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Research on the Anchoring Performance of Green and Low-Carbon Anchoring Materials for Urban Rail Transit Foundation Pit Engineering

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Abstract. Currently, most anchoring materials used in engineering are ordinary cement mortar, which has a slow hardening process, a prolonged early strength development, and high carbon emissions. In response to this, this paper proposes a new type of green anchoring material. The anchoring performance of this material is verified through indoor and field tests. Indoor tests on the basic properties of the green anchoring material were conducted, determining the optimal water-material ratio to be between 0.25 and 0.30 through tests on fluidity, setting time, and compressive strength. Field tests studied the ultimate bond strength of the new green anchoring material in typical soil-rock composite strata in Qingdao, confirming its rapid-setting and high-strength anchoring characteristics. The application of this anchoring material can reduce carbon emissions and realize the concept of green and low-carbon environmental protection.

Keywords: low carbon, green, anchoring materials.

1. Introduction

With the acceleration of urbanization and the promotion of the national concept of green, low-carbon environmental protection, the development and utilization of underground space and the construction of rail transit have become key solutions to alleviate urban land shortages and traffic congestion in China [1]. Currently, the Qingdao metro project is actively promoting green construction concepts, and when discussing metro projects, foundation pit anchoring engineering is indispensable.

At present, the primary bonding material used in domestic anchoring projects is ordinary cement mortar. However, this material has a slow hardening process and requires a long time for early strength to develop, typically taking 7 to 10 days after grouting before prestressing can be applied. This, to some extent, affects the construction schedule and causes economic losses [2]. Therefore, achieving rapid setting and early strength in anchoring materials has garnered widespread attention in the engineering community.

The new high-strength, fast-setting green anchoring material used in this study (hereinafter referred to as the new green anchoring material) is composed of various natural mineral materials mixed in specific proportions. The cost of the material is similar to that of ordinary cement, and while enhancing

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anchoring strength, it reduces cement usage, aligning with the principles of green, low-carbon, and efficient construction.

2. Research on the Anchoring Performance of New Green Anchoring Materials

2.1. Material Reaction Mechanism

The new green anchoring material is a special high-activity anchoring material made by blending various mineral materials in specific proportions, followed by activation and ultra-fine grinding. As its components are primarily mineral-based, it significantly reduces dependence on cement materials, which has strong practical significance for reducing carbon emissions and supporting the achievement of “carbon neutrality.”

Blast furnace slag is a byproduct of the iron-making process [3]. When iron oxide is calcined at temperatures exceeding 800°C, impurities such as SiO_2 and Al_2O_3 in the iron ore combine with lime and other fluxes to form slag. The main chemical components of the slag are oxides such as CaO, SiO_2, and Al_2O_3. It is estimated that about 300 kg of slag is produced for every 1,000 kg of pig iron.

The new green anchoring material used in this study includes both primary and auxiliary materials. The composition of the primary materials by weight is as follows: 50%-60% blast furnace slag, 2%-5% calcium sulfoaluminate cement, 2%-5% early-strength Portland cement, 25%-35% fine sand, 2%-5% calcium sulfate, and 2%-5% calcium hydroxide. The composition of the auxiliary materials and their respective weight percentages are: 0.5%-1.0% magnesium oxide, 0.5%-1.0% silica fume, 0.5%-1.0% naphthalene-based superplasticizer powder, and 0.05%-0.1% boric acid.

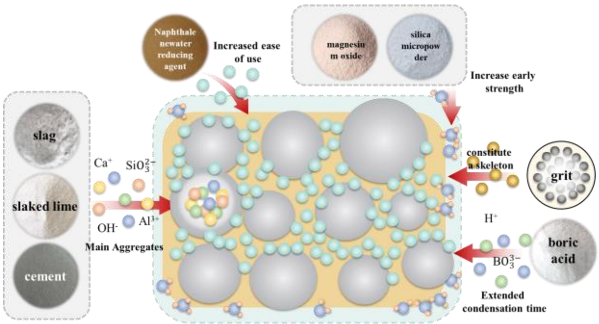

Figure 1. Reaction Mechanism of the New Green Anchoring Material

The main reaction principle is shown in Figure 1. Under hydration, CaO and SiO_2 in the slag react with other cement components to form tricalcium silicate. The hydration of tricalcium silicate produces calcium silicate hydrate gel and calcium hydroxide crystals. This hydration reaction occurs rapidly, resulting in early strength development and the release of early hydration heat. The alumina in the slag can react with hydroxide ions in water, releasing hydroxide ions and forming compounds such as aluminum hydroxide. These compounds can react with sodium silicate in the Portland cement to produce calcium silicate gel and sodium silicate gel, enhancing the cementing properties and strength of the anchoring material.

2.2. Study on Basic Properties of the Material

The water-material ratio of the anchoring material refers to the proportion of water to solidified materials. This ratio plays a decisive role in the slurry’s fluidity and strength. The slurry needs to have high fluidity to effectively fill the gaps and cracks between fractured rocks. Once the slurry is injected into the designated location, it must exhibit characteristics of high plastic viscosity, fast setting time, and early strength to ensure timely filling, consolidation, and sealing of fractured rocks, thereby ensuring their integrity. Fluidity and early strength often present a trade-off in grouting materials, which has been a challenging problem for many scientists researching grouting materials. Experimental studies on the

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relationship between the water-material ratio, slurry fluidity, and setting time of the new green anchoring material are essential for determining the optimal water-material ratio.

In this experiment, the fluidity of the anchoring material slurry was measured according to the testing method guidelines specified in Methods for Testing the Fluidity of Cement Mortar (GB/T2419-2005). The setting time and compressive strength of the anchoring material were measured following the guidelines in Standard for Test Methods of Basic Properties of Mortar for Building Construction (JGJ/T 70-2009). The test results for 30-minute fluidity, setting time, and compressive strength at different water-material ratios are shown in Table 1.

Table 1. Influence of Different Water-Material Ratios on the Performance of Anchoring Materials

Water-Material Ratio	0.20	0.25	0.30	0.35	0.40
Fluidity (mm)	-	167	192	219	241
Setting Time (min)	23	37	48	62	78
1 d Strength (MPa)	41.1	38.0	37.6	34.4	32.9
3 d Strength (MPa)	47.6	44.5	42.8	39.9	39.4
7 d Strength (MPa)	53.8	51.5	51.7	48.2	47.8
28 d Strength (MPa)	74.6	71.4	70.7	68.8	69.1

Based on the experimental data, it can be preliminarily concluded that the new green anchoring material possesses good workability and high strength. The water-material ratio significantly impacts the performance of this anchoring material. Tests conducted within the water-material ratio range of 0.2 to 0.4 reveal the following key effects:

(1) Within the water-material ratio range of 0.2 to 0.4, the fluidity of the slurry is directly proportional to the water-material ratio. However, when the water-material ratio exceeds 0.35, there is a certain degree of bleeding and segregation, while a ratio below 0.20 results in insufficient fluidity for pumping requirements.

(2) The setting time of the slurry shows a similar pattern to fluidity, with setting time directly proportional to the water-material ratio.

(3) The new green anchoring material demonstrates excellent early strength, with the 1-day compressive strength of the slurry test blocks exceeding 30 MPa. However, within the water-material ratio range of 0.2 to 0.4, the strength at each age decreases as the water-material ratio increases.

(4) From the analysis of experimental results, taking into account factors such as pumpability, fluidity, setting time, and strength, the optimal water-material ratio for this material should be in the range of 0.25 to 0.30.

3. Field Test Study of New Green Anchoring Material

The basic performance experiments indicate that the new green anchoring material has good workability and high strength. This section presents a field test study to verify the anchoring performance of the new material in a typical soil-rock composite formation in the Qingdao region, using the foundation pit construction of the Lanzhou West Road station on the Qingdao Metro Line 8 branch as the test site.

3.1. Engineering Geological Overview

The test site is located at the foundation pit of the Lanzhou West Road station on the Qingdao Metro Line 8 branch. The thickness of the Quaternary strata within the foundation pit ranges from 2.9 m to 5.6 m, consisting mainly of Holocene artificial fill and alluvial layers. The bedrock is Cretaceous Wangshi

Group Jiaozhou Formation mudstone. The metro line in this section reveals five standard strata and two sublayers.

According to the survey data, the strata of the station body, from top to bottom, are as follows: plain fill (0–1.5 m), silty clay (1.5–3.5 m), fully weathered mudstone (3.5–6.5 m), upper strongly weathered sublayer of mudstone (6.5–14.5 m), lower strongly weathered sublayer of mudstone (14.5–31.3 m), and moderately weathered mudstone (31.3 m and deeper). The anchoring section of the anchor cable is mainly in the fully weathered and upper strongly weathered sublayers of mudstone.

3.2. Test Design

According to the design data, the foundation pit support structure consists of cast-in-place piles and anchor cables. The pile size is 1000 mm in diameter, with a pile spacing of 1500 mm. The horizontal spacing of the anchor cables is 1500 mm, with one pile and one anchor. A total of five layers of anchor cables (four strands each) are arranged.

The principle of anchor cable placement for the test is that the anchor cables should be arranged at representative cross-sections of the geotechnical profile and distributed on the same side and layer of the foundation pit. The test anchor cable is arranged at the first layer. A test group and a control group are set up. The test group consists of three anchor cables (four strands of steel strands) grouted with the new green anchoring material and cured for one day. The control group consists of three anchor cables (four strands of steel strands) grouted with 425 cement slurry and cured for seven days. Both groups have a length of 15 m, with an anchoring length of 6 m.

The maximum test load is 880 kN (0.85 times the ultimate load of the steel strands). The test procedure involves multi-cycle basic testing, with specific loading steps and levels shown in Figure 2. The loading speed is 50–100 kN/min. The test results are judged as follows: an anchor cable is considered to fail if the displacement exceeds 0.1 mm during the holding period, and the load level just above the failure load is taken as the ultimate bearing capacity of the anchor cable. If the maximum test load does not cause anchor cable failure, the maximum test load is taken as the ultimate bearing capacity. If the range of ultimate bearing capacity for each group of anchor cables is less than 30% of the average value, the minimum value can be used as the ultimate bearing capacity. If the range exceeds 30%, more anchor cables should be tested, and the ultimate bearing capacity should be calculated based on a 95% guarantee probability.

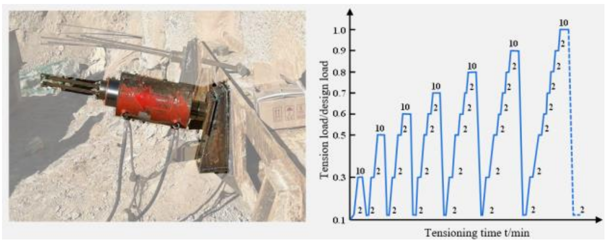

Figure 2. Basic Test Loading Process

In the control group (425 cement cured for 7 days), the ultimate bearing capacities of the three anchor cables were 480 kN, 510 kN, and 515 kN, respectively, with the lowest value of 480 kN taken as the ultimate bearing capacity. The bonding strength between the 425 cement grout anchorage and the geotechnical body was 170 kPa, as shown in [Figure 3]. In the test group (new green anchoring material cured for 1 day), the ultimate bearing capacities of the three anchor cables were 798 kN, 810 kN, and 805 kN, respectively, with the lowest value of 798 kN taken as the ultimate bearing capacity. The bonding strength between the new green anchoring material and the geotechnical body was 282 kPa, as shown in Figure 4.

Under the conditions of the strongly weathered strata, the 1-day curing bonding strength between the new green anchoring material and the geotechnical body was 1.7 times that of the 7-day cured 425 cement grout. Using the new green anchoring material for grouting can increase the anchorage force by 1.7 times.

The 1-day bearing capacity of the anchor cables grouted with the new green anchoring material met the design requirements, providing timely anchorage force to the anchor cables and significantly shortening the construction period when applied on site.

(a) Load-Displacement Curve (b) Load-Deformation Curve

Figure 3. Results of Multi-Cycle Test for 7-day Cement

(a) Load-Displacement Curve (b) Load-Deformation Curve

Figure 4. Results of Multi-Cycle Test for 1-day New Green Anchoring Material

Based on the field and basic material performance tests, it can be concluded that the new green anchoring material has higher strength, allowing for reasonable optimization of the number of anchor cables. Preliminary calculations show that, without reducing the safety factor, the number of anchor cables can be optimized by approximately 20%, achieving the goal of green carbon reduction. Due to its early strength characteristics, the anchor cables can be prestressed earlier, controlling foundation pit deformation and preventing engineering accidents. The application of this material will greatly improve the efficiency of foundation pit construction, especially for long-strip metro foundation pits. According to the Standards for Calculating Building Carbon Emissions (GBT 51366-2019), the carbon emission factor for ordinary Portland cement is 735 kg·e/t. Each anchor cable can reduce carbon emissions by approximately 0.25 tons, and a medium-sized metro station with pile-anchor support can reduce carbon emissions by approximately 300 tons.

4. Conclusion

This paper investigates the anchoring performance of a new green anchoring material through a combination of indoor and field tests, and the conclusions drawn are as follows:

(1) The new green anchoring material exhibits good working performance and high strength. The water-to-material ratio significantly affects the performance of this anchoring material, with an optimal ratio of 0.25 to 0.30. The grout within this range possesses advantages of strong fluidity and high strength.

(2) Field tests indicate that under the typical soil-rock composite strata conditions in Qingdao, the ultimate bonding strength of the new green anchoring material with the geotechnical body is 1.7 times that of the 7-day cured 425 cement material at a 1-day age.

Preliminary calculations suggest that, without reducing the safety factor, the use of the new green anchoring material can optimize the number of anchor cables by approximately 20%, achieving the goal of green carbon reduction. According to the Standards for Calculating Building Carbon Emissions (GBT

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51366-2019), each anchor cable can reduce carbon emissions by approximately 0.25 tons, and a medium-sized metro station with pile-anchor support can reduce carbon emissions by approximately 300 tons. It is recommended to promote the use of the new green anchoring material to implement a green, low-carbon, and efficient construction philosophy.

References

[1] Feng, A. J. (2022). Data statistics and development analysis of urban rail transit in China in 2021. Tunnel Construction (Chinese and English), 42(2), 336-341.
[2] Zhu, J., & Li, Z. J. (2014). Rapid support design for large-scale deep foundation pits in soft soil areas near the sea. Western Exploration Engineering, 26(10), 178-180.
[3] Wu, P., Lü, X. J., Hu, S. G., et al. (2012). Progress in the activation of the cementing performance of granulated blast furnace slag. Metal Mining, (10), 157-161.