

Experimental Study of Fatigue Damage Strength of Concrete Lining under Dry-Wet Cycles

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Abstract. The laboratory mortar test is used to simulate the actual force state of concrete lining in a dry-wet cycling environment of a high-temperature tunnel. The influence characteristics of temperature and the number of cycles on the lining concrete strength and strain are also explored. The test results suggest that the number of cycles has a great impact on the deterioration of the mechanical properties of the cement-based materials. During the early period, the higher the temperature, the more serious the loss of strength. As the number of cycle increases, the strength damage caused by dry-wet cycles gradually increases. Mortar test shows the fibbers have a good fatigue resistance. The quantitative results presented in this paper can be used as reference in similar projects.

1. Introduction

As part of a tunnel structure, lining concrete is in direct contact with the surrounding rock, and its fatigue damage strength property in a dry-wet environment is the key connection to effective stability of the supporting structure. In respect to the gradual occurrence of high temperature and thermal damage of a tunnel and the dry-wet condition, serious strength damage of the lining concrete might occur; in particular, under the action of cycling, the amount of lining concrete damage will increase continuously, which may lead to the loss of the supporting effect because of excessive strength damage. In engineering designs, if the lining fatigue effect is not taken into account, the safety and durability of a high-temperature tunnel will be greatly affected during the operational period, which may shorten the design lifespan of the tunnel or even result in the emergence of a safety incident.

In recent years many researches on the concrete lining of a high temperature tunnel are mainly focused on the distribution of the temperature field and stress field. A study was performed on the temperature distribution pattern of the rock surrounding the tunnel and the stress characteristics under an external high geothermal condition [1]. This study provides the stress characteristics of the lining structure influenced by external temperature. At the same time, some scholars carried out a study on damage degradation characteristics of different type of rocks [2-6], such as silty mudstone (2005), shale (2004), diabase (2014), etc., during a freeze-thaw cycle. The damage deterioration mechanism and mechanical properties of sandstone in different chemical solutions were studied after a freeze-thaw cycle, and it was found that the damage degree of sandstone gradually increases as the number of freeze-thaw cycle increases [7]. Han TL et al.[8]studied the damage characteristics of different rocks during a freeze-thaw cycle, and the results showed various differences in damage with a change in the number of freeze-thaw cycles and in temperature. In the studies above, although the influence of environmental factors, such as temperature and cycles, on the rock and concrete was



considered, a systemic discussion is still lacking for the fatigue damage characteristics of a lining concrete that is subjected to a dry-wet cycling action in high temperature field [9]. Obviously, more research is deserved to dispose the effect of environmental factors on the fatigue of concrete.

According to the high geothermal and high rock temperature environment formed by high temperature diversion tunnel in Xinjiang, China, and 0 °C of ice and snow melt water will pass the diversion tunnel during the operation period, the stress of the tunnel lining is very complicated. That is, the lining is in a wet state during operation while in a dry state during the maintenance period. So the lining concrete is subjected to alternating cycles of dry and wet.

Accordingly, the objective of this paper is to develop a fatigue damage law for concrete subjected to dry and wet cycles at temperatures. The fatigue damage strength of lining concrete in a dry-wet environment of a tunnel is simulated through the laboratory test. And the temperature is selected as the major parameter affecting the fatigue property of specimens because the mechanical performance and characteristics of concrete are significantly changed with temperature. In addition, the effect of cycles on fatigue is also considered. The objectives of this study are to investigate an influence of environmental factors such as temperature, dry and wet conditions on mechanical performance of mortar and concrete, and to evaluate the resistance to fatigue performance considering the temperature effect.

2. Program for Dry - Wet Cycles Test

2.1. Condition of Dry-Wet Cycles Test

The key to the dry-wet cycles test was the simulation of the dry-wet environment where the concrete lining was located. In this paper, the small specimens were selected to carry out the cycle test, and four kinds of curing conditions were chosen to simulate four kinds of dry and wet environment. To evaluate the temperature's effect on the mechanical properties, four different temperatures (25° C, 45° C, 60° C, and 80° C) were considered. The samples were molded at 25°C as a comparative object. The samples at 25°C could be molded in a room temperature environment. After being stripped, the samples were maintained in a curing room for 28 d.

For the samples in dry-wet cycles test at 45°C, 60°C, and 80°C, the samples were maintained at a given temperature for 28 d, and then they were placed in 25°C water to cool for 10 min after being removed from the temperature control box, see Figs. 1 and 3. The samples were naturally air-dried for 30 min after cooling, see Fig. 2; then, they were placed into a temperature control box for 1 hour, cooled in water for 10 min, and finally naturally air-dried for 30 min. Repetition of this process to simulate the dry-wet cycles effect on the samples. The water immersion test was performed according to the national standard GB 2575-89 "Glass fiber reinforced plastic water-resistance test method".



Figure1. Specimens immersed in water **Figure2.** Dried specimens after soaking **Figure3.** Schematic view of the cooling water temperature

2.2. Specimen Preparation

In order to show the effect of dry-wet cycles on cement-based materials clearly, this experiment replaced the concrete samples with cement mortar samples for production and maintenance. The

sample was a prism of 40 mm × 40 mm × 160 mm. Raw materials of the sample were as follows: the cement was Qinling general silicate cement of Shanxi (PO42.5R), the sand was a top-grade medium sand with a fineness modulus of $\mu_f = 2.9$ originally extracted from the Bahe River of Xi'an, and the mixing water was tap water. The three selected polymer fibers were polyester, polypropylene, and polyacrylonitrile. The fiber content of the sample was 0.9 kg/m³. The fiber property parameter and form were both shown in Table 1.

Table 1. The performance parameters of fibers

Type	Length /mm	Diameter /μm	Density /(g/cm ³)	Melting point /°C	Tensile strength /MPa
polyester	8	20	1.38	>249	>900
polypropylene	14	24	0.91	165	>400
polyacrylonitrile	12	12	1.18	260	>500

The mass ratio of sand/cement was set to 1.0. The specific material mix ratio of the sample was that cement: water: sand = 1:0.52:3.

2.3. Test Procedures

The dry-wet cycles test had four levels of cycles: 0 was the baseline, and the other levels were 10, 20, and 30 cycles. The specimens were classified as pure mortar (PM), polyester fiber mortar (PEM), polypropylene fiber mortar (PPM), and polyacrylonitrile fiber mortar (PAM). There were three samples for each combination of temperature and number of cycles, which results in a total of 192 specimens. The flexible strength of specimens was tested after the completion of the dry-wet cycles at the corresponding temperature. The maximum deviation between each specimen flexible strength test value and the average value was controlled within 10%.

3. Results and Discussion

3.1. Strength

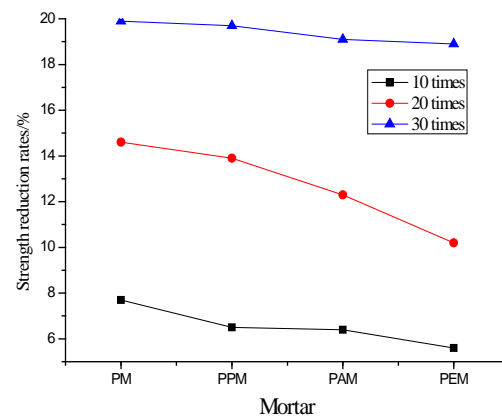
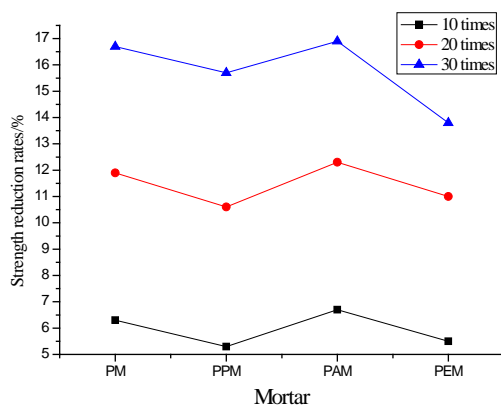
The experimental results were listed in Tables 2 and 3. The flexible strength distribution patterns were shown in Figs. 4 and 5. Compared with the strength under 0 cycle, the strength influenced by the dry-wet cycles was lower than that of 0 cycle. This strongly suggests that the sample fatigue effect was produced by the cycles, and its anti-fracture toughness gradually decreased.

Table 2. Strength results of specimens under dry-wet cycles /(MPa)

Type	Curing temperature /°C	the number of cycles			
		0	10	20	30
PM	25	4.13	3.87	3.64	3.44
	45	3.91	3.61	3.34	3.13
	60	3.61	3.28	3.01	2.8
	80	3.39	3.03	2.73	2.45
PPM	25	4.34	4.11	3.88	3.66
	45	4.31	4.03	3.71	3.46
	60	4.26	3.91	3.61	3.39
	80	3.96	3.62	3.33	3.11
PAM	25	4.32	4.03	3.79	3.57
	45	4.24	3.97	3.72	3.43
	60	4.13	3.87	3.59	3.44
	80	3.91	3.59	3.29	3.16
PEM	25	4.19	3.96	3.73	3.61
	45	4.11	3.88	3.69	3.33
	60	3.98	3.69	3.33	3.14
	80	3.82	3.54	3.32	3.09

Table 3. Strain results of specimens under dry-wet cycles

Type	Curing temperature /°C	the number of cycles							
		0		10		20		30	
		ε	$\varepsilon - \varepsilon_0$	ε	$\varepsilon - \varepsilon_0$	ε	$\varepsilon - \varepsilon_0$	ε	$\varepsilon - \varepsilon_0$
PM	25	0.363	0	0.388	0.025	0.429	0.066	0.478	0.115
	80	0.443	0.08	0.668	0.305	0.77	0.407	0.908	0.545
PAM	25	0.349	0	0.378	0.029	0.453	0.104	0.477	0.128
	80	0.421	0.072	0.525	0.176	0.643	0.294	0.727	0.378



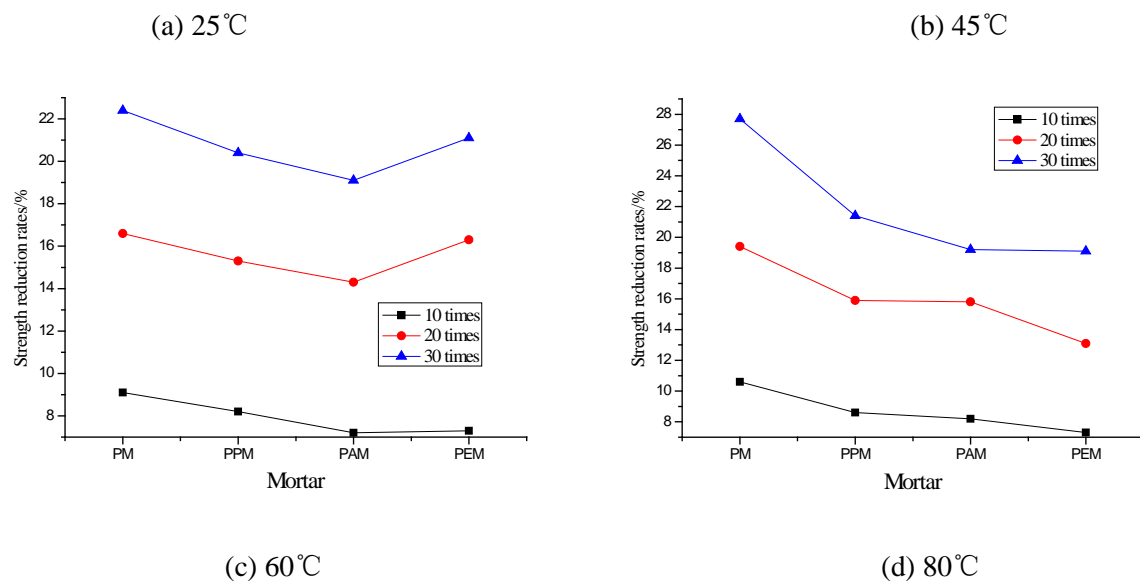


Figure 4. Relationship between the mortar strength reduction rate and the number of cycles at different temperatures

The flexible strengths of the pure mortar samples and the fiber mortar samples were shown in Table 2 for the experimental conditions of 0 cycle, 10 cycles, 20 cycles and 30 cycles.

Take samples at 60°C for example, the lowest strength reduction rates of four types of mortar after 10 cycles were, in order of large to small, polypropylene fiber mortar, polyacrylonitrile fiber mortar, polyester fiber mortar, and pure mortar. The lowest reduction rate was 5.3%, and the highest was 6.7%.

The lowest strength reduction rates of four types of mortar after 20 and 30 cycles were, in order of large to small, pure mortar, polyester fiber mortar, polypropylene fiber mortar, and polyacrylonitrile fiber mortar. The lowest strength reduction rates after 30 cycles was 20%, and the highest was 22%. And the degree of the strength reduction was even more severe at 80°C under dry-wet cycles.

It could be seen from Table 2 and Fig. 4 that (1) the sample strength decreased as the temperature increases for the same number of cycles, and (2) the sample strength decreased as the number of cycles increased at the same temperature.

In addition, the addition of fibers to the mortar could improve the loss of strength at the same temperature and cycles. For example, the strength of the pure mortar samples decreased 27% after 30 cycles at 80°C. But the strength of fiber mortar samples only decreased about 20% under the same test conditions.

3.2. Strain

Take pure mortar and polyacrylonitrile fiber mortar samples as an example. It could be observed in Table 3 that the strain of the pure mortar and polyacrylonitrile fiber mortar increased as the number of cycles and temperature increased. Correspondingly, the strain variation of the mortar specimens increased as the temperature and the number of cycles increased.

Compared with the strain at 0 cycle and 25°C, the strain of the mortar sample at 10 cycles increased by 0.025 at 25°C and 0.305 at 80°C, respectively. The strain of the mortar sample at 20 cycles increased by 0.066 at 25°C and 0.407 at 80°C. And the strain of the mortar sample at 30 cycles increased by 0.115 at 25°C and 0.545 at 80°C.

Based on the cumulative fatigue damage theory, a certain amount of fatigue damage would occur under any cyclic stress, and the severity of the damage corresponds to the number of cycles of a given stress amplitude. The cumulative fatigue damage was also affected by the number of non-cyclic loadings for the same stress amplitude.

It could be seen that the strain and strain variation of the mortar specimens increased with the increasing of temperature and cycle times. The mortar specimens showed the corresponding fatigue property. The results were consistent with the experimental results of Huang, Atkinson and Bassuoni[10-12] et al.

4. Conclusions

(1) For the same number of cycles, the mortar strength tends to decreased as the curing temperature increases. For a given temperature, the mortar strength decreased as the number of cycles increased.

(2) The strains of the mortar samples increased as the number of cycle increased, as well as when the temperature increased. Correspondingly, the amount of change in the mortar specimen strain also increased as the temperature and number of cycles increased. The incorporation of fibers facilitates improved strength and strain.

5. References.

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