Experimental Study on Mechanical Properties of Repair Materials for Underwater Rapid Construction

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Abstract. Several strength grades of sulphoaluminate cement concrete were designed, and the mechanical properties with different mix ratios were studied. This paper mainly analyzes the mechanical properties of sulphoaluminate cement concrete with the setting time test, compressive strength test and flexural test. The test results show that the setting time of cement concrete can be controlled by mixing different admixtures. One hand, the initial setting time increases from 34 min to 340 min, and the final setting time increases from 57 min to 580 min when the incorporated borax content changes from 0 to 1.0 %. Other hand, the initial setting time decreased from 34 min to 11 min, and the final setting time increased from 57 min to 18 min, when the incorporated borax content changed from 0 to 0.5 %. Furthermore, the compressive strength can reach 40 MPa, and the flexural strength can reach more than 2.5MPa after 6 hours of curing. The experiment results illustrate that the setting time and the mechanical properties satisfy the needs of the rapid construction requirements under normal temperature conditions.

1. Introduction
The number and scale of hydraulic structures in China have caught up the world level. What’s more, the Three Gorges Dam, Baihetan Hydropower Station and the South-to-North Water Diversion Project under construction have become the largest water conveyance and diversion projects in the world. However, natural disasters occur frequently in our country. Landslides and breaches caused by flood disasters, and long-term use often destroy the underwater parts of deep-water buildings, most of them begin to leak. The leakage of underwater concrete structure is mainly divided into point leakage, linear leakage and flow leakage. Point leakage is divided into one or more points, most of which are multi-point leakage. Most leakage points are dispersed and the range is relatively large. The flow leakages usually appear in the contact area between the water conveyance building and the adjacent building. Due to the long-term washing and erosion, leakage occurs in the contact area, and leakage channels are formed along the edge of the water conveyance building. Linear leakage can be divided into leakage of disease cracks, contact and expansion joints. The crack-leakage is mainly caused by penetrating cracks inside the concrete structure, while the contact joint and expansion joint leakage is mainly caused by the failure of waterproof structure used in the construction process of water conveyance buildings. The conventional plugging methods include direct plugging method, lower pipe plugging method, wood wedge plugging method and grouting plugging method. Different plugging methods are used according to different construction environments and conditions. The direct plugging method is mainly aimed at the leakage point with water pressure less than 1 m. The lower pipe plugging method is mainly aimed at the leakage channel corresponding to the water head of 1 m - 4 m,
when the wood wedge plugging method is mainly aimed at the leakage channel with depth greater than 4 meters. The grouting method can be used to seal holes with large water pressure, large holes and large water leakage. The leakage passages of underwater concrete structures in deep-water buildings are often located in the deep underwater position, especially for the leakage passages at 300 m water depth. Under the conditions of low temperature and high pressure, the grouting materials should meet the requirements of rapid hardening at low temperature, rapid development of strength and micro expansion.

Therefore, it is of great significance to develop an early-strength, high-strength and micro-expansion material for the repairment of underwater leakage channel at low temperature conditions. To overcome technical difficulties for the micro-expansion grouting materials, which can rapidly harden under low temperature conditions of underwater engineering, the project team mainly studies the theory and practice of grouting materials. The setting time, early strength, high strength and micro-expansion of grouting materials are studied, because these indexes are important to repair leakage points under low temperature conditions [1]. Usually, different types of leakage channel grouting materials have different characteristics. Ordinary Portland cement-based grouting materials are suitable for general ground engineering due to their poor water resistance and chemical corrosion resistance. Thanks to the short setting time, Sulphoaluminate cement grouting material are often used to repair the emergency construction, shotcrete anchor support, slurry anchor node, cementing plugging, winter construction application. What’s more, Sulphoaluminate cement grouting material can meet the requirements of fast hardening and early strength under the condition of low temperature [2]. Compared with the ordinary Portland cement-based grouting materials, sulphoaluminate cement-based grouting materials can be rapidly constructed at low temperature. However, the setting time is so fast that the sulphoaluminate cement concrete have been hardened before the construction is finished. Due to this reason, the sulphoaluminate cement can’t be directly used to construct. Otherwise, the only sulphoaluminate cement can’t achieve the effect of rapid construction. Instead, it blocks equipment and repair pipelines, affecting the construction period. In order to control the setting time of sulphoaluminate cement, the heating of sulphoaluminate cement should be reduced [3]. Meanwhile, the indexes of early strength, high strength, no shrinkage, and micro expansion should meet the requirements. Most researchers mixed silicate cement and sulphoaluminate cement to prepare the cement-based grouting material of silicate cement and sulphoaluminate cement. Similar preparation methods also include the cement-based grouting material composed of silicate cement and aluninate cement, but the performance is not stable when two or more types of cement are mixed, and the production processes are complex and the cost is high, which is not the best choice [4].

Firstly, the setting time of the sulphoaluminate cement should satisfy the needs of construction. Simultaneously, the subsequent strength of grouting material can increase stably. Furthermore, the construction technology of grouting material should be improved for leakage passage of underwater concrete structure. In this paper, early strength and high strength of the sulphoaluminate cement grouting material is developed. The setting time of cement clinker is reasonably controlled by the retarder and accelerator, and the preparation technology of early strength grouting material at normal temperature is developed.

2. Materials and Test Methods

2.1. Materials

Sulphoaluminate cement is produced by Beijing Arctic Bear New Building Materials Co., Ltd, and its strength grade is 42.5. The additives used in the experiment are sodium silicate nanahydrate (molecular formula: Na$_2$SiO$_3\cdot$9H$_2$O), aluminium sulfate (Al$_2$O$_3\cdot$SO$_4\cdot$18H$_2$O), Sodium borate (NaB$_4$O$_7\cdot$10H$_2$O), gluconic acid sodium salt (C$_6$H$_{11}$NaO$_7$), see tables from 1 to 4 for details. Na$_2$SiO$_3\cdot$9H$_2$O is colorless orthogonal bipyramidal crystal or white to gray-white block or powder. At 100 °C, 6 molecules of crystal water were lost, as shown in table 1. The content of sodium oxide (Na$_2$O) is 19.3 ~ 22.8 %, and the ratio of sodium oxide and silica content are 1.03 and 0.03. It should
be sealed in a cool place to save.

Table 1. Technical conditions for Na₂SiO₃·9H₂O (Maximum impurity content, %).

|                  | Chloride (c) | Sulfate (SO₄) | Carbonate | Aluminium (Al) | Iron (Fe) | Heavy metal (Pb) |
|------------------|--------------|---------------|-----------|----------------|-----------|------------------|
|                   | 0.01         | 0.01          | eligible  | 0.05           | 0.05      | 0.01             |

The aluminium sulfate (Al₂(SO₄)₃·18H₂O), the maximum impurity content isn’t more than 1 %, and the result of pH is 2.7(≥2.5, 25g/L, 25℃), see table 2.

Table 2. Technical conditions for Al₂(SO₄)₃·18H₂O (Maximum impurity content, %).

|                  | Water insoluble | Chloride | Ammonium (NH₄) | Na | Mg | K | Ca | Fe | Heavy metal |
|------------------|-----------------|----------|----------------|----|----|---|----|----|-------------|
|                   | 0.02            | 0.002    | 0.005          | 0.02| 0.002| 0.005| 0.01| 0.003       | 0.001        |

Sodium borate (NaB₄O₇·10H₂O), also known as sodium tetraborate, its properties are colorless transparent crystalline powder and it can be weathering in dry air. See table 3.

Table 3. Technical conditions for NaB₄O₇·10H₂O (Maximum impurity content, %).

|                  | HCL insoluble   | Chloride | SO₄ | PO₄ | Ca | Fe | Cu | Pb |
|------------------|-----------------|----------|-----|-----|----|----|----|----|
|                   | 0.005           | 0.002    | 0.01| 0.002| 0.005| 0.0003| 0.001| 0.001   |

Gluconic acid sodium salt (C₆H₁₁NaO₇), the maximum impurity content can’t be more than 8 %, see table 4.

Table 4. Technical conditions for C₆H₁₁NaO₇ (Maximum impurity content, %).

|                  | Chloride | Sulfate (SO₄) | Heavy metal (PO₄) |
|------------------|----------|---------------|-------------------|
|                   | <0.005   | <0.02         | <0.002            |

2.2. Test Methods

2.2.1. Setting Time. Admixtures used in the test include borax, aluminum sulfate, sodium silicate and lithium carbonate. The performance of sulfate aluminate cement was investigated when the content of admixtures changes from 0% to 0.8%. According to GB/T 1346-2001, the sand and binder ratio is 1:3, and the water consumption is determined by JC 9333-2003. Based on the water-cement ratio of 0.47, the fluidity of cement-based cement is regulated to the range of 165-175mm, and the residual test methods is carried out according to GB/T 17671-1999.

2.2.2. Compressive Test. In this experiment, a total of five groups of new rapid hardening retarding concrete were prepared, and the effects of water-cement ratio and water reducer content on rapid hardening concrete were studied.

2.2.3. Bending Test. Dimensions of 100mm×100mm×400mm concrete specimen were used in the bending test. The concrete specimens should be cured in the standard curing room, and the dimensions of these concrete specimens should be checked before the bending test. The test device is shown in figure 1. During the bending test, if the fracture position of the lower edge of the specimen is between two concentrated load action lines, the flexural strength (MPa) of the specimen should be calculated as follows:

\[
f_f = \frac{Fl}{bh^2} \tag{1}
\]
3. Test Results

3.1. Setting Time

It can be seen from Figure 2 and Table 5 that the initial setting time and final setting time of sulfoaluminate cement without borax are 34 min and 57 min, respectively. With the increase of borax content, when the borax content changes from 0 to 1.0 %, the initial setting time increases from 34 min to 340 min, and the final setting time increases from 57 min to 580 min.

As shown in Figure 3 and Table 6, there is no obvious change in the setting time of sulfoaluminate cement, the test results indicate that the aluminum sulfate has little effect on the setting time of sulfoaluminate cement.

Table 5. Setting time of sulfoaluminate cement with borax (experiment temperature 20℃).

| Content of borax (%) | 0   | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
|----------------------|-----|-----|-----|-----|-----|-----|
| Initial setting time (min) | 34  | 41  | 79  | 82  | 230 | 490 |
| Final setting time (min)   | 57  | 63  | 156 | 171 | 308 | 580 |

Table 6. Setting time of sulfoaluminate cement with aluminum sulfate (experiment temperature 20℃).

| Aluminum sulfate (%) | 0   | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
|----------------------|-----|-----|-----|-----|-----|-----|
| Initial setting time (min) | 34  | 35  | 37  | 50  | 44  | 39  |
| Final setting time (min)   | 57  | 55  | 56  | 57  | 60  | 50  |
From figure 4 and table 7, it can be seen that the initial setting time and final setting time increase first and then decrease when the sodium silicate content changes from 0 to 1.0 %. When the sodium silicate content is 0.2 %, the initial setting time is 42 min. Compared with the setting time without sodium silicate, the change was not significant. The test results indicate that the sodium silicate was not stable for the setting time of sulphonealuminate cement.

**Table 7.** Setting time of sulphonealuminate cement with sodium silicate (experiment temperature 20℃).

| Content of sodium silicate (%) | 0   | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
|-------------------------------|-----|-----|-----|-----|-----|-----|
| Initial setting time (min)    | 34  | 42  | 41  | 34  | 34  | 35  |
| Final setting time (min)      | 57  | 62  | 78  | 59  | 59  | 63  |

**Table 8.** Setting time of sulphonealuminate cement with lithium carbonate (experiment temperature 20℃).

| Content of lithium carbonate (%) | 0   | 0.1 | 0.2 | 0.3 | 0.35 | 0.4 | 0.5 |
|---------------------------------|-----|-----|-----|-----|------|-----|-----|
| Initial setting time (min)      | 34  | 20  | 16  | 14  | 15   | 13  | 11  |
| Final setting time (min)        | 57  | 31  | 28  | 24  | 20   | 20  | 18  |

As shown in figure 5 and table 8, it can be seen that the initial setting time reduces from 34 min to 11 min, and the final setting time reduces from 57 min to 18 min when the borax content changes from 0 to 0.5 %. During the setting time test, it is found that the sulphonealuminate cement concrete specimen is prone to cracks in the later curing process, if the lithium carbonate in the amount of admixture increases so much. Therefore, it is necessary to reasonably control the content of lithium carbonate when the lithium carbonate is considered as the accelerator of sulphonealuminate cement.

### 3.2. Compressive Test

Dimensions of 100 mm×100 mm×100 mm cube specimens were used in the compressive strength test. The compressive strength at 6 h, 1 d, 3 d, 7 d and 28 d were tested by the universal testing machine, as shown in figure 6. According to GB / T 50081-2019, if the difference between the maximum and minimum values and the intermediate values exceeds 15 % of the intermediate value, the test results of this group of specimens should be eliminated.
Figure 6. Compressive failure specimens.

Table 9. Results of compressive test (MPa).

| Specimen number | Water-cement ratio | Loading time |
|-----------------|--------------------|--------------|
|                 |                    | 1h | 3h | 6h | 1d | 3d |
| 1               | 0.36               | 8.9| 28.3|39.5|51.8|56.0|
| 2               | 0.4                | 7.8| 22.3|31.9|44.5|48.2|
| 3               | 0.45               | 5.9| 20.4|29.0|41.5|44.8|
| 4               | 0.48               | -  | 14.8|24.4|37.5|41.2|
| 5               | 0.60               | -  | 5.6 |17.8|31.4|36.5|

3.3. Bending Test

The experimental results of the influence of different water-cement ratios on the flexural strength of low sulfur aluminate cement concrete are shown in figure 7 and table 10.

Figure 7. Damage specimen of bending test.

As can be seen from figure 7, the concrete specimens remain integrated after the bending test. The test results indicate that the sulphoaluminate cement concrete has good toughness. As can be seen from table 10, with the increase of water-cement ratio, the flexural strength shows an increasing trend with the curing age.

Table 10. Test results of bending test (MPa).

| Specimen number | Water-cement ratio | Loading time |
|-----------------|--------------------|--------------|
|                 |                    | 6h | 1d | 3d | 7d |
| 1               | 0.36               | 4.5 |5.3 |6.2 |6.5|
| 2               | 0.4                | 3.8 |4.5 |4.9 |5.4|
| 3               | 0.45               | 3.6 |4.6 |5.1 |5.3|
| 6               | 0.48               | 3.4 |4.3 |4.8 |5.2|
| 7               | 0.60               | 2.5 |3.3 |3.7 |4.1|
4. Conclusions
In this paper, the effects of four additives on the setting time of sulfoaluminate cement concrete were studied, and the compressive strength and flexural strength of sulfoaluminate cement concrete under different mixing ratios were studied. The test results and conclusions are as follows:

   (1) Through the setting time test, the influence of four admixtures on the setting time of sulfoaluminate cement concrete was investigated. The test results show that the sodium borate for the effect of controlling setting time was better than the other admixtures. When the content of borax changed from 0 to 1.0 %, the initial setting time can increase from 34 min to 340 min, and the final setting time can increase from 57 min to 580 min. While the borax content changed from 0 to 0.5 %, the initial setting time can reduce from 34 min to 11 min, and the final setting time can reduce from 57 min to 18 min.

   (2) At the normal temperature, the compressive strength of the repair material reaches 40MPa in 6h when the flexural strength reaches 2.5 MPa at least. As a repair material, the compressive strength and flexural strength satisfy the needs of rapid hardening.

   (3) The mix design of different cement-based grouting materials and related physical and mechanical properties was investigated at normal temperature; however, the corresponding rapid construction technology at low temperature also need further research in the next step.

Acknowledgements
This study is supposed by the National Key Research and Development Program of China (Grants Nos. 2020YFC1511902).

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