Study on Secondary Grouting Slurry of Closed Cell Perlite for Shield

Yongxiang Wen¹, Ningning Shang², Cancan Cui², Shaowei Kang², Wei Zhou², Zhongzhi Han², Xiaojun Guo²,*

¹Guangzhou Nansha Engineering Company of CCCC Fourth Harbor Engineering Co., Ltd., Foshan, China
²CNPC Engineering Technology Research Co. Ltd, Tianjin, China
*Corresponding author: guoxj@cnpc.com.cn

Abstract. With high belite cement, sulphoaluminate cement and portland cement as cementing materials, closed pore perlite as aggregate and anti-washout admixtures of underwater concrete as additive, the secondary grouting slurry test of expanded perlite suitable for shield grouting was carried out. The test results show that the setting time of secondary grouting slurry of expanded perlite prepared by high belite cement is moderate, which is suitable for secondary grouting slurry preparation; the initial fluidity of slurry prepared by expanded perlite with higher bulk density and the same ratio of cementitious material to aggregate is better, and the fluidity loss is lower; when the ratio of cementitious material to aggregate is between 5:2 And 5:3, the secondary grouting slurry of expanded perlite has better secondary filling effect.

1. Introduction
In the construction of shield tunneling, the construction gap between segment and surrounding rock must be filled with grouting slurry to provide early stability for segment and integrate segment with surrounding rock mass, which is conducive to the control of shield tunneling direction and ensure the final stability of shield tunnel. The synchronous grouting system for shield is mostly the conventional slurry of "cement + bentonite + fly ash + sand", and its bulk density is generally more than 1700kg/m³. After injection, it will sink below the segment, and part of it will be taken away by the circulating slurry. Therefore, the unfilled space is located at the upper part of the tunnel. It is necessary to use secondary grouting to fill the remaining space, and the secondary grouting slurry is mostly viscous "cement + gypsum + putty" system; due to the poor fluidity of secondary grouting slurry, there is still a certain proportion of space between the segment and the surrounding rock after the whole grouting is completed, which is easy to cause the segment floating and other problems [1]. Based on this, it is necessary to develop new secondary grouting slurry to solve the above problems. In this paper, the secondary grouting slurry of expanded perlite for shield machine can meet the needs of engineering.

The buoyancy is very large when the grouting slurry is used to wrap the pipe piece [2]. According to Archimedes' buoyancy law, reducing the density of grouting slurry can reduce the buoyancy of segment. Therefore, the volume weight of slurry has the most direct effect on the segment floating. If a kind of buoyant lightweight slurry is developed, it can not only reduce the buoyancy of the segment after injection, but also accumulate above the segment first after injection, which can prevent the segment
from floating after rapid solidification and hardening. Therefore, the author proposes to develop a new
type of lightweight slurry for secondary grouting of shield to suppress the segment floating [3].

There are two main technical means to realize the material system of lightweight mortar (or concrete),
namely, introducing bubbles by foaming technology and using lightweight aggregate [4]. Considering
that the aerated mortar (or concrete) is difficult to meet the dynamic and complex environmental
requirements of shield grouting, such as high water pressure, slurry circulation and so on, the preparation
method of lightweight aggregate is adopted in this test.

Closed cell perlite is heated by electric furnace. Through the gradient heating and the precise control
of the time of air stagnation, the surface of perlite ore is dissolved and melted, and the pores are closed,
and the interior is honeycomb structure [5]. Because the closed-hole perlite has a glassy shell, it is named
vitrified bead. The glass bead insulation mortar has excellent heat insulation performance, fire resistance
and aging resistance, no hollowing cracking, high strength and convenient construction, but its
production cost is higher than that of perlite. In the building materials industry, the glass micro beads
can be used as light aggregate, which can improve the fluidity and self resistance of mortar, reduce the
shrinkage rate of materials, improve the comprehensive performance of products and reduce the
comprehensive production cost [6]. At present, most of the researches are using closed hole perlite as
light aggregate insulation mortar, but it has not been reported that light mortar is developed and applied
to shield grouting.

2. Objective of the experiment
The research of this paper is based on the water intake and drainage project of a nuclear power plant in
China. The specific requirements for secondary grouting materials are: (1) have certain consolidation
strength. The strength of the material is close to or slightly higher than that of the surrounding medium
for a certain period of time (initial setting and final setting time) after it is pressed into the building space,
so as to ensure the interaction between the tunnel lining and the surrounding soil medium. (2) It has a
certain fluidity to ensure the smooth pumping of grouting slurry to the annular gap behind the lining; it
can completely fill the gap; the volume shrinkage is small; there is no material separation after being
diluted by groundwater or injected for a long time; there is no essential change in nature after being
invaded by groundwater for a long time. (3) It has good long-term stability and reasonable viscosity to
meet the technical requirements of certain distance pumping. (4) It must do little harm to soil
environment and groundwater environment. (5) The raw material source is rich, economic, construction
management is convenient, and can meet the technical requirements of construction automation. In order
to meet the above requirements, the researchers carried out the research on lightweight slurry of
expanded perlite.

3. Raw materials
Cement:Ordinary portland cement, strength grade 42.5; high belite sulphoaluminate cement, strength
grade 42.5; fast hardening sulphoaluminate cement, strength grade 42.5. The above three kinds of
cement are produced by Tangshan polar bear building materials Co., Ltd. The chemical composition of
three kinds of cement is shown in table 1.

| Table1. Chemical composition of three kinds of cement |
|-----------------------------------------------------|
| Material name                            | SiO₂ | Fe₂O₃ | Al₂O₃ | CaO   | MgO  | SO₃  | Total alkali content |
|-------------------------------------------|------|-------|-------|-------|------|------|---------------------|
| Ordinary portland cement                 | 22.02| 2.65  | 6.19  | 58.99 | 2.53 | 2.67 | 0.70                |
| Sulphoaluminate cement                    | 7.82 | 3.12  | 20.92 | 45.14 | 1.30 | 12.55| -                   |
| High belite cement                        | 24.86| 2.15  | 3.65  | 59.97 | 2.87 | 4.06 | 0.94                |

Aggregate: three kinds of closed cell perlite with different particle size and bulk density are used.
See table 2 for specific performance parameters.
Table 2. Main performance parameters of closed cell perlite

| Closed pore perlite | Particle size/mm | Bulk density/kg.m³ | 1H Water absorption/% |
|---------------------|------------------|--------------------|----------------------|
| P1                  | 0.315-2.5        | 152                | 225                  |
| P2                  | 0.315-1.25       | 170                | 205                  |
| P3                  | 0.16-1.25        | 181                | 190                  |

Water: tap water.
Additive: anti-washout admixture UWB-II produced by CNPC Engineering Technology Research Co., Ltd.

4. Experiment and result discussion

4.1. Optimization of cement
According to the characteristics and technical requirements of shield grouting slurry, the slurry with different cement configuration can be compared and optimized from many aspects: (1) the determination of setting time of slurry; (2) the compressive strength of slurry stone body. In order to compare the setting time and compressive strength of different cement, the above three kinds of cement are used. The cement dosage: Perlite P1 is 5:1, 5:2, 5:3, and the setting time and compressive strength of the slurry are compared. See table 3 below for specific mix ratio, and see Table 4 for test results.

Table 3. Slurry mix ratio

| No. | Cement type                        | Cement | Perlite | Water | Anti-washout admixture | Water reducer |
|-----|------------------------------------|--------|---------|-------|------------------------|--------------|
| 1   | Ordinary portland cement           | 500    | 100     | 500   | 10                     | 2.5          |
| 2   | Sulphoaluminate                    | 500    | 100     | 500   | 10                     | 2.5          |
| 3   | High belite cement                 | 500    | 100     | 500   | 10                     | 2.5          |
| 4   | Ordinary portland cement           | 500    | 200     | 550   | 10                     | 2.5          |
| 5   | Sulphoaluminate                    | 500    | 200     | 550   | 10                     | 2.5          |
| 6   | High belite cement                 | 500    | 200     | 550   | 10                     | 2.5          |
| 7   | Ordinary portland cement           | 500    | 300     | 600   | 10                     | 2.5          |
| 8   | Sulphoaluminate                    | 500    | 300     | 600   | 10                     | 2.5          |
| 9   | High belite cement                 | 500    | 300     | 600   | 10                     | 2.5          |

Table 4. Test results

| Item/No.                  | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|---------------------------|------|------|------|------|------|------|------|------|------|
| Final setting time/min    | >1200| 20   | 150  | >1200| 22   | 165  | >1200| 25   | 180  |
| Strength of 1 day/MPa     | --   | 3.9  | 3.7  | --   | 1.7  | 1.6  | --   | 0.7  | 0.7  |
| Bulk density/kg.m³        | 1.11 | 1.12 | 1.12 | 0.74 | 0.73 | 0.73 | 0.54 | 0.55 | 0.53 |

It can be seen from table 4 above that the final setting time of common portland cement slurry is more than 20h, and the test block has no strength in one day; the setting time of fast setting sulphoaluminate cement slurry is less than 30min, and the pump is likely to be blocked if the setting time is too fast; the final setting time of high belite sulphoaluminate cement slurry is about 180 minutes, and the strength in one day is similar to that of fast setting sulphoaluminate cement slurry The results show that the slurry prepared with acid salt cement is similar, and the volume weight of the slurry prepared with three kinds of cement is basically the same when the perlite dosage is fixed; based on the...
final setting time, compressive strength and volume weight of the slurry prepared with three kinds of cement, the high belite sulphoaluminate cement is selected as the benchmark cement.

4.2. Optimization of cement
In order to compare the slurry performance of P1, P2 and P3 perlite in Table 2, Gaobei cement: Perlite 5:2 was used to prepare the slurry, and the water cement ratio was 1:1. The initial fluidity, compressive strength and fluidity loss of the slurry were compared, so as to select the perlite most suitable for preparing the grouting slurry. See table 5 for slurry mix proportion.

| No. | Cement | Perlite | Water | Anti-washout admixture | Water reducer |
|-----|--------|---------|-------|-------------------------|--------------|
| 1   | 500    | 200     | 550   | 10                      | 2.5          |
| 2   | 500    | 200     | 550   | 10                      | 2.5          |
| 3   | 500    | 200     | 550   | 10                      | 2.5          |

| No. | Initial liquidity/mm | 30 min Liquidity/mm | Strength of 3day/MPa | Bulk density/ kg/m³ |
|-----|----------------------|---------------------|----------------------|---------------------|
| 1   | 185                  | 150                 | 1.6                  | 0.73                |
| 2   | 195                  | 165                 | 1.7                  | 0.74                |
| 3   | 210                  | 180                 | 1.7                  | 0.74                |

It can be seen from table 6 that the difference of one-day compressive strength and bulk density of three kinds of perlite slurry is small, which can meet the requirements of compressive strength of secondary grouting slurry; the initial fluidity and 30min fluidity of perlite P3 slurry are the best, and the fluidity loss is the smallest, which can avoid the risk of pump blocking in grouting to a certain extent. Considering the initial fluidity, fluidity loss, compressive strength and bulk density of three kinds of perlite slurry, perlite P3 is selected as the aggregate of grouting slurry.

4.3. Ratio of cementitious material to aggregate
The secondary grouting of shield is limited by the working space, and most of them are injected from the top space. When the specific gravity of the slurry is greater than 1, the slurry injected first gradually sinks due to the influence of gravity. When the grouting is not continuous due to the influence of construction conditions and grouting speed, the slurry and water are mixed. After the slurry absorbs water, the water cement ratio rises, resulting in the increase of slurry setting time and the decrease of strength, which leads to a series of problems. Therefore, on the basis of previous experiments, we carried out the secondary grouting slurry mix proportion test of expanded perlite with different ratio of cementitious material to aggregate. The slurry mix proportion is shown in table 7, and the performance results are shown in table 8.

| No. | Cement | Perlite | Water | Anti-washout admixture | Water reducer | Bulk density/kg·m³ |
|-----|--------|---------|-------|-------------------------|--------------|-------------------|
| 1   | 500    | 50      | 380   | 10                      | 2.5          | 1300              |
| 2   | 500    | 100     | 460   | 10                      | 2.5          | 1160              |
| 3   | 500    | 150     | 520   | 10                      | 2.5          | 940               |
| 4   | 500    | 200     | 550   | 10                      | 2.5          | 790               |
| 5   | 500    | 250     | 600   | 10                      | 2.5          | 630               |
| 6   | 500    | 300     | 700   | 10                      | 2.5          | 560               |
| 7   | 500    | 350     | 750   | 10                      | 2.5          | 510               |
| 8   | 500    | 400     | 800   | 10                      | 2.5          | 490               |
Table 8. Slurry performance

| No. | Initial liquidity/mm | 30 min Liquidity/mm | Strength of 3day/MPa | Bulk density/kg·m$^{-3}$ |
|-----|----------------------|---------------------|----------------------|--------------------------|
| 1   | 200                  | 160                 | 2.2                  | 1300                     |
| 2   | 205                  | 165                 | 1.8                  | 1160                     |
| 3   | 200                  | 165                 | 1.3                  | 940                      |
| 4   | 195                  | 170                 | 0.9                  | 790                      |
| 5   | 200                  | 170                 | 0.6                  | 630                      |
| 6   | 205                  | 175                 | 0.4                  | 560                      |
| 7   | 195                  | 170                 | 0.3                  | 510                      |
| 8   | 200                  | 175                 | 0.2                  | 490                      |

According to table 7 and table 8, when the volume weight of secondary grouting slurry of expanded perlite is lower than 630kg/m$^3$, the amount of perlite is too high, which will cause the strength of slurry to be lower than 0.5MPa after consolidation, and it will not meet the construction requirements and increase the cost. When the slurry proportion is greater than 1, the slurry will sink into the bottom of the annular space after grouting, which is not conducive to grouting construction; within the range of 630-940kg/m$^3$, the slurry will float above the back space of shield wall and not settle, which can effectively block the top space that synchronous grouting can not be fully filled. When the ratio of cementitious to bone is between 10:3 and 10:5, the secondary grouting slurry of expanded perlite can meet the requirements of compressive strength and maintain relatively low slurry cost, and has a better secondary filling effect.

5. Conclusions
The setting time of secondary grouting should not be too long or too short. Ordinary portland cement cement and sulphoaluminate cement are not suitable for preparing secondary grouting slurry of expanded perlite. The setting time of slurry prepared by high belite cement is moderate, which is suitable for being used as cementing material of secondary grouting slurry.

With the same ratio of cementitious material to aggregate, the slurry prepared by expanded perlite with smaller particle size and higher bulk density has better initial fluidity and lower fluidity loss.

When the bulk density of expanded perlite secondary grouting slurry is 630-940kg/m$^3$, And the specific gravity is between 5:2 And 5:3, the expanded perlite secondary grouting slurry has better secondary filling effect and lower cost.

Reference
[1] Hou Jianjun, Zhao Yunchen, Technical measures for shield tunneling across the Yangtze River in Wuhan, J. Geotechnical foundation, 2(2008)17-20.
[2] HUANG Zhonghui, SHU Yao, JI Chang, et al, Analysis of weight influencing factors of shield tunnel segment uplifting during construction based on equivalent beam model, J. Tunnel Construction, 36(2016)1295-1299.
[3] NIU Zhanwei,ZHANG Wenxin,LI Yuntao,etal, Super diameter subsea shield tunnel construction segment floating and cracking control technology, J. Building Technology, 50(2019)26-30.
[4] WANG Xuecheng,CAO Yang,WU Meisheng, Preparation of light mortar and its performance, J. Building energy efficiency, 47(2019)33-39.
[5] Tong Jixian, Discussion on the application of new expanded perlite exterior wall external insulation system, J. CNBM, 2005 (12)38-40.
[6] Zeng Liang, Huang Shaowen, Hu Xin, et al, Effect of aggregate gradation on properties of expanded perlite vitrified micro bead thermal insulation mortar, J. New building materials,12(2008)56-59.