Durability Experimental Study on the Heat-Supplying Tunnel Lining Structure under Thermal-Mechanical Coupling

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Abstract. Based on the operating heat-supplying tunnels in Beijing, the durability of its lining structure under the action of large thrust and thermal effect is studied. It mainly consists of two aspects, the disease composition analysis of the lining structure through ESEM-EDS and the indoor durability experiment. The field specimens' higher carbon content shown by ESEM-EDS indicated that carbonization was the main durability problem of the concrete lining structure of the heat-supplying tunnel. Considering the specific durability problem, the carbonization test of concrete under the action of temperature and stress was carried out. The results indicate that the coupling effect of high temperature- high tensile stress is the most unfavorable condition to the durability of tunnel structures. When the compressive stress increases from 0 to $0.5f_c$ (axial compressive strength of concrete), the carbonization depth decreases. If the compressive stress increases to $0.75f_c$, the carbonization depth will rebound.

1. Introduction

Distinguishing themselves from traffic and other municipal tunnels in terms of function and environment, heat-supplying tunnels are built for district heating pipelines in cold regions of the world. High-temperature fluid transmission throughout the pipe leads to the temperature rising in heat-supplying tunnels. In addition, the pressure pipeline also produces a huge longitudinal thrust on the tunnel structure through the fixed brackets in the tunnel. The coupling of large thrust by the operating pipeline and thermal effect is always accompanied by cold and hot cycles and dry and wet alternation, which leads to the decrease of structural durability and residual life. In Beijing, for example, a large number of heat-supplying tunnels were built in the 1990s. Heat-supplying tunnels in these regions were subject to structural degradation over time, causing latent risks to the above-grade traffic safety. Therefore, it is necessary to study the durability of the tunnel lining structure under the thermal-mechanical coupling effect.

As far as thermal-mechanical coupling is concerned, Many researchers [1-4] have conducted lots of researches on the tunnel structure under the effects of thermal-mechanical coupling mainly on the tunnel fire. In contrast with the existing researches, although the temperature of the operating heat-supplying tunnel cannot reach a high temperature under fire, the pressurized pipeline laid inside it will cause huge longitudinal thrust to the tunnel structure through the fixed brackets. High-temperature environment

leads to a long-term heat deterioration process for tunnel structures. This type of problem is a required field of study for evaluating the durability of heat-supplying tunnels, yet there are few preceding studies on this matter. For the durability of structures, most of the existing researches [5-7] relate to the above-ground structures. There are few reports on the durability of tunnels and underground structures.

In this paper, durability disease composition analysis based on the ESEM-EDS was conducted at first. As the result, carbonization was found to be the main disease of the operating heat-supplying tunnel. Then, considering the unique characteristics, the carbonization test of concrete under the action of temperature and stress was carried out. Ultimately, the study results may provide some theoretical supports for the life prediction of heat-supplying underground engineering.

2. Durability Disease Composition Analysis

2.1. Preparation
Firstly, it should be pointed out that the field specimens were produced from collected samples through field investigation on the heat-supplying tunnel. Then, the control group pieces were concreting referred to the same mixture proportion. Fig. 1 shows the observation specimens and the ESEM-EDS equipment.

(a)   (b)
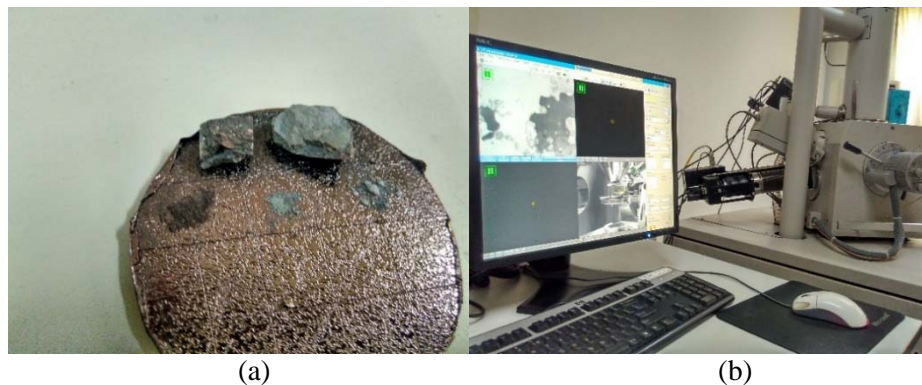
**Figure 1.** (a) Specimens, (b) FEI Quanta 250.

2.2. ESEM-EDS Results
The scanned images magnified 5000 of field specimens and control group pieces by FEI Quanta 250 environmental scanning electron microscope are shown in Fig. 2 (a) and (b). Fig. 2 (c) and (d) describe the results of Energy Dispersive Spectrometer analysis.

2.3. ESEM-EDS Analysis
As Fig. 2 (a) and (b) shown, the microstructure of heat-supplying tunnel lining before and after service is different. There are also differences in cement hydration phase structure, pore distribution and micro-fracture development. Comparing the field specimens and control group, the most remarkable change is that the $Ca(OH)_2$ phase of cement hydrate decreases greatly and the hexagonal prism $CaCO_3$ appears. The microstructure of the field specimens becomes loose with more cracks and pores. The reason for this is inseparable from a series of physical-chemical changes in lining concrete at the operating high temperature. High temperature may accelerate the carbonization of concrete and produced carbonized product $CaCO_3$.

Fig. 2 (c) and (d) display the EDS results. Chlorine cannot be detected in the concrete of field specimens, which indicates that there is rare chloride ions corrosion in the lining structure. The low content of sulfur indicates that the influence of SO_4^{2-} on the concrete structure is negligible in the surrounding rock environment. The content of carbon in the field concrete is 1%~2% higher than that of the control group. It can be concluded that the lining concrete in the heat-supplying tunnel absorbs CO2 from the environment. Moreover, carbonized product CaCO3 does exist in ESEM scan image.

Therefore, in view of this durability type, the carbonization effect of the lining structure can be focused on.
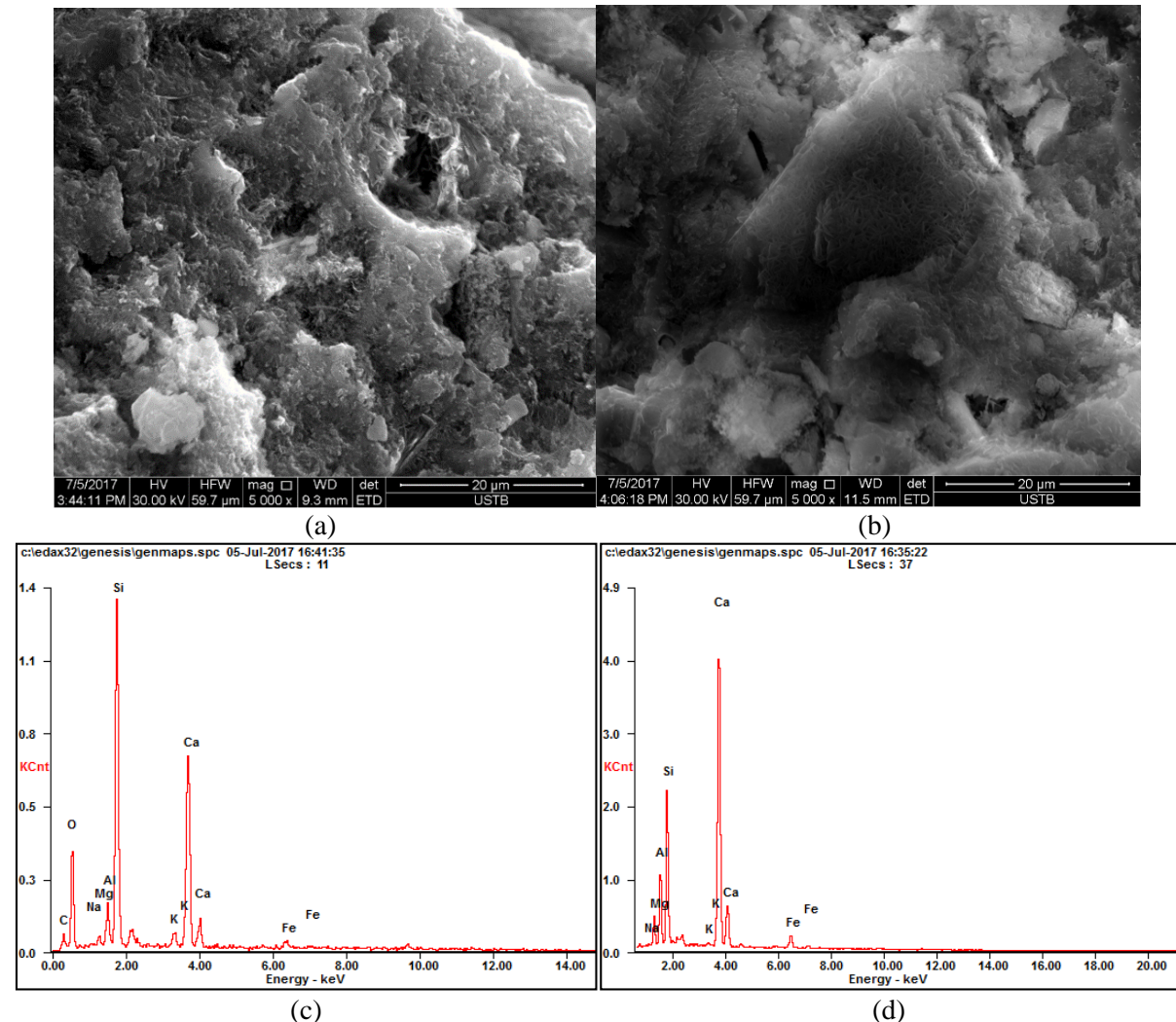
Figure 2. ESEM-EDS results. ESEM results: (a) field specimen, (b) control group; ED's results (c) field specimen, (d) control group.

3. Carbonization Test Under Temperature-Stress

The mechanical response of the lining structure of a heat-supplying tunnel under the condition of multi-field coupling in the operation period was obtained as Zhang [8] offered. Combining the research results and the characteristics of the high CO_2 concentration in the heat-supplying tunnel, the carbonization depth of concrete specimens under different temperature and stress conditions can be discussed.

3.1. Testing Scheme

According to the inner wall temperature of heat-supplying tunnel lining, the carbonization chamber temperature was set to three temperature states of 40^0C, 50^0C and 60^0C. Referring to the stress field distribution of the heat-supplying tunnel, the stress state would be set to 7 stress states. They were respectively non-stress state, the tensile stress state: $0.25f_t$ (axial tensile strength of concrete), $0.5f_t$, $0.75f_t$ and the compressive stress state: $0.25f_c$, $0.5f_c$, $0.75f_c$.

There are 12 groups of 36 rectangular test pieces with the size 100mm×100mm×400mm for compressive state and non-stress state test, and the rest 9 groups of 27 rectangular test pieces with the

size 100mm×100mm×450mm for the tensile state test. Considering the strength of lining structure concrete, all the test pieces were produced as standard C30 (Chinese standard GB50010-2010)[9]. The mix proportion is shown in Table 1.

Table 1. Mix proportion

Strength Standard	Cement /kg	Coarse Aggregate /kg	Sand /kg	Water Reducer /kg	Water /kg	W/C	Fly Ash	Fine Slag /kg
C30	220	1017	833	2.59	170	0.46	88	62

3.2. Testing Method

Test pieces were placed in carbonization chamber to accelerate corrosion, and it has the function of automatically controlling temperature, humidity and CO_2 volume. On the basis of GB/T50082-2009[10], the setting of the carbonization environment was as follows: volume fraction of CO_2 (20±3) % and humidity (70±5) %.

Considering the limited volume of the carbonization chamber and the actual stress state of the lining structure of the heat-supplying tunnel, the way to apply tension load should be the bending stress as shown in Fig. 3 (a) rather than directly applied axial tensile stress. On the other hand, axial compressive stress can be applied as Fig. 3 (b) performed.

(a)

(b)
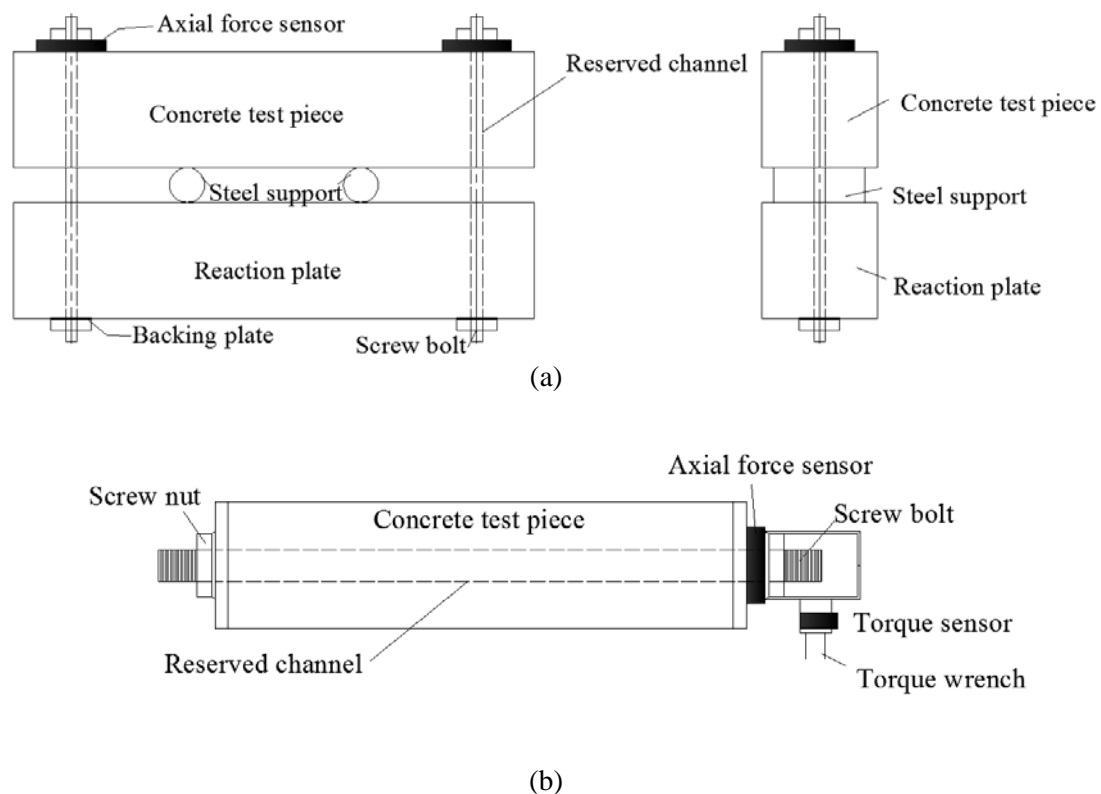
Figure 3. Loading method of test pieces. (a) Bending tensile stress loading method; (b) axial compression stress loading method.

3.3. Testing Results

Referring to the time span of the heating period of the heat-supplying tunnel, the carbonization depth of the concrete specimens were measured on 30d, 45d, 60d and 90d, and the results were respectively shown in Figure 4 (a), (b), (c) and (d).
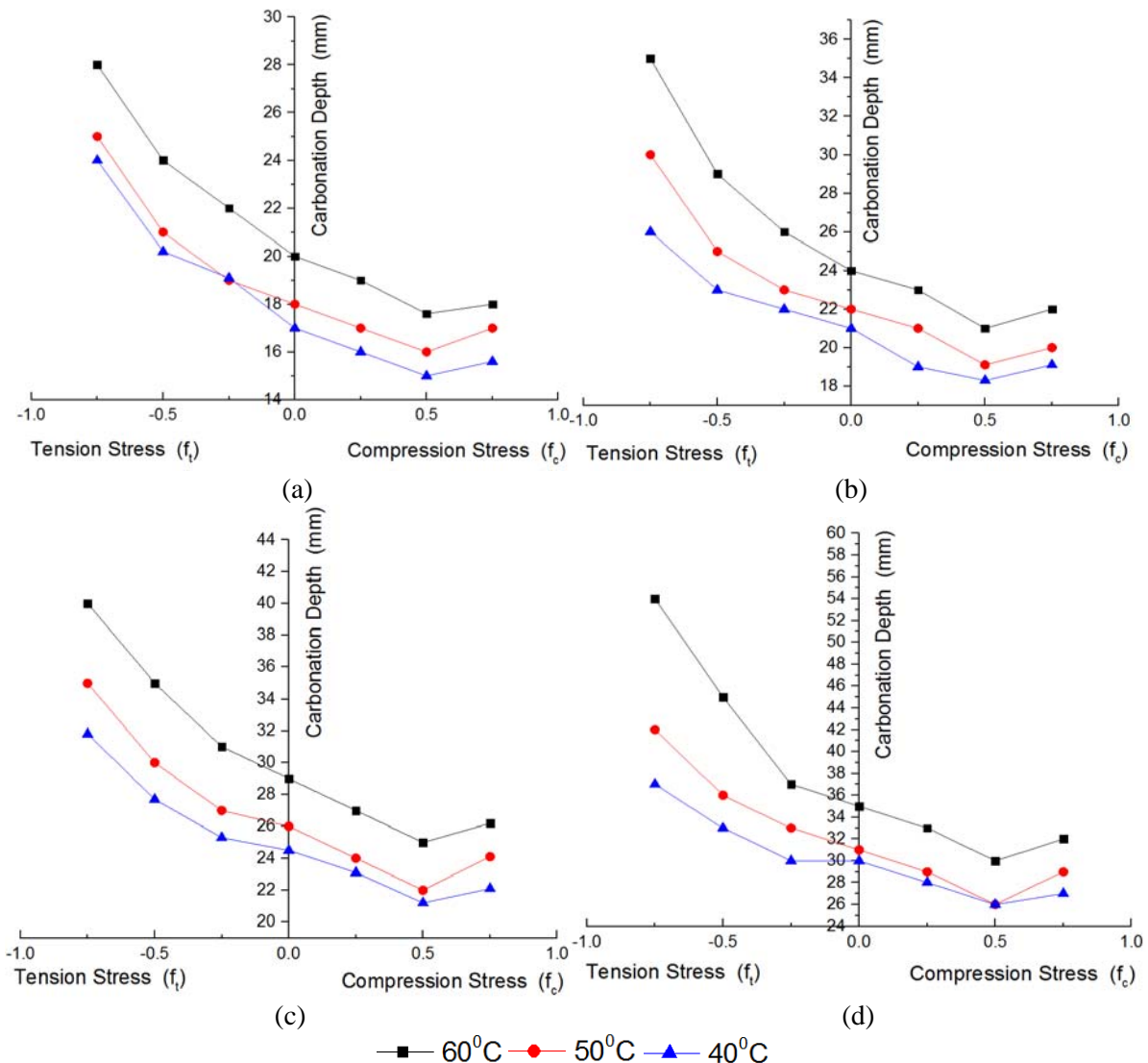
Figure 4. Relationship between carbonization depth and stress under different temperature.(a) 30d, (b) 45d, (c) 60d, (d) 90d.

Fig. 4 indicates that: (1) At the same observation time and under the same stress condition, the higher the temperature, the deeper the carbonization will be. It also proves that the heat-supplying tunnel needs to be ensured that the insulation layer wrapped outside the pipeline is intact to drop the high temperature on the inner lining as far as possible. (2) As the other conditions are fixed, the carbonization depth of concrete under tensile stress increases with the increase of tension. When the tension exceeds $0.5f_t$, owing to the large tensile stress that can rapidly expand and connect cracks in concrete, the carbonization depth increases more rapidly. The tensile stress area near the fixed brackets in the heat-supplying tunnel should be paid more attention. (3) Under the same temperature and stress environment, the carbonization depth of concrete structure increases with time. (4) The carbonization depth of concrete specimens

decrease as compressive stress increase within a certain range at the same observation time and under the same stress condition. This is because the pressure on the concrete can produce a certain compaction effect, which leads to the original cracks squeezed in the microstructure to prevent the invasion of CO_2. From Fig. 4, it can be found that the pressure range is within 0~0.5fc. When the compression exceeds $0.5f_c$ and reaches $0.75f_c$, the durability of concrete decreases. (5) Obviously, the carbonization depth increases most significantly under the coupling of high temperature and tensile stress. It is shown that the coupling effect of high temperature and tensile stress can aggravate the durability decline of heat-supplying tunnel structure.

4. Conclusion

In this paper, preliminary conclusions and recommendations are as follows:

- Through large amounts of ESEM-EDS analysis, Carbonization was the main durability problem of the concrete lining structure of the heat-supplying tunnel in Beijing.
- High temperature-tensile stress is detrimental to the heat-supplying tunnel lining structure in durability. The tensile stress area near the fixed brackets in the heat-supplying tunnel should be paid more attention.
- In contrast, compression is often considered to be beneficial, but when the compression increased to $0.75f_c$, the internal accumulation damages would lead to the rise of the erosion degree. It can be found that $0.5f_c$ may be an ideal state of stress on the durability.

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