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Research Article

Effect of Low Atmospheric Pressure on Bubble Stability of Air-Entrained Concrete

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The effect of low atmospheric pressure of the environment on the air content and bubble stability of air-entrained concrete was investigated in Beijing and Lhasa. The results indicate that the reduction of atmospheric pressure can weaken the air-entraining capability of air-entraining agents (AEAs). The air content of fresh concrete decreased by 9%–39% when the atmospheric pressure dropped to 64 kPa. The bubble stability of concrete mixed at a low atmospheric pressure becomes worse. Within 50–55 min after mixing, the air content of concrete mixed at a low atmospheric pressure decreases greatly, and the void spacing factor increases obviously. The concrete mixed at a low atmospheric pressure will lose more air content when vibration time increases, leading to the decrease of air content and the increase of the spacing factor, which are more significant than the concrete mixed at normal atmospheric pressure. On the basis of the experiment results in this study, the type of AEAs must be carefully selected, and the vibration time must be strictly controlled to ensure that the air content of concrete will meet the design requirements in low atmospheric pressure areas.

1. Introduction

The Qinghai-Tibet Plateau is over 4,500 m above the sea level on average, and its average annual temperature is below 0°C; therefore, freeze-thaw damage is the main failure mode of many concrete structures in this area [1, 2]. An important technical approach to improving the frost resistance of concrete is to entrain numerous steady air bubbles into the concrete using air-entraining agents (AEAs) [3, 4]. Entraining many small bubbles into concrete and ensuring their stability are an extremely complex physical-chemical process that is affected by many factors, such as the mixing process [5–7], concrete mixture proportioning [8], fine and coarse aggregate characteristics [9], physical and chemical properties of Portland cement [10], other chemical admixtures, and supplementary cementing materials [11, 12].

In addition to the above influencing factors, recent studies have found that low atmospheric pressure (LAP) will weaken the air-entraining performance of AEAs [13, 14]. In [15–17], the authors studied the effect of air pressure drop on the air-entraining performance of AEAs by simulating the plateau environment with a low-pressure environment chamber. The results showed that the air-entraining capability of AEAs decreases linearly with the decrease of air pressure. The experiments based on the air-entraining cement slurry also showed that the foaming capability of AEAs is obviously weakened under low pressure.

Although the above research results provide a useful reference for the preparation of air-entrained concrete in low-pressure environments, studies on the influence of LAP on AEAs and the performance of air-entrained concrete remain few. In addition, the above research still has the following shortcomings. Due to the limitation of test conditions, the test method designed in the literature [15–17] cannot guarantee that the entire process of preparation and testing of the air content of concrete is conducted under LAP, and the change of external air pressure during the test is bound to affect the results. Moreover, generally, the concrete needs to undergo mixing, transportation, pouring, and vibration during the entire molding process. However, the current research mainly focuses on the influence of LAP on the air content of fresh concrete and does not pay sufficient attention to the time dependency of the internal bubbles of concrete prepared under LAP and the loss of bubbles during vibration.

In this study, the air content of fresh concrete mixed in normal atmospheric pressure (NAP) and LAP area was initially conducted to verify the influence of air pressure reduction on the capability of AEAs. Subsequently, the influence of air pressure reduction on the air content and void structure of air-entrained concrete in the above process was studied by simulating the transport and vibration of concrete.

2. Experimental Work

2.1. Materials and Mixture Proportions. Ordinary Portland cement (P.O. 42.5) was used in the experimental concrete. The coarse aggregate was crushed stone, and the fine aggregate was river sand. In the experiment, three types of AEAs and a type of nonair-entraining superplasticizer were used to produce the air-entrained concrete. Table 1 presents the material properties of cement, sand, and coarse aggregate. Tables 2 and 3 show the chemical and physical properties of cement, AEAs, and superplasticizer, respectively.

Concrete in actual structures often have different demands on workability. Therefore, reference batches of concrete with different slumps were produced. Table 4 presents the mix proportions and properties of the reference concrete.

2.2. Experimental Program. This experiment was conducted in laboratories located in Beijing (44 m above the sea level) and Lhasa (3658 m above the sea level), and the experimental temperature was guaranteed to be 20 ± 1°C. According to the relation between altitude and air pressure [15], the air pressure in Beijing and Lhasa is 101 kPa and 64 kPa, respectively. To ensure the reliability of results, the raw materials used in the two laboratories were completely the same during the experiment. The experiment consisted of three parts, and the details are as follows.

(i) Part 1: in the laboratory in Beijing (101 kPa), three types of AEA were used to ensure the air content of the air-entraining concrete with air content levels of 3%, 5%, and 7% using the mix ratio shown in Table 4 (error of air content was controlled within ±0.3%). Then, the experiment was repeated in Lhasa (64 kPa) to study the influence of LAP on the air-entraining performance of AEAs.

(ii) Part 2: two types of AEA, whose air-entraining capability was less affected by LAP based on the experimental results from Part 1, were utilized to produce the concrete with initial air content of 7% under Beijing (101 kPa) and Lhasa (64 kPa). After mixing, the concrete was placed in a certain time (10–15, 30–35, 50–55, or 80–85 min), and air content was then measured. During the placement, the concrete was mixed for 2 min and let to stand for 8 min within every 10 min to simulate the transport process of concrete. In addition, a group of air-entrained concrete using the same AEA, due to less air content loss of concrete with time duration, was selected to cast the concrete sample with $100 \times 100 \times 100$ mm and kept in a moist-curing room for 28 days to test the air void parameters.

(iii) Part 3: a group of air-entrained concrete, whose air loss with time duration was minimal, was selected based on the results from Part 2. Then, the corresponding AEA was utilized to produce concrete with initial air content of 7% and 5% under Beijing (101 kPa) and Lhasa (64 kPa), respectively. The mix proportions of concrete were mix no. 3, as shown in Table 4. The produced concrete was vibrated for 15, 30, 60, and 90 s on the vibrating table with vibrating frequency of 50 Hz. After the air content was tested, the produced concrete was cast sample with $100 \times 100 \times 100$ mm and kept in a moist-curing room for 28 days to test the air void parameters. The testing procedure is similar to Part 2.

During the experiment, the air content of fresh concrete and the air void analysis of hardened concrete were tested according to the standard for the test method of performance on ordinary fresh concrete [18] and ASTM C457 [19], respectively.

3. Results and Discussion

3.1. Effect of LAP on the Air Content of Fresh Concrete. As shown in Figure 1, the test results clearly indicated that when the mix proportions were the same, the air content of air-entrained concrete mix under LAP (AEC-L), in which three types of AEA were added, decreased when the air pressure was reduced to 64 kPa. This result was observed regardless of the initial air content of the concrete mixed under NAP (AEC-O). The normalized results listed in Table 5 show that when the air pressure dropped to 64 KPa, the air content of AEC-L was reduced by 9%–35% (saponin), 17%–39% (alkyl sulfonate), and 10%–34% (polyether).

The above test results are similar to the conclusion based on the low atmospheric environment chamber mentioned in the literature [15], that is, low pressure will weaken the air-entraining capability of AEAs, resulting in difficulties in air entraining. This phenomenon is more obvious in concrete with large slump or high air content. This finding may be related to the difficulty of suppressing the bubble overflow when the concrete viscosity is small or the poor stability of the bubbles when the air content is high. The specific reasons still need to be further studied.

3.2. Time-Dependent Behavior of the Air Content and Void Parameters of Air-Entraining Concrete. According to the test results (Table 5), saponin and polyether were the two types of AEAs whose air-entraining capability was less affected by the varying of atmospheric pressure. Thus, they were used in the studies on time-dependent behavior of the air content and

Table 1: Material properties.

Parameter	Cement	Fine aggregate	Coarse aggregate
Type	P.O 42.5	River sand	Crushed stone (maximum size: 20 mm)
Specific surface (cm^2/g)	3,310	—	—
Specific gravity	3.15	2.65	2.56
Fineness modulus	—	2.85	—
28-day compressive strength (MPa)	49	—	—

Table 2: Chemical properties of ordinary Portland cement (P.O 42.5).

Ingredient	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	K_2O	Loss on ignition
Proportion by mass (%)	62.01	21.67	5.32	3.42	3.19	2.34	0.84	1.18

Table 3: Chemical and physical properties of AEAs and superplasticizer.

Agents	Chemical nature	Physical state
	Saponin	Solid
Air-entraining agents	Alkyl sulfonate	Solid
	Polyether	20 percent aqueous solution
Superplasticizer	Polycarboxylate	20 percent aqueous solution

Table 4: Mix proportions and properties of reference concrete.

Mix no.	Mix proportion ($kg \cdot m^{-3}$)					Slump (mm)	Air content※ (%)
	Cement	Water	Sand	Coarse aggregate	Superplasticizer		
1#	380	175	720	1125	—	50	1.7
2#	380	152	729	1139	2.66	50	1.9
3#	380	175	720	1125	2.66	140	2.0

※Note: the air content refers to the air entrained in the reference concrete without the air-entraining agent under NAP.

void parameters of air-entraining concrete with an initial air content of 7% casted under different air pressure environments (101 kPa and 64 kPa).

The results showed that the air content of concrete decreased with time whether the atmospheric pressure was low or not, and the change in air content mainly occurred within 50–55 min (Table 6). Moreover, the lower the atmospheric pressure was, the larger the air content would be reduced, especially in mix proportion with higher slump. By comparison, the bubble stability is poorer in concrete casted under LAP than NAP, and the bubble stability of concrete with the addition of polyether was relatively better. However, the air content of all mix proportions did not decrease by more than 1.9% within 80–85 min.

The air content of fresh concrete could not accurately reflect the void structure parameters, which are directly related to the frost resistance of concrete. Thus, under different atmospheric pressures (101 kPa and 64 kPa), the variation of the void spacing factor of hardened concrete with polyether over time was tested.

The results showed that similar to the results of the time-dependent behavior of the air content of fresh concrete, the change of the void spacing factor of hardened concrete also mainly occurred within 50–55 min for all mix proportions (Figure 2). In addition, the loss of air content after hardening of the concrete mixed under LAP was larger, which caused the void spacing factor to be larger than that of the concrete mixed under NAP. These phenomena were more obvious when the slump was larger and the superplasticizer was added. The above results suggest that the bubble stability of concrete mixed under LAP was considerably poorer.

To evaluate the stability of the void spacing factor, $L_{\min}$ and $L_{\max}$ are defined as the minimum and maximum void spacing factor of the concrete during the test, respectively (i.e., $\Delta L = L_{\max} - L_{\min}$

represents the variation of the void spacing factor). Table 7 presents the changes of the void spacing factor of concrete with different mix proportions and mixed under different air pressure conditions. The results indicated that when the atmospheric pressure was the same, ΔL of concrete with high flowability was larger than that of concrete with low flowability, and the stability of the air bubble of concrete with the addition of the superplasticizer was considerably poor than that of concrete without the addition of the superplasticizer. Moreover, ΔL of AEC-L was greater than that of AEC-O for given mix proportions. Thus, adding the superplasticizer worsened the stability of the air bubbles.

The results confirmed that a large number of microbubbles entrained into concrete increased the solid-liquid-air interfacial free energy, which caused bubble collapse,

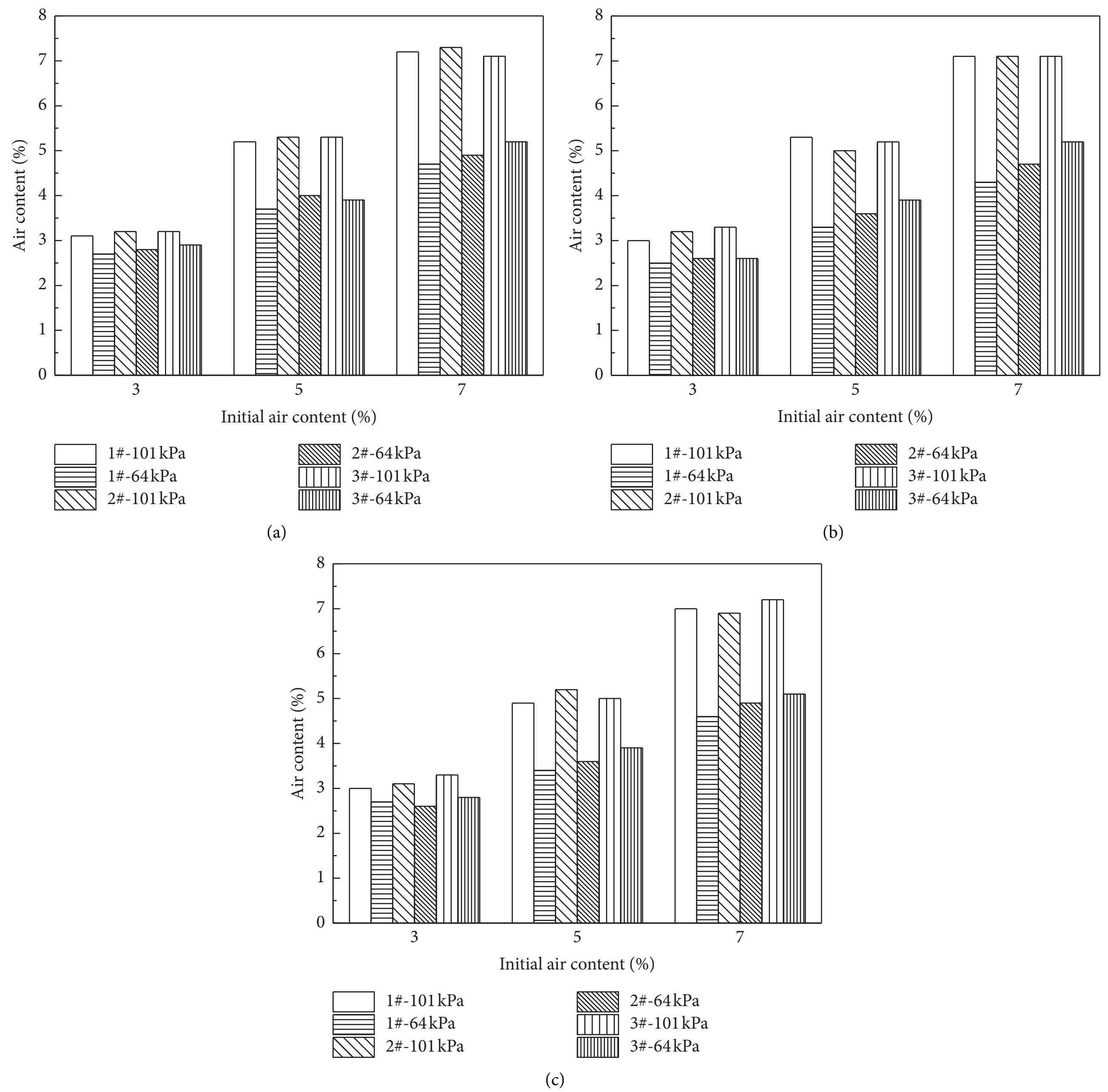

Figure 1: Tendency of air content of air-entrained concrete with air pressure decline. (a) Saponin. (b) Alkyl sulfonate. (c) Polyether.

Table 5: Reduced value of air content of concrete when air pressure falls to 64 kPa.

Initial air content/%	Reduced value of air content (%)		
	Saponin	Alkyl sulfonate	Polyether
3	9–13	17–21	10–16
5	26–29	25–38	22–31
7	27–35	27–39	29–34

overflow, and coalescence. Therefore, regardless of the atmospheric pressure environment, the air content of concrete with the addition of the two types of AEA decreased with time. However, the increase in the surface tension of the liquid in LAP was more likely to cause the fusion and rupture of the bubbles [15]. In this manner, the air content of AEC-L was reduced more significantly than that of AEC-O, which led to the void spacing factor of AEC-L increasing more obviously.

In addition, the viscosity of concrete is an important factor that affects bubble stability. The increase of viscosity prolongs the bubble gravity discharge and gas diffusion

Table 6: Decline of air content in concrete with time increase.

Mix no.	Air-entraining agent	Air pressure (kPa)	Air content (%)			
			10–15 min	30–35 min	50–55 min	80–85 min
1#	Saponin	101	7.0	6.6 (5.7)	6.0 (14.3)	5.8 (17.1)
		64	7.1	6.6 (7.0)	5.7 (19.7)	5.4 (23.9)
2#	Saponin	101	7.2	6.7 (6.9)	5.6 (22.2)	5.7 (20.8)
		64	6.8	6.4 (5.9)	5.3 (22.1)	5.1 (25.0)
3#	Saponin	101	7.1	6.4 (9.8)	5.5 (22.5)	5.4 (23.9)
		64	7.2	6.2 (13.9)	5.5 (23.6)	5.3 (26.4)
1#	Polyether	101	6.9	6.7 (2.9)	6.3 (8.7)	6.4 (7.2)
		64	7.2	6.3 (12.5)	5.9 (18.1)	5.8 (19.4)
2#	Polyether	101	7.0	6.5 (7.1)	6.4 (8.6)	6.3 (10.0)
		64	6.8	6.3 (7.4)	5.6 (19.1)	5.5 (19.1)
3#	Polyether	101	7.1	6.5 (8.5)	5.5 (22.5)	5.3 (25.4)
		64	7.0	7.2 (−2.9)	5.3 (24.3)	5.2 (25.7)

Note. The final relative reduced air content of air-entrained concrete is given in brackets.

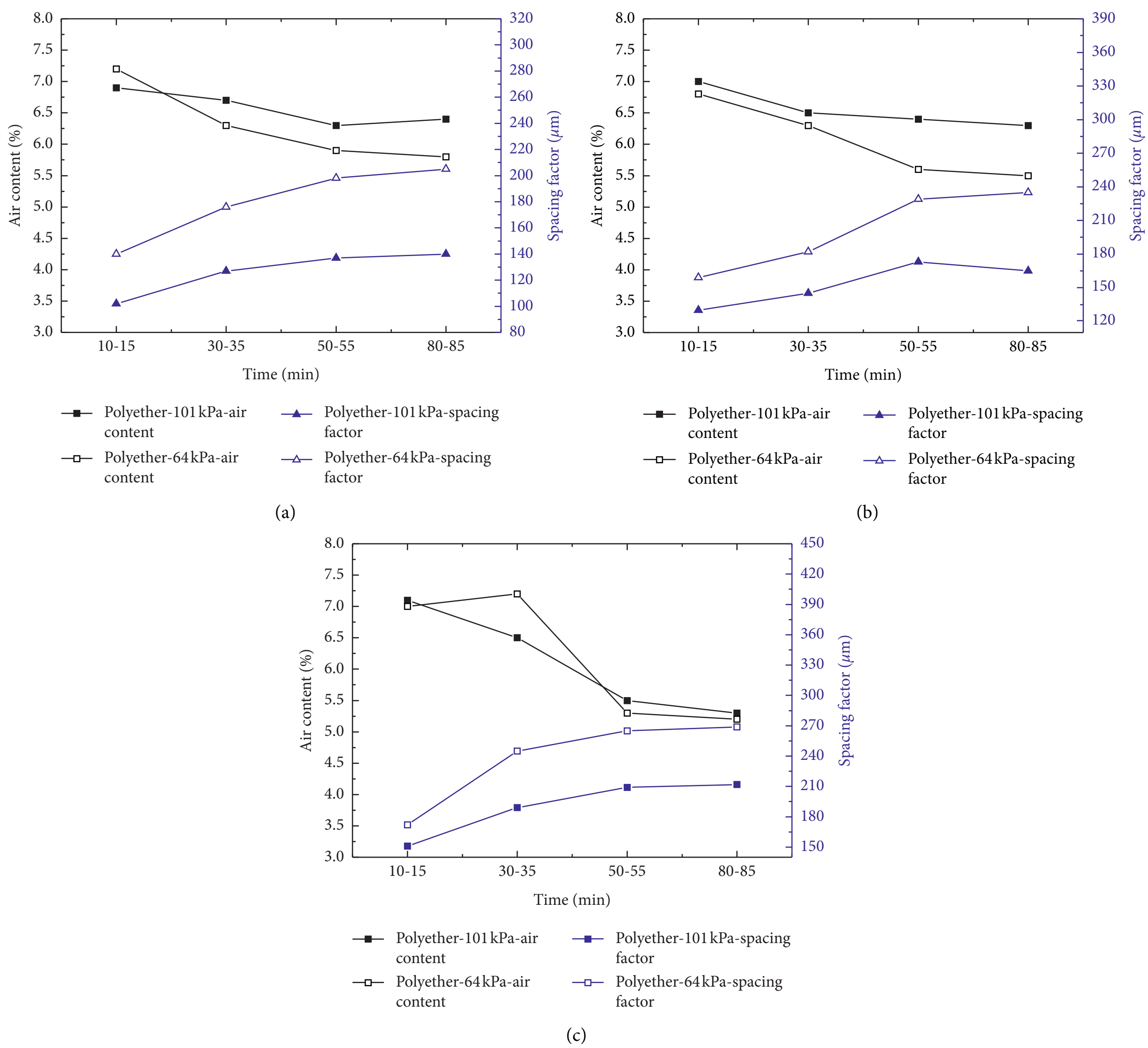

Figure 2: Variation trends of the void spacing factor and air content with increase of time. (a) 1#. (b) 2#. (c) 3#.

Table 7: Variation trend of the spacing factor under different air pressure.

Air pressure (kPa)	Mix no.	Slump (mm)	L_{min} (μm)	L_{max} (μm)	$\Delta L = L_{max} - L_{min}$ (μm)
101	1#	50	102	140	38
101	2#	50	130	173	43
101	3#	140	151	212	61
64	1#	50	140	205	65
64	2#	50	159	235	76
64	3#	140	172	269	97

Table 8: Relative reduced air content of air-entrained concrete.

Initial air content (%)	Air pressure (kPa)	Relative reduced air content (%)				
		0 s	15 s	30 s	60 s	90 s
7	101	7.2	5.4 (25)	5.1 (29)	4.5 (38)	4.3 (41)
7	64	7.2	5.1 (28)	4.3 (40)	4.2 (42)	4.1 (43)
5	101	5.3	4.2 (21)	3.7 (30)	3.6 (32)	3.4 (36)
5	64	5.2	3.8 (27)	3.3 (37)	3.2 (38)	3.1 (40)

Note. The final relative reduced air content of air-entrained concrete is given in brackets.

relaxation time, thereby prolonging the half-life of bubbles. The greater the viscosity is, the greater the resistance encountered by the bubble overflow or fusion will be, which decreases the reduction range of the air content of concrete. Therefore, regardless of NAP or LAP, the loss of the air content of concrete with low slump becomes relatively small over time. With the increase in time, the continuous hydration of the cement in the concrete and the evaporation of water will consume a part of the water. As a result, the viscosity of the slurry will continue to increase, and the air content of concrete will tend to stabilize. Moreover, with the increase in time, the continuous hydration of cement in concrete and the evaporation of water will consume a part of the water. This phenomenon will make the slurry viscosity increase continuously, and the air content value will tend to be stable simultaneously. Therefore, in this study, when the time exceeded 50–55 min, the air content of AEC-O remained basically unchanged, whereas that of AEC-L was slightly reduced. This result also showed that the internal bubbles of concrete mixed under LAP were not sufficiently stable. Moreover, the void spacing factor was basically unchanged; thus, the large bubble burst mainly occurred at this time, and it did not greatly affect the void spacing factor.

3.3. Influence of Vibration Time on the Air Content and Void Structure of AEC-L. The above test results showed that polyether was less affected by LAP in comparison with saponin and alkyl sulfonate. Therefore, polyether was used in this part of the experiment.

Table 8 shows the change of the air content of fresh concrete at different vibration times. The results showed that regardless of NAP or LAP, when the vibration time was 0–30 s, the air content decreased continuously with the increase of vibration time, and the decreasing rate was larger. When the vibration time exceeded 30 s, the change of air content tended to be moderate, and this phenomenon was more obvious in AEC-L. By calculating the reduction value of the air content of concrete under different vibration times, the reduction range of the air content of concrete with a higher initial air content (7%) was found to be greater than that of concrete with a lower initial air content (5%).

Figure 3 shows the variation of void structure parameters with vibration time in hardened concrete. The results showed that regardless of AEC-L or AEC-O, the spacing factor and specific surface area of bubbles increased with the vibration time. At the same time, the increase of the spacing factor of AEC-L was slightly larger than that of AEC-O; however, both of them were smaller than the change range of the air content of concrete. For example, after 90 s vibration, the increase of the void spacing factor of AEC-L with initial air content of 7% and 5% was 27% and 18%, respectively, whereas that of the air content decreased by 43% and 40%, respectively.

It is well known that the bubbles in the air-entraining concrete are classified into two types. One is the entrapped air bubbles under the mechanical entrapment with a large diameter and an irregular shape; and, the other is the regular spherical bubbles introduced by the AEAs, the diameter of which is generally tens to hundreds of microns. Concrete will liquefy under the action of vibration, which will cause the internal solid particles to tend to the most suitable stable position due to the decrease of the viscosity of the concrete and the effect of its own gravity. This process will make the trapped air bubbles in the process of mixing and the large diameter of bubble introduced by the AEAs discharge, whereas the tiny bubbles introduced by the AEAs are less affected by the effect of vibration.

In the experiment described in this study, when the vibration time was within 0–30 s, the trapped air and bubbles with a large diameter were discharged by the vibrating action, resulting in a rapid decrease in the air content of concrete. Then, the vibration continued (after 30 s) because the fine bubbles were less affected by the vibration time, and

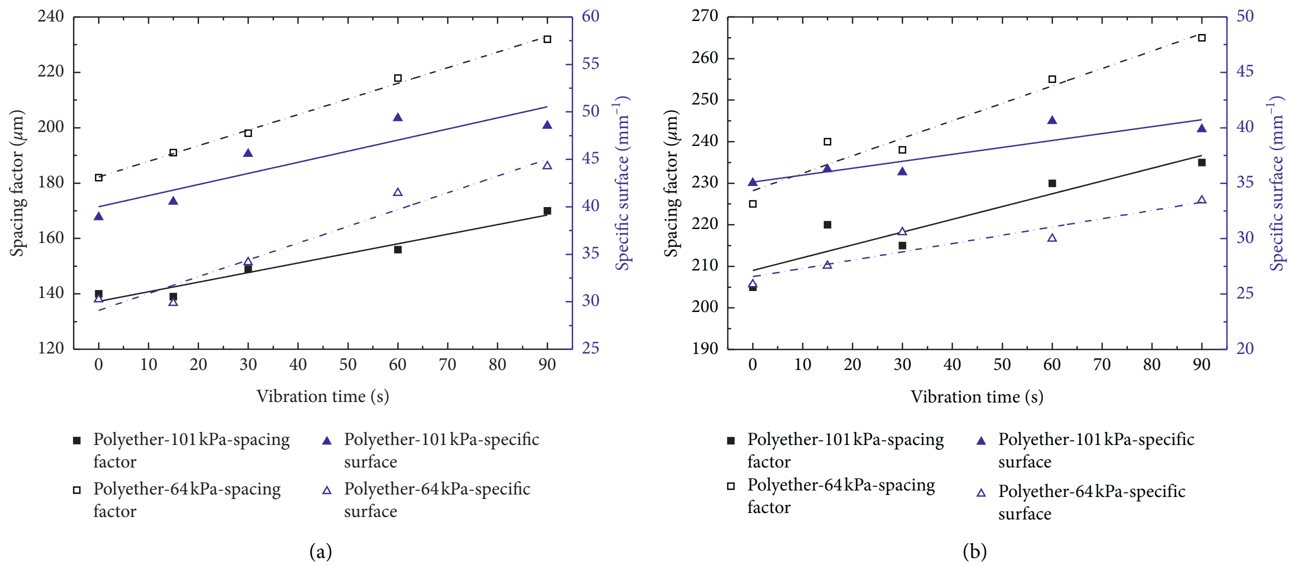

Figure 3: Air void system of hardened concrete after different vibration times. (a) 7%. (b) 5%.

the change range of the air content of concrete decreased. Given that the void spacing factor mainly depends on the number of bubbles with a small diameter, the variation range of the void spacing factor during the vibration time of 0–90 s was obviously smaller than that of the air content. However, the results also showed that the influence of LAP on the air content or void spacing factor of concrete was greater than that of NAP. Thus, LAP not only led to the decline of the air-entraining capability of AEAs but also to the bubbles introduced becoming unstable, which resulted in more bubble loss due to prolonged vibration time.

4. Conclusions

(1) On the basis of the field experiment under LAP, the reduction of atmospheric pressure can weaken the air-entraining capability of AEAs, and this phenomenon is more obvious in concrete with large slump or high air content. In comparison with the air content of AEC-O, the air content of AEC-L decreases by about 9%–35% (saponin), 17%–39% (alkyl sulfonate), and 10%–34% (polyether) when the atmospheric pressure drops to 64 KPa.

(2) The bubble stability of air-entrained concrete mixed in LAP becomes worse. Within 50–55 min after mixing, the air content of AEC-L decreases greatly, and the void spacing factor increases obviously. The prolongation of vibration time leads to more air bubbles being lost in AEC-L, which leads to the decrease of air content and the increase of the void spacing factor being greater than that in AEC-O.

(3) On the basis of the experiment results in this study, the type of AEAs must be carefully selected and the vibration time must be strictly controlled to ensure that the air content of concrete will meet the design requirements in LAP.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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