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Research Article

Influence of Wet or Dry Conditions on the Fatigue Life of Grout Cementitious Materials under Cyclic Loading

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Grouting cementing material is a kind of sealing cementing material widely used in underground space. However, the influence of the fatigue life after cementation hardening is often ignored when subjected to, for example, cyclic traffic loads. Therefore, it also often causes engineering problems such as joint cracking, leakage, and plate bottom emptiness. The prediction of fatigue life of grouting cementation material is of great significance to the stability of underground tunnel structure. In this paper, the fatigue characteristics of hardened grout specimens under different fatigue loads and cycle frequencies are studied. Test the cyclic compression load repeatedly in different environments (dry or wet). The results show that the fatigue properties of grout materials are reduced in both air and water and significantly reduced when the stress level is 65% or above of static compressive strength in wet environment, especially when the loading frequency in water drops from 10 to 35 Hz. The main mechanism of fatigue life decline is splitting effect caused by water extrusion in the sample under cyclic loading. Water washes away abrasive action in the cracks. The dry-wet fatigue aging characteristics of superhigh strength grout cement materials lay a foundation for the evolution simulation of underground foundation structures under cyclic loading.

1. Introduction

In order to relieve the urban traffic pressure, the construction of underground tunnel traffic has been widely recognized by most countries [1]. The subway that runs through the underground of the city has very high requirements on the bottom foundation [2, 3]. Besides ensuring sufficient dynamic strength and small deformation, the life of the foundation material can not be ignored. Among them, the grouting material after track positioning has strict control on sealing, dynamic strength, and fatigue deformation. The underground foundations are all qualified when they are first built, but after several years of operation, various engineering problems such as cracking, deformation, and leakage are common [4–6]. Nowadays, in addition to the dynamic parameters of basic materials, more attention has been paid to their fatigue life. In the past, the research on foundation materials mostly focused on soil and concrete, but little attention was paid to grouting materials, which were often ignored in engineering modeling calculation and practical design [7]. However, more and more cases show that grout cementing material is especially important in track foundation filling, and its fatigue life parameters are indispensable.

Grouting, as a filling material, has the basic requirements of high intensity, strong fluidity, dense filling, and small drying deformation. Ordinary fine stone concrete has a good filling effect on the wide gap, but it is difficult to fill the narrow gap completely due to the limitation of fluidity and aggregate diameter, so it is easy to produce gaps. However, the high-performance grouting material has strong fluidity and fast flow speed, which can achieve self-leveling; a small size of aggregate can fill large and small gaps well to ensure dense filling of gaps. In addition, the strength of high-performance grout materials after filling and drying can reach approximately 10 MPa at 12~15 h, 20~30 MPa at 15~20 h, and 30~40 MPa at 24 h [8, 9]. Nevertheless, subway tunnels are usually located below groundwater level, and the evolution law of grout material properties is very complicated due to the influence of traffic cyclic load and dry and wet environment [10].

Myrtja et al. [11] quantitatively analyzed the fatigue behavior of grout by considering different stress levels and loading frequencies. The damage mechanism is analyzed from the aspects of strain development, temperature rise, and stiffness evolution. Results from the evolution of strain and secant modulus, it can be seen that similar to the compressive fatigue behavior of high strength concrete, the loading frequency has a significant effect on the degradation process. Otto et al. [12] explored the relationship between fatigue failure and specimen temperature rise in a large number of high-strength grout fatigue tests at a relatively high test frequency. The results show that the temperature rise degree of the specimen depends on many factors such as the type of cementing material, the size of the specimen, and the test frequency. One possible cause of this premature failure is the interaction of temperature rise and dehydration process against compressive strength. Kim et al. [13] studied the static and fatigue properties of grouting type transverse joints between precast concrete slabs. The shear and fatigue strength of grouting transverse joints are improved by determining the influence of prestress on the specimens. The results show that longitudinal prestressing is an effective method to improve the shear strength and fatigue strength of grouting transverse joints. Based on the static load test, a reasonable method to estimate the crack and ultimate load of grouting transverse joints is put forward. Boswell et al. [14] studied the details and results of test protocols carried out on tubular structures to determine the effectiveness of grout filling as a means of repairing the damage. The results show that the presence of grouting improves the strength of the pipe string compared with the same but unfilled damaged member. The study on fatigue strength of grout in the underground structure under wet and dry conditions is less than that under single dry conditions [15–23] Therefore, it is necessary to conduct further research on it. Most of the existing researches focus on the performance of cement slurry, but few study on the performance of special grouting materials, especially the life characteristics of grouting materials under fatigue load.

Accordingly, several groups of tests were conducted to investigate the fatigue life, performance, and failure mechanism of ultra-high-performance grout under different loads, different environments (dry or wet), and different loading frequencies in this paper. The ratio of ultimate load to test load and number of cycles to failure were analyzed; the formulas for calculating fatigue life of ultra-high-performance grout are proposed based on the regression analysis of the test results.

2. Specimens and Methods

2.1. Grout Specimens. The investigated grout was a commercially available product based on a high-performance cementitious binder material; it is a mixed powder of superplasticizer, ultrahigh strength sand ($0 \sim 4.75$ mm), and ultra-high-performance cementitious binder material contains silica fume and other active minerals and being prepared at certain water to a cementitious material ratio (0.09) which was at the range of recommended value in the product manual (0.09~0.12). The manufacturer claims that the strength of the product can reach 120 MPa under the standard curing conditions (20 ± 2°C, RH $\geq$ 90%, 28 d) for 28 days.

Within references [24, 25], the cylindrical shape specimens, 60 mm in diameter and 120 mm in height, were cast to investigate the fatigue life of grout material. To ensure the comparability of the test results, the same specimen size was used in this experiment. In addition, cylindrical specimens were used in this experiment, and the basic mechanical properties of grout material were tested according to the standard. All specimens were cast in the air; the formwork was removed after 1 d and then cured under standard curing conditions for 28 d.

2.2. Test Rig and Parameters. Ultimate limit state (ULS) test and fatigue tests are carried out on cylindrical specimens. The ultimate bearing capacity of samples of various sizes is tested first and is denoted as F_u. The fatigue tests are conducted on a servo-hydraulic actuator with a capacity of $F_{max} = \pm 500$ kN dynamic loading and loading frequency ranging from 0.01 Hz to 10 Hz. The actuator integrates a load cell and an LVDT to measure the load on a specimen and the deformation response. Only compression fatigue tests can be realized due to the properties of the test rig. The minimum and maximum load F and the corresponding deformation u per load cycle are detected and stored during the fatigue tests. The bearing plate is specially designed for the ambient changing purposes (in air and in water). A circular groove is cut around the circumference of the plate; then, a transparent acrylic tube is stuck in the groove. The joint is sealed with waterproof glue which can stick steel and acrylic together to prevent water leakage (Figure 1).

According to previous investigations [24–26], three parameters can be determined to have an influence on the fatigue performance of grout specimens, namely, ambient condition (in air, AC; and in water, WC), maximum compression load F_{max}, and loading frequency f. In this test, two ambient conditions (in air and in water), three maximum loads F_{max} (0.45 F_u, 0.65 F_u, 0.75 F_u), and two loading frequencies (0.35 Hz and 10 Hz) were considered. For the sake of saving time and energy, the loading frequency 0.35 Hz was only considered for the specimens in water condition so as to simulate real-time subway action, and the target number of cycles was set to either about two times of the results of Ref. [27] or 2 million. Detailed combinations of parameters are shown in Table 1.

At first, the static compressive strength F_u was determined using 6 cylindrical specimens at a loading rate of 1 MPa/s; then, another 6 specimens were tested in compression fatigue loading, force controlled, with a minimum load of 20 kN, and the specified maximum load, applied sinusoidally at a specified frequency. The minimum load of 20 kN was chosen to secure an efficient fixation of the specimen in the test machine at all time. The fatigue cycles were continued until the specimen broke or until a target number of cycles was reached [28].

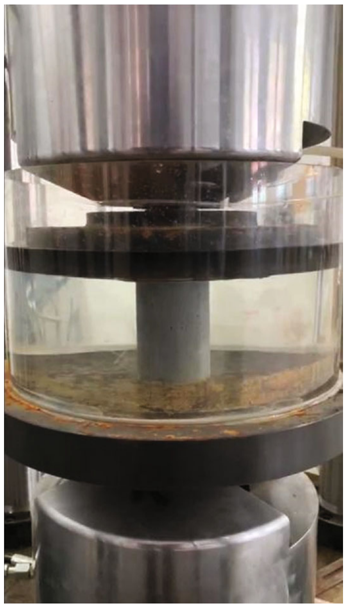

Figure 1: Test rig for the submerged fatigue tests.

Table 1: Combinations of test parameters and target numbers of fatigue cycles.

Maximum load	Environment	Loading frequency	Target number of fatigue cycles
0.45 F_u	In air	0.35 Hz	—
		10 Hz	2,000,000
	In water	0.35 Hz	—
		10 Hz	2,000,000
0.65 F_u	In air	0.35 Hz	—
		10 Hz	300,000
	In water	0.35 Hz	15,000
		10 Hz	300,000
0.75 F_u	In air	0.35 Hz	—
		10 Hz	50,000
	In water	0.35 Hz	3,000
		10 Hz	6,000

3. Results and Discussion

3.1. Static Strength and Stiffness. Figure 2 shows the strength and stiffness properties of the specimens. The figure includes information from the manufacturer's official data sheets and the results of independent material tests conducted during this test. In the independent material test, the compressive strength of specimens of different shapes was tested, and the mean value with a 95% guarantee was obtained. In addition to the compressive strength, the material's bending strength, tensile strength, and elastic modulus were also measured.

For the outlined test results, the mean strength and stiffness are higher than stated by the manufacturer. Clearly, the slender specimens tend to give higher variances. Furthermore, many lower limits of the 95% confidence intervals are still higher than the values stated by the manufacturer. These indicate that the material used in the fatigue test is stable and reliable. The independent test supplemented the information of the key parameters of commercial grouting and had a clear understanding of the basic static parameters after cementing. The test results showed that the grouting materials used in the test meet the requirements of engineering standards in tensile, compressive, bending strength, and elastic modulus parameters.

3.2. Fatigue Performance. The results of the fatigue tests are shown in Figure 3 for each individual specimen tested. In general, each test (at given maximum load, loading frequency, and environment) comprised 6 specimens. However, when testing at 0.75 F_u, 10 Hz in air, 3 out of 6 specimens were discarded because of nonparallel compression surfaces of the specimen. The series of 0.45 F_u, at 10 Hz, in air and in water, contains only 3 results, since each specimen takes about 3 days to reach 2 million cycles. Nevertheless, at 0.35 Hz, it takes more than two months to reach two million cycles, for which reason such test series were limited to a few specimens.

The specimens tested in water showed significantly lower fatigue strength than those in air. Figure 3 shows the fatigue result at 65% as well as 75% maximum stress level. However, under lower maximum stress and lower static compressive strength, the fatigue strength of specimens is basically the same. This is probably because the lower pressure makes the water's role in the fracture less obvious. In the air, several samples in each series survived more than two million cycles. The differential strain that may be caused by the moisture gradient of some dry specimens cannot explain this phenomenon, and the fatigue capacity of saturated samples is low. It has also been suggested that the decrease in wet sample capacity is due to the wedging of water trapped in cracks.

In general, the fatigue life increases with the decrease of the maximum load ratio linearly. The regression lines are shown in Figure 3. It was established based on 12 tests in air (AC) and 27 tests in water (WC):

$$\begin{gathered}\log N = -11.20 \cdot S_{\max} + 11.91\,; R^2 = 0.90, \\ \text{for} AC, \qquad f_p = 10\text{Hz}, \\ \log N = -11.00 \cdot S_{\max} + 11.76\,; R^2 = 0.91, \\ \text{for} \quad WC, \quad f_p = 10\text{Hz}, \\ \log N = -9.47 \cdot S_{\max} + 9.86\,; R^2 = 0.66, \\ \text{for} \quad WC, \quad f_p = 0.35\text{Hz}. \end{gathered} \tag{1}$$

Obviously, the fatigue life results vary in a wide range within each test series. This is similar to the fatigue behavior found for normal concrete which also shows a large spread of fatigue capacity. Since it is impossible to measure the static strength of each fatigue specimen, uncertainty is

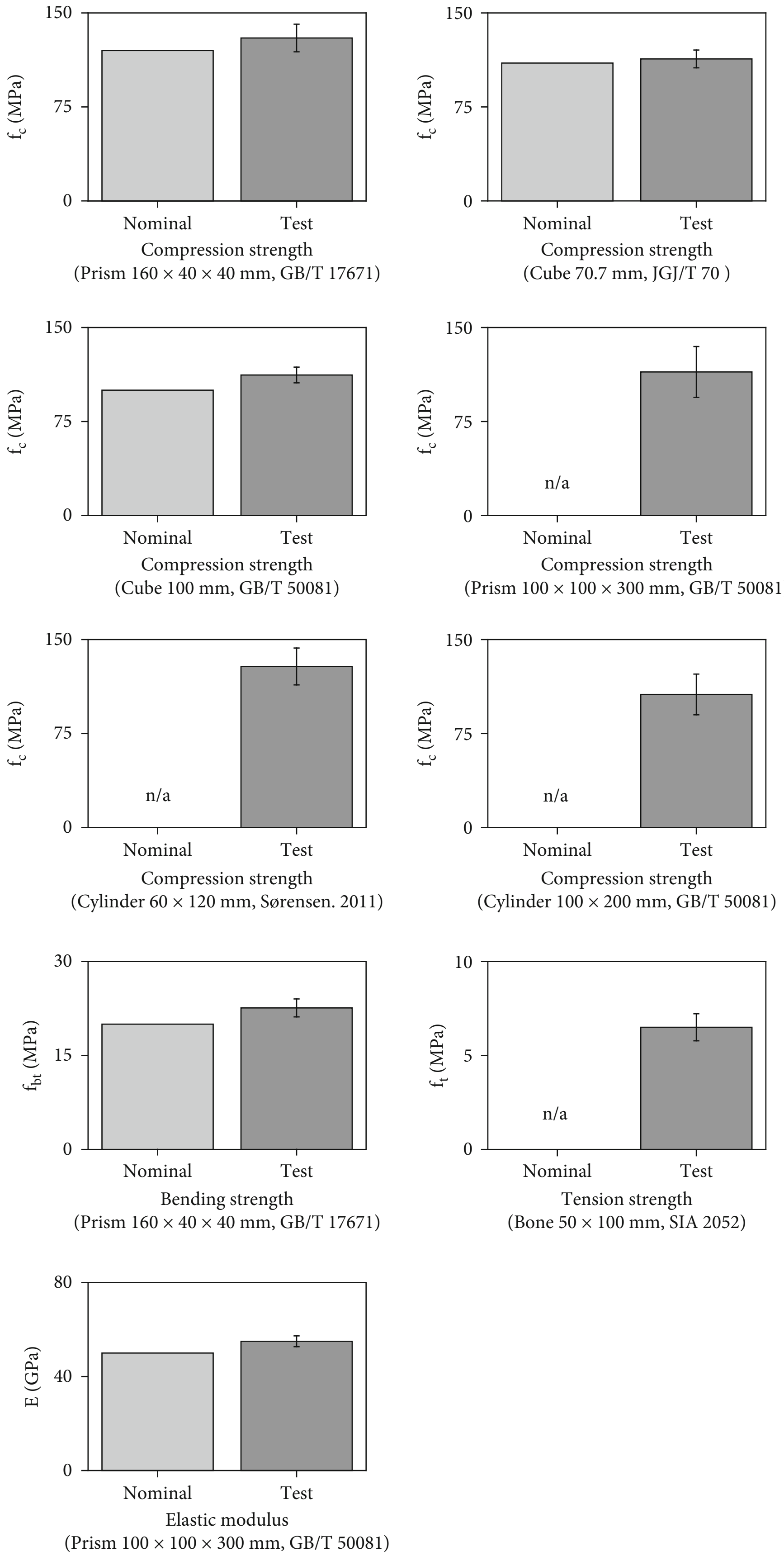

Figure 2: Strength and stiffness properties with a 95% confidence interval for the grout material.

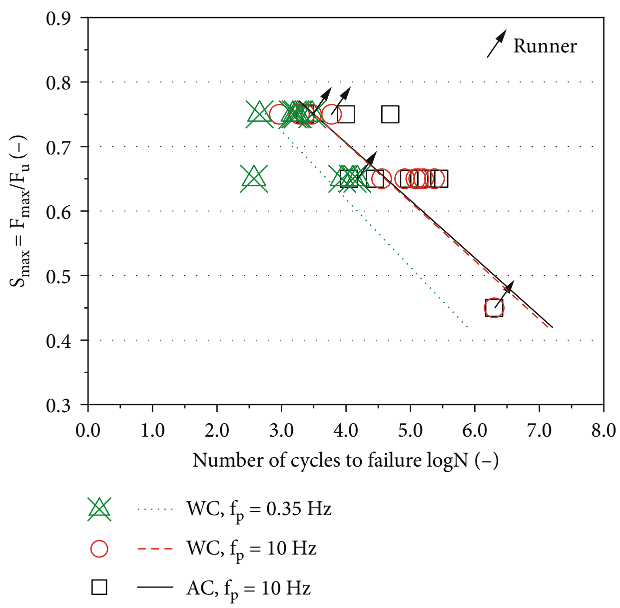

Figure 3: Fatigue test results and regression lines.

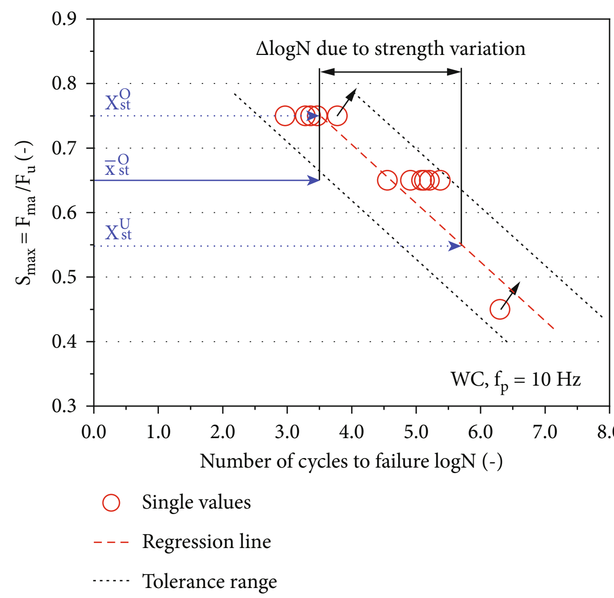

Figure 4: Example of fatigue life change due to static strength variation.

introduced due to individual differences. Ref. [27] suggested that these variances might be related to the variances in the static compressive strength. Hence, a normal distribution was used to describe the static compressive strength and the logarithmic numbers of cycles to failure. The tolerance range, which results from the variances in the static compressive strength, can be determined for the 95% level of confidence.

Figure 4 compares the tolerance range of static compressive strength with the tolerance range of fatigue life for $S_{max} = 0.65$ at $f_p = 10$ Hz. The variance of static compressive strength affecting the true stress level in the fatigue test is consistent with the allowable range of the regression line. No additional variances could be observed based on the fatigue test results.

While under the same loading frequency of $f_p = 10$ Hz, the fatigue life test results are similar. In other words, the environmental factor has little influence at $f_p = 10$ Hz. However, significant differences were found between test results in water with loading frequency of $f_p = 10$ Hz and $f_p = 0.35$ Hz.

According to the published literature, the effect of water on the performance of cement-based material is not clear, and some reported results are contradictory. Ref. [25] reported that dry specimens performed better than water submerged ones and suggested that this degradation was the result of wedging action of water trapped in cracks. Others hold the view that moisture status does have an effect on the fatigue performance: the partially dried specimens performed worst, the totally dried specimens performed best, and the saturated ones were in between. This phenomenon is believed to be caused by strain induced by moisture gradient [29–32].

In this test, there is no big difference between fatigue life at $f_p = 10$ Hz in air and water. As a matter of fact, the specimens in the air were partially dried due to the curing conditions, but the fatigue life is not much different from that in water. Therefore, the assumption of strain field caused by moisture gradient is not applicable in this test. In addition, the fatigue life at $f_p = 0.35$ Hz is drastically lower, again indicating that the moisture gradient hypothesis is not suitable for this test. Hence, it appears that the loading time and surrounding water are the key to explain the fatigue failure of cement-based material in water.

A well-known mechanism of fatigue failure is the occurrence and development of microcracks when tensile stress levels are reached under repeated loading. Due to Poisson's effect, tensile stress occurs even when the specimen is compressed. With the increase of microcracks, they will merge and form a macrocrack which gives the surrounding water a way to penetrate the specimen. Under fatigue load, some water will be enclosed in the specimen's cracks and pores; it might exert pressure on the frame of the specimen. If this pressure is high enough, wider crack formation and new cracks will occur.

Moreover, the water pumping effect and grinding effect could be suspected to accelerate the fatigue failure of ultra-high-performance grout in water. Due to a large amount of cementitious material used in specimens and the brittle nature of ultra-high-performance grout, water pumping in and out might bring the scaled fine powders away from the crack which makes the crack wider. To achieve high-strength, grout material also contains a large amount of ultra-high-strength fine aggregates. Together with water, these aggregates may form a "cutting fluid." Under the action of fatigue load, "cutting fluid" constantly wear crack on both sides, so that the crack width increases. Although no direct evidence of these effects could be observed, there may be some brightness on the cracked surfaces of debris in the water and polished aggregate surfaces. The fact that the lowest fatigue life in water was observed at $f_p = 0.35$ Hz might be explained by the lower frequency providing more time for water to ingress during each unloading cycle and more time for inside pressure build-up and grinding during each loading cycle.

Further tests are recommended to observe the microstructural changes due to fatigue load in the air and water, including additional tests at lower stress levels to simulate the real underground environment and traffic load.

4. Conclusions

(a) Experiment of compressive fatigue performance of ultra-high-performance grout for shield tunnel showed that the variances in fatigue life correspond with the static strength variances

(b) The fatigue properties of grout materials are reduced in both air and water tests at $f_p = 10$ Hz. The fatigue life of grout is significantly reduced when the stress level is 65% or above of static compressive strength in wet environment

(c) The fatigue life of grout material decreases dramatically when the loading frequency in water drops from 10 to 35 Hz. The main mechanism of fatigue life decline is splitting effect caused by water extrusion in the sample under cyclic loading. Water washes away abrasive action in the cracks. These two effects are more obvious at lower load frequencies

In addition, this paper provides a supplement for the failure behavior of grouting under cyclic loading in dry or wet environment. The empirical formulas provided an important reference for the design of fatigue cementation properties of grouting materials. Of course, the paper also has some shortcomings because of some objective reasons: first, because of the long test period, no low-frequency air fatigue test; secondly, the microscopic explanation of specimen failure is still in the stage of speculation, and further experimental exploration is still needed. Future study should focus on the microstructural changes of the grout material under fatigue loading both in air and in water. It is recommended that further tests be carried out to observe microstructure changes caused by fatigue loads in air and water, including additional tests at lower stress levels to simulate real underground environments and traffic loads.

Data Availability

The data reported in this article are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

The manuscript is approved by all authors for publication.

Acknowledgments

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