



# Property transformation of a modified sulfoaluminate grouting material under pressure circulation for a water-sealed underground oil cavern



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## HIGHLIGHTS

- Modified sulfoaluminate grouting material is developed for water-sealed underground caverns.
- Its property transformation under pressure circulation is found and studied.
- Its effectiveness and practicability are verified in grouting of underground caverns.

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## ABSTRACT

Water-sealed underground oil caverns are quite different from conventional underground projects because of the harsher conditions. For one of the largest such caverns in China, conventional grouting materials could not meet the project standard. Therefore, the authors invented a new grouting material based on sulfoaluminate cement (SAC) and studied its properties under pressure circulation. During circulation, the time to the hydration exothermic peak time was reduced, and the peak temperature increased with the pressure. The compressive strength decreased during circulation and with the circulation time. These results were important for grouting during the project.

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## 1. Introduction

Large water-sealed underground oil cavern groups are used for storing crude oil or product oil. They are usually composed of dense caverns excavated in granite. Water-sealed systems are used to prevent the oil gas from flowing out. Thus, the geological and hydrological conditions are very harsh. During construction, the underground water environment should not be disturbed more than necessary, so grouting is often used to enhance the impermeability and anti-seismicity.

Depending on the aims of a project, two types of grouting agents can be used: cementitious and non-cementitious grouts [1]. Injecting non-cementitious grouts like chemical materials in and around rock can increase the strength of the mass and restrict the flow of water. Because of their superior performance compared to other grouts, chemical grouts are used in most tunnel projects. However, concerns over the environmental risk, long-term durability, and oil/gas safety mean that chemical grouts are not widely applied in underground storage caverns [2]. Sand and clay or other

soft fillings may be used to limit water leakage from the joints of a rock mass. The most widely used grouting material is Portland cement [3].

However, the current Portland cement grouting is sometimes not very suitable for the complicated conditions of large underground water-sealed storage caverns. For the Kuji underground oil storage facility in Japan, a low-pressure injection clay grouting was applied in order to decrease the permeability of the surrounding rock mass. Oligocene Kuji clay was used; this consists of kaolin and quartz [4]. For the Okayama underground caverns in Japan, superfine powdered cement (1.5–3.5  $\mu\text{m}$  grain size) was applied in order to seal micro-fractures and control the groundwater flow. The water/cement ratio was 2:1, the injection pressure was about 4.2 MPa, and the setting time of the cement was about 4.5 h. The results showed that the permeability could be controlled to less than 0.35 Lu for the planar-type flow path. However, the micro-sheeting-type flow path showed a high resistance to grouting; in the most difficult case, the total number of grouting holes and grouting times were greater than those for the planar-type flow path [5]. For an underground oil storage cavern in Korea, there was a leakage problem where the groundwater inflow into the cavern was about 2000 tons/d. Cement grouting was applied within a

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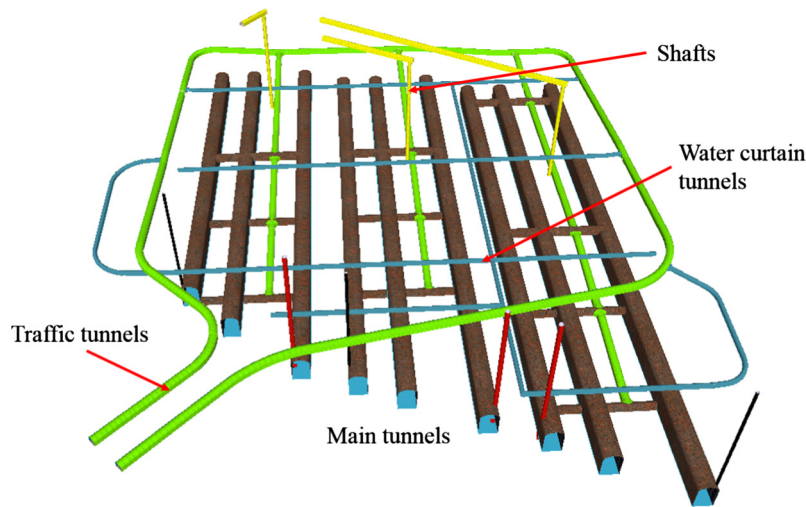


Fig. 1. Structure of the underground water-sealed storage cavern.

**Table 1**  
Typical bulk chemical compositions of SAC.

Clinker	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	CaO (%)	SO <sub>3</sub> (%)
SAC	3–13	25–40	1–3	36–45	8–15

**Table 2**  
Properties of SAC.

Item	Standard	SAC
Surface area (m <sup>2</sup> /kg)	≥350	437
Initial setting (min)	≥25	26
Final setting (min)	≤180	59
1d rupture strength (MPa)	6.0	7.6
3d rupture strength (MPa)	6.5	8.1
28d rupture strength (MPa)	7.0	–
1d compressive strength (MPa)	30.0	41.8
3d compressive strength (MPa)	42.5	47.4
28d compressive strength (MPa)	45.0	69.5

Note: The GB20472-2006 standard was used. The 3-d rupture strength was higher than the 28-d rupture strength, so the latter is omitted.

radius of 10 m around the cavern, but the permeability was often increased again by both blasting and stress relief after grouting [6].

Large underground water-sealed storage cavern projects are quite different from conventional underground projects. They are usually constructed in an area with a stable underground water environment and a hard and integrated rock mass like granite or gneiss with few faults [7]. The fissures in the rock mass should be closed with low permeability; they are often filled with water at a certain pressure. Tunnels have a large span, high rock wall, and no lining [8,9]; oil is stored in the unlined tunnels directly.

The tunnels are generally arranged very densely, so there are many working faces during the construction period. With excavation and water leakage, stress concentrations easily form on a high rock wall. Rock spalling and section twist are then likely to occur [10,11]. In order to ensure the long-term safety of an underground project, the number of exploration boreholes should be limited, and chemical grouting is often not allowed. The construction progress is fast, and construction blasting frequently affects the working faces (about two blasting cycles in 24 h). Tunnels are close together, and the underground water environment cannot be disturbed. Thus, water cannot be drained to reduce the pressure; in fact, water should be actively supplied to maintain a stable water table if necessary. When the project is complete and the oil is stored, repairs cannot take place during the operating period [12].

Thus, grouting the rock mass of water-sealed underground storage caverns is a new challenge. Sulfoaluminate cement (SAC) is one of the new materials being considered for the grouting process. SAC hardens rapidly, has high early and final strengths, is slightly expansive, and is self-stressing [13]. SAC is made by burning a mixture of limestone, bauxite, and gypsum with an appropriate composition at a moderate temperature of 1300–1350 °C, which is 100–150 °C lower than that required for ordinary Portland cement (OPC) [14], to obtain a clinker with the following major mineral components: Ca<sub>4</sub>Al<sub>6</sub>O<sub>12</sub>SO<sub>4</sub> (ye'elimite), CaO-SiO<sub>2</sub>, and an Al-rich ferrite. After cooling, it is interground to a fine power with added gypsum. The paste hydration products consist mainly of ettringite, monocalcium sulfoaluminate hydrate, alumina gel and ferrite gel [15]. In the mid-1970s, the SAC series was put into industrial production, and relevant Chinese standards were published in 1981 [16]. SAC has been successfully used on an industrial scale in China for about 35 years. As the output of SAC has increased, its global market has developed. However, compared with OPC, studies and

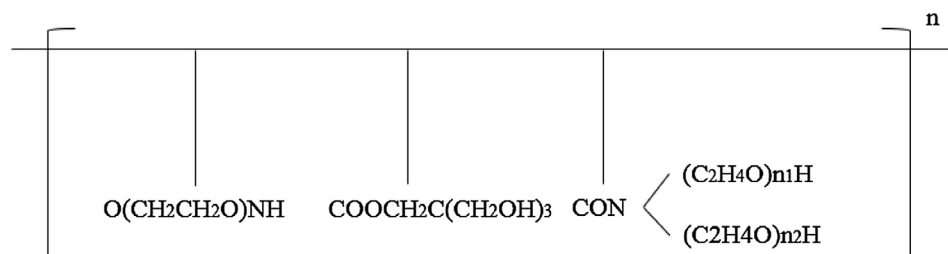


Fig. 2. Molecular structure of polycarboxylate superplasticizer.

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