Research on Porosity and Performance of Self-compacting Backfill Materials

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Abstract: This paper researched and developed a new type of self-compacting backfill material behind the wall of underground pipelines, and compared and analyzed the relationship between the water-binder ratio, porosity and compressive strength of the two backfill materials. The average pore size of the foam backfill material increases with the water-binder ratio. While increasing, the porosity tends to decrease with the increase of water-binder ratio, and the compressive strength first increases and then decreases with the increase of water-binder ratio; self-compacting backfill material has excellent properties such as self-compacting, light weight and anti-vibration. It is a new type of building materials which can meet the requirements of fluidity and strength for backfilling after penetrating the yellow pipe wall.

1. introduction

In recent years, with the rapid development of national economic construction, there has been an increasing number of water tunnel and subway tunnel projects, and the number of projects crossing the Yellow River and Yangtze River dikes has gradually increased\cite{1,2}. Dyke-crossing pipelines may affect the safety of the dikes during the construction and operation periods, and will have certain impacts on river flooding, river regime stability, dike safety, flood control, etc., especially if the backfill around the pipeline is not dense and the surrounding soil will be prone to settlement, deformation, water seepage and displacement, which not only causes stratum loss, but even causes major accidents such as the collapse of dikes and the collapse of nearby buildings\cite{3-5}.

Although the grouting material and raw soil are used for backfilling, it is not dense and requires multiple backfilling. At the same time, due to the long setting time, the construction period is affected, and embankment settlement and collapse may occur \textsuperscript{[6,7]}. In the construction of large-scale yellow tunnels or water pipelines, there are a large number of backfill areas behind the pipe wall. The treatment of these areas not only needs to meet the mechanical performance requirements, but also it should meet the requirements of compactness, reduced settlement, and short backfilling time. This requires that the backfill materials have relatively high fluidity and volume stability, by adding appropriate stabilizing materials and admixtures, not only it can improve material strength and fluidity, reduce sedimentation\textsuperscript{[8,9]}, but it will also meet the requirements of sustainable development.
The self-compacting foam backfill material has outstanding characteristics in engineering, with low self-weight, good fluidity, and compressive strength that can be adjusted and controlled within a certain range\cite{10,11}; it also has characteristics such as excellent construction performance, self-standing after curing, permeability and low water absorption performance; it has other properties such as heat preservation, earthquake resistance, frost resistance\cite{12,13}. Foam backfilling materials are used in the backfilling after crossing the yellow pipeline wall, which can avoid the damage to the environment such as high filling and high excavation, and protect the embankment and the surrounding ecological environment\cite{14-16}.

The self-compacting foam backfill material has high requirements for the comprehensive performance of all aspects of the material due to long-term service in the underground humid environment\cite{17,18}. In this study, self-compacting foam was prepared using the self-made FC-1 high-performance foam with lightweight filling materials, water-binder ratio, fly ash content, etc. as variables, and through a large number of experiments to determine the range of changes, through optimizing the ratio design, to explore its impact on the physical and mechanical properties of self-compacting foam filling materials, based on direct methods such as measurement and electronic scanning to test material pore structure parameters and analyze the influence mechanism of these macro factors on the micro-structure to provide a theoretical basis for its large-scale application in the backfill of underground pipeline walls of the Yellow River embankment.

2. Test raw materials and test methods

2.1 Test raw materials

This test research uses 42.5MPa ordinary Portland cement and Grade II fly ash, which come from Nanjing and Zhenjiang respectively. The performance indicators of cement and fly ash meet the requirements of "General Portland Cement" GB175-2007 and according to "Fly Ash Used in Cement and Concrete" GB/T1596-2005, the performance indicators of cement and fly ash are shown in Table 1.

The foaming agent used in the experiment is the FC-1 foaming agent developed by the research group. The dilution ratio of the foaming agent is 40, the bleeding rate in one hour is about 5% to 15%, and the settlement distance in one hour is 4 to 7 mm. The water-reducing agent used is a polycarboxylic acid-based water-reducing agent, from a water-reducing agent company in Nanjing, with a water-reducing rate of about 32%. In the process of designing the mix ratio of the self-compacting backfill material, by controlling the total amount of raw materials in the foam backfill material per unit volume, the quality of various raw materials in the material under different water-to-binder ratios is determined. The dry density and water glue ratio of the two self-compacting backfill materials used in the test are shown in Table 2.

| Table 1 Physical properties of cement and fly ash |
|-----------------------------------------------|
| Project | Cement | Test results | Fly ash | Test results |
| Specific surface area (m²/kg) | Specific surface area (m²/kg) | 370 | 315 |
| SO3 (%) | SO3 (%) | 2.14 | 0.35 |
| Ignition loss (%) | Ignition loss (%) | 1.80 | 3.87 |
| MgO (%) | Bulk density (kg/m³) | 1.50 | 2.1 |
| Chlorine content (%) | Fineness (45 µm) | 0.007 | 18 |
| Initial/final setting time (min) | Moisture content (%) | 120/205 | 0.2 |
| Standard consistency (%) | Water demand ratio (%) | 28 | 94 |
| 3/28 days Flexural strength (MPa) | Strength activity index(%) | 6.7/9.0 | 78 |
| 3/28 days Compressive strength (MPa) | SiO2+Al2O3+Fe2O3 (%) | 30.0/50.0 | 89 |
| Stability | f-CaO (%) | Qualified | 0.35 |
| Alkali content (%) | Alkali content (%) | 0.47 | 0.40 |
Table 2 Dry density and water-binder ratio of self-compacting backfill materials

| Specimen | Dry density kg/m³ | Water-binder ratio % |
|----------|-------------------|----------------------|
| FC700-1  | 734               | 0.40                 |
| FC700-2  | 723               | 0.50                 |
| FC700-3  | 720               | 0.55                 |
| FC700-4  | 736               | 0.60                 |
| FC700-5  | 741               | 0.65                 |
| FC900-1  | 928               | 0.40                 |
| FC900-2  | 916               | 0.50                 |
| FC900-3  | 908               | 0.55                 |
| FC900-4  | 893               | 0.60                 |
| FC900-5  | 906               | 0.65                 |

2.2 Test method

After the self-compacting backfill material is mixed according to the dry density and water-binder ratio described in Table 1, the mixed self-compacting backfill material is immediately poured into a mold of 100mm×100mm×100mm, vibrated, formed and flattened, and then placed in the room. (24±2) hours later, the mold will be removed, and the sample will be cured in a standard curing room for 28 days for performance testing and microanalysis.

The self-compacting backfill material specimens cured for 28 days were cut into 20mm thick slices, and the surface morphology characteristics were observed and collected by an electron microscope, and the pore structure of the material was analyzed using Image-J software to calculate the average pore size and pores of the self-compacting backfill material. The porosity rate I is directly measured by the mass-volume method[4], and calculated according to formula (1):

\[ I = \frac{\rho - \rho_0}{\rho} \]  

(1)

In the formula: \( \rho \) - the dry density of the test piece, in kg/m³; \( \rho_0 \) - the actual density of the test piece, in kg/m³.

3 Test results and analysis

3.1 Research on the fluidity of self-compacting backfill materials with different water-to-binder ratios

Due to the low density and high volume utilization of self-compacting foam backfill materials, when used in different underground backfill projects, due to the surrounding environment of the pipeline, it is usually impossible to vibrate and compact. The fluidity of the backfill material determines the compactness of the backfill. The degree and different construction requirements are shown in Figures 1 and 2 as a schematic diagram of the fluidity of the self-compacting backfill material with a density of 700 kg/m³ as a function of the water-binder ratio and the amount of fly ash.

(a) The effect of water-binder ratio on fluidity

(b) Influence of fly ash content on fluidity

Figure 1 The influence of different components on the fluidity of backfill material slurry
It can be seen from Figure 1(a) that the fluidity of the self-compacting backfill material slurry shows an upward trend with the increase of the water-to-binder ratio. When the water-to-binder ratio increases sequentially, the fluidity increases by 30.43%, 39.13%, 43.48% and 60.87%. The fluidity of the backfill material slurry increases with the increase of the water-to-binder ratio. The increase in the water-to-binder ratio increases the dispersion of foam and cement in the slurry, and the packing of the air bubbles by the cementitious material also becomes more uniform, which promotes greater fluidity.

The influence of fly ash content on the fluidity of backfill material slurry is shown in Figure 1(b). With the increase of fly ash content, it first increases and then decreases. It has a good fluidity when the content of fly ash is 35%~45%; when the fly ash content gradually increases, the fluidity of the backfill material slurry increases by 11.25%, 18.75%, 23.75% and 8.13%, respectively. This is because the addition of fly ash improves the dispersion of cement particles to a certain extent, which promotes the relative movement between bubbles, and improves the fluidity of the slurry; if the amount of fly ash is too large, it will affect the hydration of cement particles and reduce the degree of mobility\cite{4}.

Figure 2 shows the fluidity of backfill materials with different water-to-binder ratios. It can be clearly seen that the fluidity and surface morphology of the low water-to-binder ratio are not good. Therefore, the water-to-binder ratio used in the research is selected as 0.40~0.65.

3.2 Compressive strength of backfill materials with different water-binder ratios

Figures 3 and 4 are schematic diagrams of the compressive strength of self-compacting backfill materials with density grades of 700 kg/m$^3$ and 900 kg/m$^3$ as a function of water-binder ratio.
It can be seen from Figures 3 and 4 that the compressive strength of the self-compacting backfill material gradually rises first and then slightly decreases with the increase of the water-to-binder ratio. The compressive strength of the backfill material with a density of 700 kg/m$^3$ reaches the maximum when the water-to-binder ratio increases. The compressive strength of the backfill material with a density of 900 kg/m$^3$ reaches the maximum when the water-to-rubber ratio is 0.55, which is 2.73MPa, and basically exceeds 2MPa (except for the slightly lower water-to-rubber ratio of 0.40), and the compressive strength fully meets the design requirements of the backfill material for the Yellow River Crossing Project. This is because as the water-binder ratio in the self-compacting backfill material increases, the viscosity of the slurry decreases, the bubbles in the slurry merge with each other, and the volume of the bubbles in the slurry decreases; the flow of bubbles will promote the gelation in the backfill material, which makes the hydration reaction of the material more complete; the hydration product fills the gap between the pore walls, which reduces the porosity, and improves the compressive strength of the backfill material$^{[19]}$; if the water-binder ratio increases again, the porosity of the backfill material decreases, however, the increase of the pore diameter makes the pores in the backfill material unevenly distributed in the material, and stress concentration is prone to occur, which reduces the compressive strength of the backfill material.

### 3.3 Research on the average pore size and porosity of backfill materials with different density levels

Figures 5 and 6 are the average pore size and porosity test results of self-compacting backfill materials with density grades of 700 kg/m$^3$ and 900 kg/m$^3$.

![Average Pore Size](image1)

![Porosity](image2)

It can be seen from Figure 5 and Figure 6 that as the water-to-binder ratio increases, the average pore size of the self-compacting backfill materials of different density grades is on the rise, and the average pore diameter of the backfill materials of the density grade of 900 kg/m$^3$ is smaller than 700 kg/m$^3$; As the water-binder ratio increases, the porosity of backfill materials of different density grades decreases slightly, and the porosity of backfill materials with density grades of 900 kg/m$^3$ is lower than 700 kg/m$^3$. This is because as the water-to-binder ratio increases, the bonding performance of the cementitious material gradually decreases, and the ability to wrap bubbles is correspondingly weakened. A large number of bubbles in the backfill material merge and communicate with each other, and the average pore size shows an upward trend$^{[20]}$; If the water-binder ratio of the backfill material is further increased, the increase in the pore size of the bubbles due to the friction between the cementitious materials will be correspondingly weakened. For backfill materials with different density levels under the same water-to-binder ratio, the average pore size decreases with the increase of the density level of the backfill material. This is because as the density level of the backfill material increases, the cementitious material accounts for the proportion of the backfill material gradually increase, the resistance encountered during bubble formation and movement also increases, and its average pore size also decreases.
3.4 Research on the morphology of backfill materials with different density levels

Figure 7 is a schematic diagram of the morphology of the self-compacting backfill material with a density of 700 kg/m³ and 900 kg/m³ when the water-binder ratio is 0.50.

![Figure 7 Internal bubble morphology of backfill materials with different densities](image)

It can be seen from Figure 7 that the water-binder ratio is 0.50, and the self-compacting backfill materials with different densities have different morphologies. As the density level increases, it is obvious that the bubble diameter in the backfill material gradually decreases. For example, the pore size of the backfill material with a density of 700 kg/m³ in Figure 7 (a) is significantly larger than that of 900 kg/m³ in Figure 7 (b). This is basically consistent with the average pore size test result in Figure 5; at the same time, the number of bubbles has increased significantly, the pore distribution is more uniform, the bubble spacing is also significantly reduced, and the porosity is reduced, which is basically consistent with the porosity test results in Figure 6. The porosity decreases, the compactness of the backfill material increases, the contact surface and adhesion of the cementitious material also increase, the rate and degree of cement hydration reaction increase, and the compressive strength of the self-compacting backfill material increases. This matched the result of compressive strength in Figure 3.

4. Conclusion

The physical and mechanical properties, pore structure and morphology of self-compacting backfill materials with densities of 700 kg/m³ and 900 kg/m³ are studied through experiments, and the following conclusions are drawn:

1) The fluidity of the self-compacting backfill material slurry increases with the increase of the water-binder ratio. The fluidity of the backfill material slurry is better when the water-binder ratio is greater than 0.4; the fluidity of the backfill material slurry increases with the amount of fly ash. First rises and then declines. When the content is 35%~45%, the fluidity is better.

2) The compressive strength of the self-compacting backfill material first gradually increases with the water-binder ratio and then slightly decreases, gradually increasing with the increase in density; the compressive strength of the backfill material with the water-binder ratio is greater than 0.4 and the density of 900 kg/m³ is greater than 2MPa, which meets the design requirements for backfill materials for the Yellow River Crossing Project.

3) The average pore size of the self-compacting backfill material increases slightly with the increase of the water-binder ratio, and decreases with the increase of the density; the porosity decreases slightly with the increase of the water-binder ratio, and decreases with the increase of the density.

4) Through the analysis of the microstructure and morphology, it can be observed that the morphology of the self-compacting backfill materials of different densities is different, the density increases, and the bubble diameter in the self-compacting backfill material decreases, indicating that the pore structure and strength have a certain correlation.
The project was supported by the traffic construction in Tongling (20210023) and Jiangxi Province (2020H0047), Jiangsu Natural Science Foundation (BK20200429), Post-doctoral fund of China and Jiangsu (2020M671485, 2020Z321).

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