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Effect of Sulfate Attack on Compressive Strength of Foamed Cement Paste under Static and Cyclic Loading

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Abstract.*Foamed cement paste has been increasingly used as backfill material in roadways and railway embankments due to its advantages of adjustable density and strength. The embankments constructed by foamed cement paste in coastal regions is subjected to both traffic loading and chemical erosion in service life. This paper conducted a series of durability tests to investigate the reduction of static and dynamic strength of foamed cement paste after the specimens were immersed in sodium sulfate solutions. The specimens were prepared with densities of 800 and 900 kg/m*^{3}*. The influence factors of specimen density, concentration and cation type of sulfate solution on the strength degradation of the specimens were discussed. The results showed that the corrosion resistant coefficient of the specimens was reduced with the increase of immersion time and concentration of sodium sulfate solution. The degradation of the compressive strength under cyclic loading is more serious than that under static loading. The high-density specimens perform better durability than low-density specimens, as the specimens with 900 kg/m*^{3} *under 28 and 56 days of sulfate attack had smaller reduction in both dynamic and static strengths than the specimens with 800 kg/m*^{3}.

Keywords: *foamed cement paste; sulfate attack; compressive strength; cyclic loading; durability*

1 Introduction

Foamed cement paste is a type of lightweight material, which is made of preformed foam and cement paste, and sometimes sand can be also added (Amran et al., 2015; Sang-Yeop et al., 2017). Due to its superior engineering characteristics, such as adjustable strength and density, ease of construction, and excellent performance, foamed cement paste has been extensively used as backfill material in roadways and railway embankments over the past decades (J. J. Huang et al., 2017; Shi et al., 2020).

In the transportation application, foamed cement paste is subjected to million times of traffic loading(Khajeh et al., 2020). The mechanical behavior of foamed cement paste could be different from that under static loading, as traffic loading can cause both elastic and cumulative plastic deformations (Othuman Mydin et al., 2022). However, the foamed cement paste in coastal regions is further subjected to both traffic loading and chemical erosion in service life (Brown & Doerr, 2001). Sulfate attack affects the long-term strength of foamed cement paste (Al-Dulaijan et al., 2003; J. Liu et al., 2022). However, there have been limited studies focused on the strength degradation of foamed cement paste under both cyclic loading and chemical erosion. This paper is aimed at investigating the strength degradation of foamed cement paste eroded by sulfate attack. The specimens were prepared with densities of 800 and 900 kg/m^3. The sodium sulfate solution had concentrations of 0.5% and 5%, respectively, and the magnesium sulfate concentration of 4.24%, which had an equivalent SO_4^{2-} concentration with the 5% sodium sulfate solution. The strength reduction of the foamed cement paste under static and dynamic loading after sulfate attack was analyzed.

2 Material and Methods

2.1 Material

Foamed cement paste in this study were mixed by cement, foaming agents and tap water. The cement with 28 days unconfined compression strength of 42.5 MPa (P.C 42.5) was used. The foaming agent was a plant protein foaming agent (Southern Chemical, Dezhou, China). This foaming agent had pH value of 6.5 to 7.5, and can effectively reduce the surface tension of liquid and produce a large amount of uniform size and stable foams (Kuzielova et al., 2016). Previous studies suggest that the optimal water/cement (W/C) ratios are in a range of 0.4 to 0.8 (Lim et al., 2013; Zhao et al., 2015). This study adopted W/C ratio of 0.45 through the trial test. As the strength of foamed cement paste at a curing period of 28 days is approximately 90% of that at a curing period of 90 days (Falliano et al., 2018), this study selected the curing age of 28 days. The foamed cement paste has the density of 700 to 1000 kg/m^3 is commonly used in practice (J. Huang et al., 2020), thus the specimens with densities of 800 kg/m^3 and 900 kg/m^3 were prepared in the study. A series of trial tests were conducted to determine the relationship between specimen density and foam volume ratio, which is defined as a ratio of foam volume to water volume. The trial test showed that the specimens of 800 kg/m^3 and 900 kg/m^3 were made with foam volume ratios of 3.85 and 3.45, respectively. The results showed that the measured density had a derivation within 5% as compared with the required density.

2.2 Specimans preparation

The dry method was adopted to prepare the foamed cement paste in this study, as the prepared foam is more stable compared to the wet method (Koudriashoff, 1949). The foaming agent was mixed with water in the ratio of 1:20 by volume to form a foaming agent solution, and then the solution was mixed with compressed air to form foam. The created foam was mixed with the cement paste to form the uniform foamed cement mixture. The foamed cement mixture was carefully poured into a mold of 38 mm in diameter and 80 mm high. After the specimen solidified for 24 h, it was removed from the mold. All the specimens were cured in a curing room for 28 days at a temperature of 25°C±1°C and humidity greater than 95% before being tested.

In order to investigate the erosion resistance of the specimen against sulfate attack, Na_2SO_4

and $MgSO_4$ solutions were selected in this study. The Na_2SO_4 solutions with mass-mass concentrations of 0.5% and 5%, respectively, were prepared according to the exposure conditions provided by the Chinese code (GB/T 50082, 2009). The $MgSO_4$ solution with a concentration of 4.24% was prepared, which had the same SO_4^{2-} concentration with the Na_2SO_4 solution with concentration of 5%. The specimens were immersed in the sulfate solution at periods of 28 days or 56 days before loading tests.

2.3 Test program

After reaching the immersion period, the uniaxial static loading test and uniaxial cyclic loading test were carried out using the GDS dynamic triaxial test apparatus. The uniaxial static loading test was performed at a displacement rate of 0.2mm/min to obtain the peak strength of the specimen. When conducting the uniaxial cyclic loading test, the cyclic loading was applied with an increment of 200 kPa. The staged cyclic load was terminated when either the specimen failed or the test reached the loading capacity of the equipment. Table 1 summarizes the test program.

Table 1. Test program

Type of loading test		Density (kg/m^{3})	Chemical solution	Concentration (%)	Immersed time (d)
Static	Dynamic				
S1	D1	800	N/A	N/A	N/A
S2	D2	800	Na_2SO_4	0.50	28
S3	D3	800	Na_2SO_4	0.50	56
S4	D4	800	Na_2SO_4	5.00	28
S5	D5	800	Na_2SO_4	5.00	56
S6	D6	800	$MgSO_4$	4.24	28
S7	D7	800	$MgSO_4$	4.24	56
S8	D8	900	N/A	N/A	N/A
S9	N/A	900	Na_2SO_4	0.50	28
S10	N/A	900	Na_2SO_4	0.50	56
S11	D9	900	Na_2SO_4	5.00	28
S12	D10	900	Na_2SO_4	5.00	56
S13	D11	900	$MgSO_4$	4.24	28
S14	D12	900	$MgSO_4$	4.24	56

3 Results and discussion

3.1 Deterioration of static properties of foamed cement paste

The stress-strain relationships of the specimens under static loading were similar, thus only some typical results are shown here, as shown in Fig.1. At the initial stage, the axial stress rose rapidly with the increase of the axial strain until reaching the peak strength. After that, the stress decreased gradually to its residual strength.

Table 2 summarizes the static strength of the specimens under uniaxial static loading tests. As expected, the remained strength of the specimen decreased with the sulfate immersion time irrespective of specimen density, the concentration of sulfate solution, and cation type. The specimen after being eroded for 56 days, the strength of the specimen soaked in the 0.5% Na_2SO_4 solution decreased approximately by 37.0%, meanwhile, the strength of the specimen soaked in the 5% Na_2SO_4 solution decreased approximately by 65.7%. The sulfate solution with high concentration has a serious impact on the degradation of static strength of the foamed cement paste. Comparing the peak strength of the specimens of 800 kg/m^3 with those of 900 kg/m^3, the higher density specimens have greater resistance against the sulfate attack. The strength reduction after being eroded by 5% Na_2SO_4 solution was more serious than that by the 4.24% $MgSO_4$ solution. This might be explained by a fact that the magnesium ions in the solution react with calcium ions in cement to form $MgOH_2$, which is attached to the surface of the specimen to prevent further erosion of the magnesium sulfate solution and the destruction of the internal structure (Brown & Doerr, 2001).

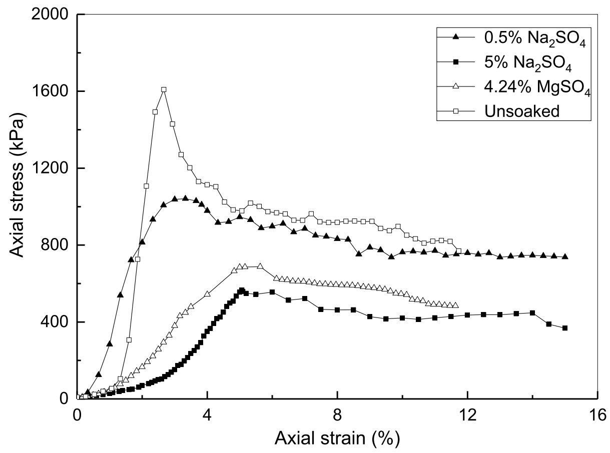


Figure 1. Stress-strain relationship curves of foamed cement paste 800 kg/m^3 under sulfate erosion.

Table 2. Static peak strength of specimen (MPa)

Immersed time (d)	800 kg/m^3			900 kg/m^3	
	0.5% Na_2SO_4	5% Na_2SO_4	4.24% $MgSO_4$	5% Na_2SO_4	4.24% $MgSO_4$
0	1.653	1.653	1.653	2.653	2.653
28	1.264	0.837	0.906	2.179	2.646
56	1.041	0.567	0.688	1.610	2.111

3.2 Deterioration of dynamic properties of foamed cement paste

Fig. 2 shows the variations of the accumulated plastic strain with the cyclic number for the tests with the specimens of 800 kg/m^3, and those of the specimens of 900 kg/m^3 were similar. When the specimen was applied by a relatively small cyclic load, the accumulated plastic strain approached a constant value after server cycles. When the specimen was applied by a large cyclic load, the accumulated plastic strain was either increased at a constant rate or increased sharply, indicating a specimen failure under the cyclic loading.

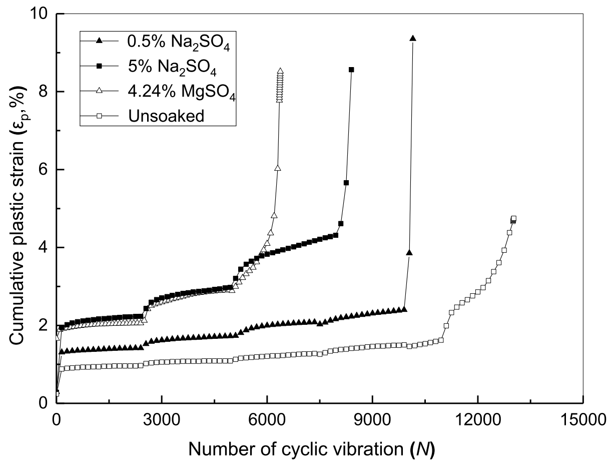


Figure 2. Cumulative plastic strain with number of cyclic vibration relationship

Table 3 lists the dynamic strength of the specimens under uniaxial cyclic loading tests. Due to the capacity limitation of equipment, the test obtained the dynamic strength of the specimens of 900 kg/m^3 without sulfate attack yet. Similar to the uniaxial static loading test, the specimens of 900 kg/m^3 had greater resistance against the sulfate attack as compared with those of 800 kg/m^3. The deterioration of dynamic strength of the specimens eroded by the $MgSO_4$ solution erosion was less than that by the Na_2SO_4 solution with the same SO_4^{2-} concentration. As compared with Table 2, the dynamic strength of the specimen was lower than the static strength of the corresponding specimen.

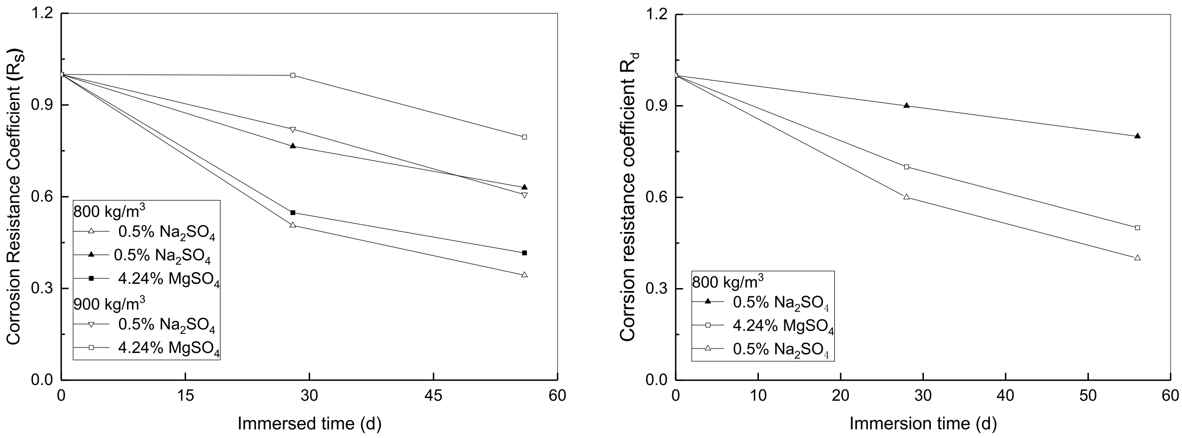
Table 3. Dynamic peak strength of specimen (MPa)

Immersion time (d)	800 kg/m^3			900 kg/m^3	
	0.5% Na_2SO_4	5% Na_2SO_4	4.24% $MgSO_4$	5% Na_2SO_4	4.24% $MgSO_4$
0	1.365	1.365	1.365	N/A	N/A
28	1.065	0.637	0.806	1.212	1.203
56	0.875	0.583	0.799	1.072	1.302

3.3 Degradation of static and dynamic strength

To estimate the durability of the foamed cement paste after sulfate attack, corrosion resistance coefficient R was introduced, which is defined as a ratio of the remained peak strength of the specimen after sulfate immersion to the initial peak strength without sulfate immersion. The corrosion resistance coefficient ranges from 0 to 1. This value closer to unity means stronger durability.

Fig. 3 shows the variation of the corrosion resistance coefficient of the specimens after being eroded by different conditions. R_s represents the corrosion resistance coefficient in terms of static strength, and R_d represents the corrosion resistance coefficient in terms of dynamic strength. It can be concluded under the same erosion condition, the specimen with high density had higher corrosion resistance coefficient than the specimens with low density. The same results were also presented by previous study(K. Liu et al., 2015). According to previous studies on concrete, the specimen with high density has denser microstructure and finer pore structure which could effectively prevent the sulfate solution from seeping into the specimen(Yang et al., 2022). Fig. 3 also indicates that the higher the concentration of the sulfate solution, the more serious the deterioration of the peak strength, both under static and cyclic loading, the longer immersed time prolong, the more reduction of the peak strength.



(a) Static strength (b) Dynamic strength

Figure 3. Variation of corrosion resistance coefficient with immersion time

To evaluate the fatigue of the foamed cement paste considering sulfate attack, the accelerated stress ratio is introduced, which is defined as a ratio of the dynamic strength of the specimen to its static strength after being eroded by the same condition. Fig. 4 shows the variation of the accelerated stress ratio of the specimen of 800 kg/m^3 with the immersion time. It is noted that the immersion time, concentration, and cation type of sulfate solution all had a minor influence on the accelerated stress ratio, and the accelerated stress ratio had an average of 0.7. In other words, the static and dynamic strength of the specimen degraded at a similar rate under different conditions of sulfate attack.

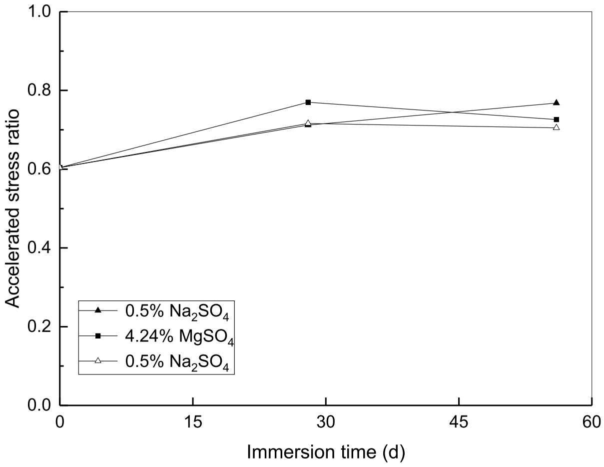


Figure 4. Variation of accelerate stress ratio with soaking time

4 Conclusion

This study conducted a series of durability tests to investigate the reduction of the static and dynamic strength of foamed cement paste after the specimens were immersed in sulfate solutions. The influence factors of specimen density, concentration, and cation type of sulfate solution on the strength degradation of the specimen were discussed. Based on the results and analyses, the following conclusions can be drawn:

- The static and dynamic strength of the foamed cement paste decreased with the immersion time. The sulfate solution with high concentration significantly impacted the degradation of the static and dynamic strength of the foamed cement paste. The strength reduction after being eroded by the Na_2SO_4 solution was more serious than that by the $MgSO_4$ solution with the same SO_4^{2-} concentration. The higher density specimens have greater resistance against the sulfate attack.
- The immersion time, concentration, and cation type of sulfate solution all had a minor influence on the accelerated stress ratio, and the accelerated stress ratio had an average of 0.7. In other words, the static and dynamic strength of the specimen degraded at a similar rate under different conditions of sulfate attack.

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