ISSN 1027-5495. Functional Materials, 30, No.2 (2023), p. 235-242.
doi:https://doi.org/10.15407/fm30.02.235

Application of binders for ecological pile foundations made of concrete

Deyang Chen[1], *Zhe Wang*[1], *Fucheng Yu*[1], *Xinying Ai*[2]

[1]China Construction Third Engineering Bureau Group Co., Ltd (Shenzhen), Shenzhen, 518000 Guangdong, China
[2]School of Environment and Civil Engineering, Dongguan University of Technology, Dongguan, 523808 Guangdong, China

Received April 25, 2023

To improve the compressive strength and frost resistance of concrete, the influence of the ratio of water and glue and the number of binder piles was analyzed. It is shown that the ratio of water and glue affect the frost resistance and compressive strength of concrete and improve the effect of concrete curing at low temperatures. It is shown that the compressive strength and frost resistance of the pile foundation are inversely proportional to the coefficient of adhesion with water, and the amount of binder is proportional to the strength and frost resistance of the pile foundation.
Keywords: concrete, pile foundations, water-to-adhesive ratio, material ratio.

Застосування в'яжучих матеріалів для екологічних пальових фундаментів з бетону. *Deyang Chen, Zhe Wang, Fucheng Yu, Xinying Ai*
Для підвищення міцності на стиск і морозостійкості бетону проведено аналіз водоадгезійних і кількісних співвідношень в'яжучих паль. Показано, що співвідношення води і клею впливає на морозостійкість і міцність бетону на стиск і покращує ефект твердіння бетону при низьких температурах. Показано, що міцність на стиск і морозостійкість пальового фундаменту обернено пропорційні коефіцієнту зчеплення з водою, а кількість в'яжучого пропорційна міцності і морозостійкості пальового фундаменту.

1. Introduction

In order to increase the energy strength of concrete in compression and frost resistance, the countries of the world are actively developing a number of binders [1] with different ratios of water to glue and the proportion of mineral materials [2]. C30 as the main material for the construction of pile foundations, with a wide range of applications, compressive strength, strong frost resistance [3], long service life and wide temperature advantages, is widely used in cold, saline alkaline soil and other harsh environments. However, the hydration heat negatively affects the thermal stability of frozen soil, reducing the scope of C30 concrete [4]. In a low-temperature frozen soil environment, the strength of pile foundation concrete develops relatively slowly [5]. An engineering challenge often encountered in building on frozen ground on a plateau in China is the thawing and heaving of the frozen soil [6]. Therefore, the search for the ratio of binders for pile foundations, suitable for low-temperature environments and meeting the needs of construction on frozen soils in cold regions [7], is of great importance for ensuring the safety of bridge structures [8]. Simply put, the conventional concrete ratio has problems such as poor compressive ability and weak drought resistance, which restricts the performance of C30 concrete [9]. Therefore, by adjusting the water-glue ratio and the dosage of gelling rice materials as well as calculating various mineral additives, better compressive strength and frost resistance of concrete can be achieved, which is an important way to improve the pile foundation. This paper analyzes the compressive strength and frost resistance depending on the water-adhesive ratio [10], the gelling dosage, and the mineral additive ratio, aiming to improve the overall performance of the pile foundation.

2. Description of the use of cementitious materials for pile foundations

A. Raw materials

Cement: ordinary Portland cement is used [11]. Fly ash: grade I fly ash[12]. Silica ash: silicon ash produced by Elkem. Fine set: good medium sand [13]. Coarse aggregate: 5 ~ 31.3 mm crushed stone. Admixture: polycarboxylic acid high-efficiency water reducing agent. Early strengthening: compound early strength.

The processes of action of different materials are shown in Equations (1), (2), and (3). Cement curing reaction:

$$3CaO \cdot SiO_2 + 6H_2O \leftrightarrow \leftrightarrow \pm 3CaO \cdot SiO_2 + 3Ca(OH)_2 . \quad (1)$$

Water absorption process:

$$2CaO \cdot SiO_2 + 4H_2O \leftrightarrow \pm 3CaO \cdot SiO_2 . \quad (2)$$

Hardening process:

$$3CaO \cdot Al_2O_3 + 6H_2O \leftrightarrow \leftrightarrow \pm 3CaO \cdot Al_2O_3 \cdot 6H_2O . \quad (3)$$

C30 is better in terms of drought and stress resistance; the specific results are shown in Table 1.

C30 works significantly better than C15 and C45, with higher acid and alkali resistance, more excellent cold resistance, relatively long life [14], and a wide operating temperature range. Currently, C30 is already a comprehensive concrete grade widely used in the construction process of pile foundations [15]; so in this paper this is considered as an object of study to analyze the use of cementitious materials. [16]. At the same time, the continued interest in concrete and binders and the continuous enhancement of market demand provide development space for pile foundation cementitious materials [17].

B. Cementitious materials used for pile foundations

Many studies have shown that the amount of pile binder used and the ratio of water to adhesive depend on the concrete,

Table 1. Comparison of performance of various concrete

Label	C30	C15	C45
High-temperature dynamic modulus of elasticity	85	75	65
Low-temperature pressure resistance, MPa	45.6	40.6	35.6
Acid resistance, pH	4.6	5.2	5.3
Alkali resistance, pH	7.9	7.1	7.2
Curing time, d	6 ~ 10	8 ~ 15	9 ~ 20
Absorption, %	85	75	65
High-temperature dynamic modulus of elasticity, %	86	80	83
Low-temperature pressure resistance, MPa	4.6	40.3	39.7
Cure stability, %	95	75	68

mineral ratio, temperature and acid-base environment. In the past, pile cementitious materials in 350 kg dosage were mainly used [18], which was better integrated with concrete materials. However, the binder is dispersed, the melting rate with CaO is low, it cannot reach the C30 grade, the voids in the concrete are large, and the acid and alkali resistance is low. If the dosage of the cementitious material is lifted to 350 kg, the fusion rate with CaO is higher, the complexation between molecules is increased, and the physical properties of concrete are more potent. Therefore, adjusting the amount of binders for a pile foundation is an important direction and content of the development. Adjusting the amount of binder and the water-adhesion ratio of the pile foundation can improve the concrete grade of the pile foundation, reduce the voids of the concrete, too much permeability, and it will have good mechanical properties. With the same acidity, alkalinity and temperature, a large amount of binder materials contributes to an increase in the density of concrete and a decrease in voids in concrete. At the same time, cementitious materials can reduce the aperture and increase the density of the pile foundation.

C. Test process of water-adhesive ratio and material ratio

The key to using cementitious materials is to further study the water-adhesive and material ratios of the pile foundation. In the actual project, the design strength of the pile foundation or soil is C30, and the slump degree is 180±20 mm, and the main concrete parameters of the pile foundation and their influence are studied during in-

Table 2. Various ratios of pile foundation concrete

Label	Key parameters		Amount of raw materials per square meter of concrete					
	Water-to-adhesive ratio	Cementitious material dosage, kg/m^3	cement	Fly ash	Silica ash	water	Fine aggregates	Coarse aggregate
W-0.45	0.45	380	380	0	0	170	730	1000
W-0.48	0.48	380	380	0	0	175	730	1000
W-0.50	0.50	380	380	0	0	180	730	1000
B-320	0.45	320	380	0	0	172	730	1000
B-350	0.45	350	380	0	0	171	730	1000
B-380	0.45	380	380	0	0	171	730	1000
FA0-SF0	0.45	380	380	0	0	171	730	1000
FA10-SF5	0.45	380	380	0	0	171	730	1000
FA10-SF10	0.45	380	380	38	0	171	730	1000
FA20-SF5	0.45	380	380	38	0	171	730	1000
FA20-SF10	0.45	380	380	76	20	171	730	1000

Note: WB-0.45 represents a water-to-adhesive ratio of 0.45, B-320 is a binder with a dosage of 320 kg/m^3, and FA10-SF10 is fly ash at the equivalent of 10 % cement replacement and silica ash at the equivalent of 10 % cement replacement. Other numbers and so on.

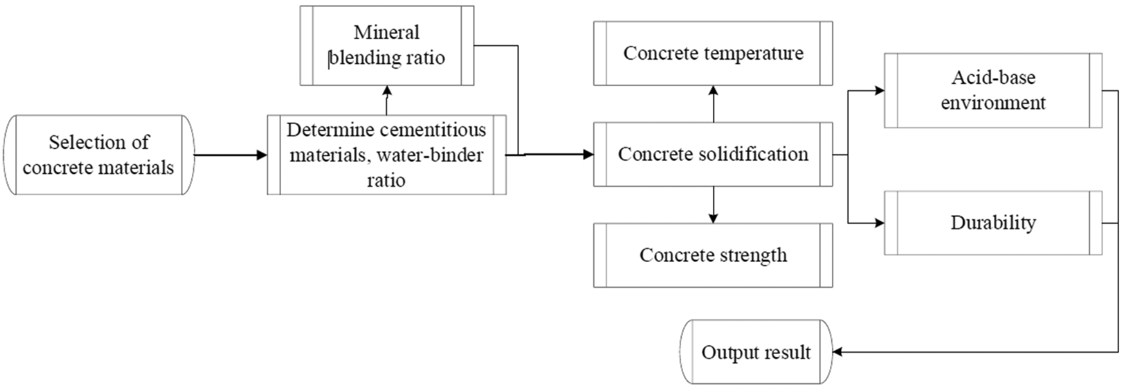

Fig. 1. Test procedure for cementitious materials.

door experiments. Among them, the indicators of the water-adhesive ratio are 0.45, 0.48, and 0.50, the research objects are the mechanical properties, frost resistance, and acid and alkali resistance of pile foundation concrete. Among them, the advantages of fly ash as a mineral additive are mainly considered, which can reduce the heat of hydration while enhancing the compactness of concrete and the acid resistance of concrete. The advantage of silica ash is to improve the early strength of concrete. This paper mainly studies the performance of pile foundation concrete under the condition of fly ash and silica ash compounding, as shown in Table 2.

D. Test method

In order to simulate the environmental characteristics of alpine pile foundation concrete, a low-temperature method for concrete component curing is used in this paper; the specific operation is as follows: the concrete component is cured for 4h by a standard procedure, then it is placed into the refrigerator and oven, and the coating surface is cured at 38 ~ −15°C for aging; then the mechanical properties and frost resistance tests are carried out. The following aging times were used: 3d, 7d, 14d, 28d and 56d. According to the data in Table 1, the binder dosage test was carried out, and the test process is shown in Fig. 1.

3. Pile foundation concrete cementitious material test

A. Effect of water-adhesive ratio on concrete strength

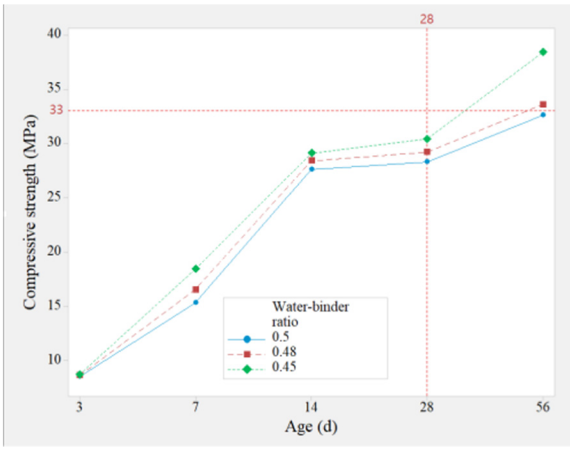

Fig. 2. Pressure resistance of water-adhesive ratio.

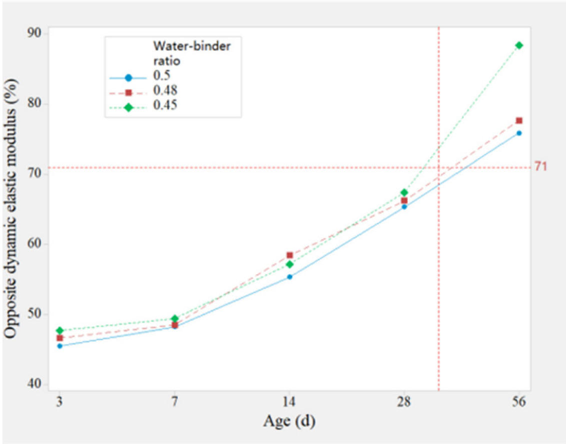

Fig. 3. Freeze resistance of the water-adhesive ratio.

Table 3. Compressive strength (MPa) under different water-to-adhesive ratios

Age	Water-to-adhesive ratio				
	3d	7d	14d	28d	56d
0.50	8.52	15.31	27.62	28.32	32.62
0.48	8.63	16.51	28.43	29.23	33.63
0.45	8.72	18.43	29.11	30.41	38.44

Table 4. Antifreeze performance (MPa) under different water-to-adhesive ratios

Age	Water-to-ad hesive ratio				
	3d	7d	14d	28d	56d
0.50	45.51	48.23	55.32	65.32	75.84
0.48	46.63	48.52	58.42	66.23	77.63
0.45	47.72	49.43	57.13	67.41	88.4

(1) Pressure resistance under conditions of various water-adhesive ratios Compressive strength values of concrete at different ages are shown in Table 3.

The data in Table 3 shows that when the water-adhesive ratio is 0.45 and 0.48, the concrete of 28d age is the strongest, and C30 has compression resistance. With an increase in the water-to-adhesive ratio, the compressive strength of concrete decreases. When the water-adhesive ratio increased from 0.45 to 0.48 and 0.50, the compressive strength of concrete decreased from 33.6 MPa to 32.6 MPa, the reduction reached 8.5 % and 16.8 % respectively. The reasons for the above phenomenon are mainly an increase in the water-to-adhesive ratio, an increase in the porosity of concrete, a decrease in the compactness of concrete, and a significantly decrease in the compressive strength on its surface. The specific change process is shown in Fig. 2.

From Table 3, it can be seen that the compression resistance at a water adhesive ratio of 0.45 is significantly greater than at 0.48 and 0.5, and there is a significant increase after 56d, indicating that the pressure resistance is proportional to the water adhesive ratio, and the pressure resistance with a water-adhesive ratio of 0.45 is better.

(2) Antifreeze performance of water-to-adhesive ratio Under different water-to-adhesive ratio conditions, the frost resistance of concrete at different ages is shown in Table 4. The data in Table 4 show that with a water-adhesion ratio of 0.45 and 0.48, concrete after 28 days is the most durable, and the dynamic modulus of elasticity corresponds to C30. With an increase in the water-to-adhesive ratio, the kinetic elastic modulus of concrete decreases. After 28 days, the kinetic modulus of elasticity of the water-adhesion ratio decreases from 85 % to 72 %. The reasons for the above phenomenon are mainly an increase in the water-to-adhesive ratio, an increase in porosity of concrete, an increase in the water absorption, a decrease in the permeability resistance, and a significant reduction of frostiness on its surface. The specific change process is shown in Fig. 3.

The frost resistance in Fig. 3 is proportional to the water-to-adhesive ratio. The frost resistance increases significantly at the water-to-adhesive ratio of 0.45 in comparison with the water-adhesive ratios of 0.48 and 0.5. Therefore, the water-to-adhesive ratio of 0.45 is recommended to use for pile foundation concrete in cold areas to en-

Table 5. Chemical composition and porosity of binders with various water-adhesive ratios

Age, days	Hydroadhesive ratio, none	Porosity, %	Chemical composition
0	0.45	4.41	$CaO \cdot SiO_2 + 3Ca(OH)_2$
3	0.45	15.44	$CaO \cdot SiO_2 + 3Ca(OH)_2$
7	0.45	21.39	$CaO \cdot SiO_2 + 3Ca(OH)_2$
14	0.45	25.26	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$
28	0.45	35.15	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$
56	0.45	30.72	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$
0	0.48	5.05	$CaO \cdot SiO_2 + 3Ca(OH)_2$
3	0.48	25.01	$CaO \cdot SiO_2 + 3Ca(OH)_2$
7	0.48	35.04	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$, $CaO \cdot$ *BH4‘%Atp4B*$SiO_2 + 3Ca(OH)_2$
14	0.48	41.05	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$, $CaO \cdot$ *BH4‘%Atp4B*$SiO_2 + 3Ca(OH)_2$
28	0.48	45.12	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$, $CaO \cdot$ *BH4‘%Atp4B*$SiO_2 + 3Ca(OH)_2$
56	0.48	48.12	$CaO \cdot Al_2O_3 \cdot$ *BH4‘%Atp4B* $6H_2O$, $CaO \cdot$ *BH4‘%Atp4B*$SiO_2 + 3Ca(OH)_2$
0	0.50	5.53	$CaO \cdot SiO_2 + 3Ca(OH)_2$
3	0.50	11.38	$CaO \cdot SiO_2 + 3Ca(OH)_2$
7	0.50	16.06	$CaO \cdot SiO_2 + 3Ca(OH)_2$

Table 6. Compressive strength (MPa) with various amounts of cementitious materials

Dosage, kg/m^3	Age				
	3d	7d	14d	28d	56d
320	7.32	12.32	21.12	26.32	31.22
350	7.43	12.53	22.13	27.23	31.03
380	7.22	16.23	23.32	30.11	34.43

sure its good strength and frost resistance. Based on the above studies, the chemical structure of binders with various water-adhesive ratios can be obtained, and the results are shown in Table 5.

B.The effect of binder dosage on concrete

(1) The compressive strength at various dosage of the binder. Table 6 shows the compressive strength of concrete with various dosage of different cementitious materials at different ages.

The data in Table 5 shows that when the amount of the binder is 380 kg/m^3, the concrete of 28d is the strongest, and the compression resistance corresponds to C30 requirements. As the amount of the binder decreases, the compressive strength of concrete decreases. The reasons for the above phenomenon are mainly a decrease in the compactness of concrete and a significant decrease in the compressive strength on its surface. The specific change process is shown in Fig. 4.

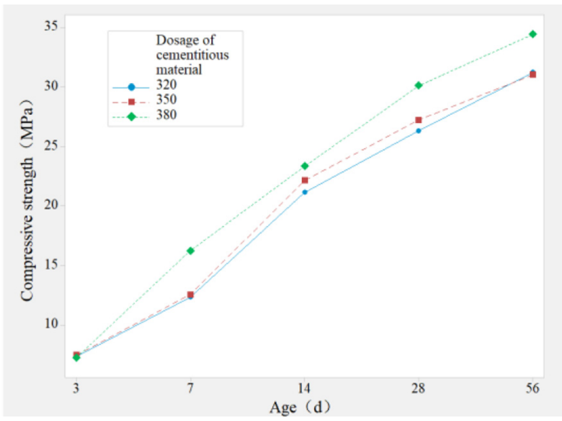

Fig. 4. Compressive strength depending on binder dosage.

It can be seen from Fig. 4 that at different dosages of binders, the compressive strength is much greater at 380 kg/m^3 of binder than at 350 and 320; in addition, there is a significant increase after 56 days of aging, indicating that the compression

Table 7. Antifreeze performance (MPa) with different dosages of cementitious materialTable

Material Dose, kg/m^3	Age				
	3d	7d	14d	28d	56d
320	41.51	41.23	54.32	62.12	71.24
350	42.63	43.52	56.12	63.11	73.61
380	43.72	44.33	58.23	67.36	85.4

resistance is proportional to the amount of binder, and the best pressure resistance is observed when using 380 kg/m^3 of binder.

(2) Antifreeze performance of the amount of cementitious material The frost resistance of concrete at different ages and with different dosages of various binders is presented in Table 7.

The data in Table 7 show that at a binder dosage of 380 kg, concrete after 28 days of aging is the most durable and meets the requirements of C30 in terms of the dynamic modulus of elasticity. With an increase in the binder dosage, the kinetic elastic modulus of concrete increases. The kinetic modulus of elasticity of concrete with a binder dosage of 380 kg/m^3, 350 kg/m^3 and 320 kg/m^3 increased from 85.4 % to 71.24 %, respectively after 56 days. The reasons for the above phenomenon are mainly an increase in the amount of the binder, a decrease in porosity of concrete, an increase in the amount of hydration products, a decrease in water absorption, and the enhancement of permeability resistance, so that the frost resistance on the surface is significantly improved; the specific change process is shown in Fig. 5.

The frost resistance of concrete in Fig. 5 is proportional to the amount of the binder material. At the dosage of 380 kg/m^3, the frost resistance increased significantly, and was higher than at the dosages of 350 kg/m^3 and 320 kg/m^3. Therefore, it is recommended that pile foundation concrete in cold areas should use the 380 kg/m^3 dosage of cementitious material to ensure its good strength and frost resistance.

C. Effects of mineral admixtures

(1) The compressive strength of mineral admixtures Table 8 shows the compressive strength of concrete with different mineral admixture amounts at different ages.

The data in Table 8 show that with the FA10-SF10 mineral admixture, the concrete of is the strongest after 28d aging, and the compressive resistance meets the C30 requirements. Comparing the compressive

Table 8. Compressive strength (MPa) of concrete with different mineral admixturesTable

Mineral admixtures	Age				
	3d	7d	14d	28d	56d
FA0-SF0	7.82	13.52	22.22	23.13	31.22
FA10-SF5	7.53	14.61	23.63	28.42	31.03
FA10-SF10	7.92	15.42	24.22	29.33	38.33
FA20-SF5	6.85	13.42	20.65	28.42	37.52
FA20-SF10	7.32	12.95	21.85	27.62	36.95

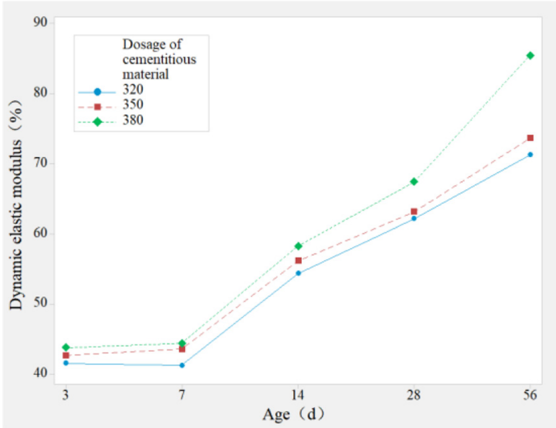

Fig. 5. Freeze resistance of cementitious material dosage.

strength values of concrete with different silica ash content and with the same fly ash ratio, it is found that the amount of silica ash has a significant effect on the early strength of concrete, which contributes to the hardening of concrete, and can also increase the strength of concrete at a late stage. At the fly ash content of 10 %, when the silica ash content rises from 5 % to 10 %, the compressive strength of concrete increases by 10 % for 56 days. When the fly ash content is 20 %, while the silica ash content increases from 5 % to 20 %, the compressive strength of concrete increases by 21 % for 56d. The reason for the above phenomenon is that silica ash has a large specific surface area, increases water contact, and participates in the hydration of early cement materials, improving the early strength of concrete. In addition, comparing the compressive strength of concrete with different fly ash content and with the same silica ash content, it is found that the concrete strength decreases with an increase in the fly ash content; and when the silica ash content is 10 %, and the fly ash content increases from 10 % to 20 %, the compressive strength of

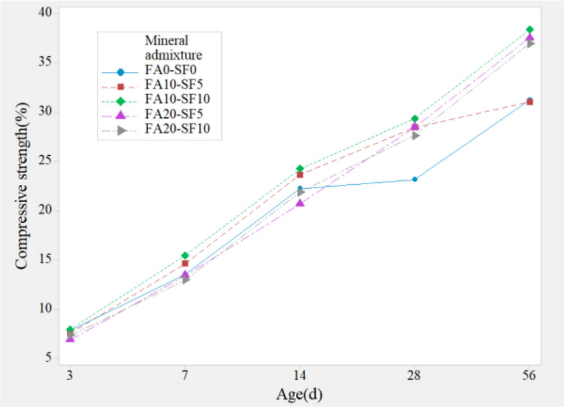

Fig. 6. Compressive resistance of mineral admixtures.

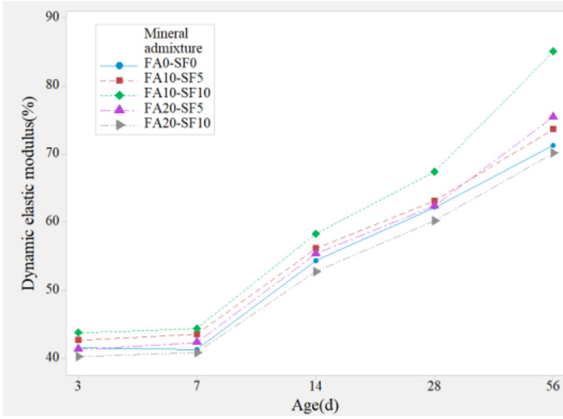

Fig. 7. Freeze resistance of mineral admixtures.

concrete after 56d significantly decreased by 10.7 %. When the silica ash content is 5 %, and the fly ash content is increased from 10 % to 20 %, the compressive strength of concrete after 56 days is reduced by 20 %. The specific change process is shown in Fig. 6.

(2) Antifreeze performance of mineral admixtures

The frost resistance of concrete with different content of a mineral admixture at different ages is shown in Table 9.

From the data in Figle 6, it can be seen that with the mineral admixture FA10-SF10, the concrete of age 28d is the most durable, and the dynamic elastic modulus meets the requirements for C30. Although the dynamic modulus of elasticity is 85.42 %, the FA20-SF10 additive is the worst, since after 150 subfreeze-thaw cycles the kinetic modulus of elasticity becomes only 70.09 %; the specific change process is shown in Fig. 7.

The frost resistance in Fig. 7 is proportional to the content of the mineral admixture. With the mineral admixture of FA10-SF10, the frost resistance is significantly increased and is higher than that of FA20-SF5 and FA0-SF0 Mineral admixtures. Therefore, it is recommended to use the mineral admixture FA10-SF10 in the concrete of the pile foundation in cold areas to ensure its good strength and frost resistance.

It has been established that mineral additives have a positive effect on the compressive strength and frost resistance of concrete, which correlates with their effect on C30 concrete of a pile foundation in alpine regions. It is recommended to combine fly ash and silica ash and use their advantages to achieve complementarity of various mineral additives. At the same time, given that ash silica has a significant inhibitory effect

Table 9. Antifreeze performance (MPa) at different mineral admixture contents

Mineral admixtures	Age				
	3d	7d	14d	28d	56d
FA0-SF0	41.51	41.23	54.32	62.12	71.24
FA10-SF5	42.63	43.52	56.12	63.11	73.61
FA10-SF10	43.72	44.33	58.23	67.36	85.02
FA20-SF5	41.26	42.30	55.31	62.33	75.41
FA20-SF10	40.22	40.82	52.71	60.19	70.09

on its fluidity after introduction into concrete and enhances the effect on the heat of early hydration, it is recommended to use 10 % fly ash and 5 % fly ash formulationand 5 % silica ash compounding.

4. Conclusion

The results show that: 1) in a low-temperature environment, compressive strength and frost resistance of concrete decrease with increasing the water-adhesive ratio, and the two are negatively correlated. The compressive strength of concrete increases with increasing binding capacity; the larger the age, the greater the difference in compressive resistance. Increasing the amount of binder increases the frost resistance of concrete. 2) In a low-temperature environment, the compressive strength and frost resistance of concrete with FA10-SF10 additive is significantly increased, and the best value is achieved. The incorporation of silica ash improves the early strength of concrete, and the frost resistance is significantly increased. The reduction of the fly ash content can significantly reduce strength and frost resistance of the concrete, and the two are negatively correlated.

3) In concrete C30 pile foundations in alpine areas, it is recommended to set the water-adhesion ratio to 0.45, the binder dosage to 380 kg/m^3, and to use 10 % fly ash and 10% silica ash for remixing.

References

1. Xuefeng Yuan, Gang Liao, *Funct.Mater.*, **2**, 29 (2022).
2. Luo Yeke, Yu Zhouping, *Funct.Mater.*, **1**, 29 (2022).
3. A.Hegyi, A.V.Lazarescu, H.Szilagyi et al., *Materials*, **5**, 14 (2021).
4. N.Ichikawa, T.Hamamoto, *Journal of Advanced Concrete Technology*, **12**, 19(2021).
5. I.A.Kanellopoulou, I.A.Kartsonakis, C.A.Charitidis, *Applied Sciences-Basel*, **2**, 11 (2021).
6. M.Khan, M.L.Cao, *Magazine of Concrete Research*, **10**, 73 (2021).
7. J.Yoon, H.Kim, S.H.Sim, S.Pyo, *Construction and Building Materials*, **30**, 284 (2021).
8. L.Boquera, J.R.Castro, A.L.Pisello et al., *Journal of Energy Storage*, **7**, 54 (2022).
9. A.L.Brooks, Y.W.He, N.Farzadnia et al., *Cement & Concrete Composites*, **21**, 129 (2022).
10. A.Hamdan, T.Kim, A.Hajimohammadi et al., *Cement and Concrete Research*, **14**, 153 (2022).
11. M.Hojati, Z.Z.Li, A.M.Memari et al., *Results in Engineering*, **9**, 13 (2022).
12. G.F.Huseien, M.L.Nehdi, I.Faridmehr et al., *Benefits and Challenges, Sustainability*, **4**, 14 (2022).
13. I.Navarrete, Y.Kurama, N.Escalona et al., *Cement and Concrete Research*, **10**, 151 (2022).
14. A.Nikvar-Hassani, L.Y.Zhang, *Materials and Structures*, **4**, 55 (2022).
15. C.Perez, C.Lors, B.Erable, *International Biodeterioration & Biodegradation*, **44**, 175 (2022).
16. M.A.Reda, S.E.Chidiac, *Materials*, **20**, 15 (2022).
17. J.Sobhani, M.Najimi, A.R.Pourkhorshidi, *Civil Engineering Infrastructures Journal-Ceij*, **1**, 55 (2022).
18. A.Murugesan, A.A.M.Ismail, D.Srinivasan, *Innovative Infrastructure Solutions*, **4**, 8 (2023).