling is mainly in cone type. After the sub-high temperature cycling, when the specimen is unloaded to 10% of peak loading, collapses were generally found in the specimens, and lots of lump-shaped concrete or aggregates peel off from the specimens. However, for the specimens without temperature cycling that is unloaded to 10% of peak loading, a large penetration crack from top to bottom was generally found with rare aggregate peeled off from the specimen. It is found that the cohesive force of mortar and aggregate
will drop after the sub-high temperature cycling. The aggregates are easier to peel off after peak loading.

![Figure 5. Mass loss of concrete.](image)

![Figure 6. Typical failure modes under uniaxial loading.](image)

### 3.3. The influence of sub-high temperature cycling on the mechanical properties of concrete

1) Stress-strain curve

The information such as load and displacement was recorded in the whole process of the loading of the specimens. The signals of force sensors, the displacement meters and the strain gauges were synchronously sampled by the data collector. The signals of force sensors and displacement meters are used to calculate the stress-strain relation, and the signals of strain gauges are used to calculate the Poisson’s ratio. In Figure 7, the stress-strain curves of Test A, B and C after 0, 1, 10, 30 and 50 times of sub-high temperature cycling are listed. Only the curves of Test A after 10, 30 and 50 temperature cycling are from single specimen, while others are the calculated average value of a set of specimens.

It is found that as the number of loops increases, the peak stress decreases, and the ascending stage of the curve gets slower meaning the stiffness of concrete is degenerated and the ability to resist deformation is reduced. Except for the specimen in Test A after 50 loops that is unloaded quickly, other curves show that the descending stage gets gentler as the number of loops of temperature cycling increases.

![Figure 7. Stress-strain curves of the three batches of concrete after different temperature cycling.](image)

2) Compressive strength

The compressive strength of the three batches of concrete is counted and the mean values are calculated. The second order exponential function is adopted to fit the data. To compare the reduction range and analyze the reduction trend of compressive strength in the three batches of concrete, their compressive strength is normalized, and the resultant data are shown in Figure 8(a). The coefficients of determination are 0.61, 0.76, and 0.85, respectively. After the sub-high temperature cycling, the changing trend in the compressive strength of concrete is relatively similar, that is, the compressive
strength decreases as the number of loops of temperature cycling increases. The reduction range after the first loop is the largest, and the quantitative results are 12.97%, 17.41%, and 19.36% for the three batches. The reduction of compressive strength of Test B and C is close as concrete of normal strength is used in these two batches. However, high strength concrete is used in Test A, as the number of loops of temperature cycling increases, the reduction of strength is slightly gentler than that of normal concrete.

As shown in Figure 8(a), the second order exponential function can well represent the changing law of the compressive strength of different batches. Therefore, the prediction formula of concrete strength against the loop of sub-high temperature cycling is fitted by the second order exponential function based on the test data with the least-square fitting technique. The axial compressive strength of concrete is noted as \( f_c \), and the number of loops of temperature cycling is noted as \( x \). The prediction formula of compressive strength \( f_{cw} \) against the loop of sub-high temperature cycling is herein written as:

\[
f_{cw} = [0.18 \times e^{-0.0028x} + 0.81 \times e^{-0.0028x}] f_c \tag{1}
\]

3) The elastic modulus

The data of the elastic modulus of the three batches of concrete, the statistical mean value and the fitted curve are obtained from the tests. The second order exponential function is applied in the fitting procedure. For comparison of the elastic modulus of the three batches of concrete, the test data is normalized. The changing trend of the elastic modulus of the three batches is quite similar. The reduction in elastic modulus after 1 loop is the largest, and the reduction slows down afterwards. The elastic modulus of Test C dropped less than that of Test A and B in the first sub-high temperature cycling. The reason could be that the resting time of Test C is longer than the rest of the batches and the stiffness of concrete recovered partially.

The data of the elastic modulus of the three batches of concrete, the statistical mean value and the fitted curves are shown in Figure 8(b). The coefficients of determination are 0.68, 0.75, and 0.82, respectively. The second order exponential function can well capture the changing law of the elastic modulus of concrete against sub-high temperature cycling. Therefore, it is applied to fit the stiffness reduction trend of concrete based on the elastic modulus measured at different strength levels of concrete in the sub-high temperature cycling test. Taking the elastic modulus \( E_c \) of concrete at room temperature as a known constant, the prediction function of elastic modulus \( E_{cw} \) against the sub-high temperature cycling can be given by:

\[
E_{cw} = [0.32 \times e^{-1.05x} + 0.68 \times e^{-0.0042x}] E_c \tag{2}
\]

4) The peak strain

The test data, statistical mean value and fitted curve of peak strain in the three batches of concrete against the loop of sub-high temperature cycling are obtained, as shown in Figure 8(c). The coefficients of determination are 0.55, 0.69, and 0.79, respectively. The variance of the peak strain in the three batches of concrete is relatively large, but the overall trend is that the peak strain increases as the number of loops of sub-high temperature cycling increases. The changing trend in the peak strain of concrete in different batches can be well fitted by first order exponential function. As the number of loops increases, the stiffness of concrete reduces and the peak strain increases. The test data can be fitted by the first order exponential function. Taking the peak strain \( \varepsilon_c \) of concrete in the room temperature as a known constant, the prediction function of peak strain \( \varepsilon_{cw} \) of concrete against the loop of sub-high temperature cycling can be built as:

\[
\varepsilon_{cw} = 0.99 \times e^{0.005x} \varepsilon_c \tag{3}
\]
5) The Poisson’s ratio
To study the growth law of Poisson’s ratio against stress ratio under different loops of temperature cycling, the changing trend in Poisson’s ratio against stress ratio in Test B and C is normalized. The stress ratio represents the ratio of stress to the compressive strength. By taking different levels of stress, the evolution law of the Poisson’s ratio against the stress after different loops of sub-high temperature cycling can be compared. As the number of specimens in Test A after 3 loops of sub-high temperature cycling is scarce, the change in Poisson’s ratio is not recorded in this batch. The Poisson’s ratio appears to decrease as the loop of temperature cycling increases when the stress ratio is at 0.2. As the stress ratio increases, the Poisson’s ratio in different batches increases. The change in Poisson’s ratio of the specimen without temperature cycling in Test B is lower than that of the rest of the specimens.

4. Concluding remarks
The uniaxial compression tests of three batches of concrete with different strengths after different number of loops of sub-high temperature cycling are conducted. The appearance feature and the mechanical properties of concrete after different loops are compared and analysed. The prediction formulas of mechanical properties such as compressive strength and the elastic modulus against the number of loops of sub-high temperature cycling are fitted. Major conclusions are as follows:

1) The evaporation of free water in concrete causes the micropores and microscopic cracks to develop in the sub-high temperature cycling, and the change in appearance feature of the high strength concrete is more obvious than that of the normal strength concrete.

2) The sub-high temperature cycling will induce severe degradation in the mechanical properties of concrete. This is mainly reflected in the decrease of compressive strength, elastic modulus, Poisson’s ratio and the increase of peak strain. The reduction trend of elastic modulus of concrete with different strengths is the same, and the reduction of first loop is largest while slows down in the following loops.

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