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Durability of cement-sodium silicate grouts with a high water to binder ratio in marine environments

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HIGHLIGHTS

- The *w/b* of cement-sodium silicate grouts is 1.1–2.5, which is higher than previous studies.
- The sodium silicate solution is adopted 4.4–7.5 wt% as an accelerator.
- The setting time, sulphate resistance, permeability and shrinkage are investigated.
- A workable and durable mixture is obtained in marine environments.

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ABSTRACT

This study aims to investigate the durability and microstructure of cement-sodium silicate grouts with high water to binder ratios (*w/b*) of 1.1–2.5 upon exposure to sea water. Grout specimens were prepared by mixing ordinary Portland cement paste and 4.4–7.5 wt% sodium silicate (water glass solution), which was adopted as an accelerator to prevent dilution and displacement during injection for geological strengthening and water control. The setting time, sulphate attack resistance, permeability and autogenous shrinkage of the grouts were assessed and compared. The microstructures were investigated in terms of the morphology and structure of the pores and cracks.

The results reveal that satisfactory properties and durability, such as a setting time of 60–120 s, a flexural strength reduction of −3–6% after sulphate attack by sea water, a permeability of 1.2–1.6 MPa and an autogenous shrinkage of −0.298–1.22 milli, were obtained in cement-sodium silicate grouts with a *w/b* of 1.1–1.6 and dosages of sodium silicate of 4.4–5.7 wt%. However, hardened grouts suffered serious deterioration due to sulphate attack in 3 wt% sodium sulphate solutions and fatal drying shrinkage when exposed to air with a relative humidity of 60% at 20 °C. The cement-sodium silicate grout with the recommended composition is feasible and durable in marine environments, but special care must be taken when this grout is applied in environments with a high sulphate concentration or wetting-drying cycles.

1. Introduction

Generally, all rock types contain geological discontinuities (such as bedding planes and/or joint sets) that affect water transmission through the rock mass and the rock strength. [1]. For sub-sea and coastal tunnels, grouting is necessary for geological strengthening and water control (GSWC) during construction. The lower seepage after grout injection remarkably reduces the earth and hydraulic pressure upon tunnel linings, and thus, the thickness of the linings and the excavation volume can be reduced to lower costs [2,3]. However, the pressure will increase and exceed the bearing capacity if the grout fails to consolidate the surrounding rock and control the seepage, which can lead to slumping and ponding behind linings. Therefore, grout durability is essential to the security of tunnels.

Cementitious grouts are often used for GSWC in tunnel projects based on cost and environmental conservation. For dilution and displacement by moving water during grout injection, rapid setting times and accelerators are required [4,5]. The sodium silicate solution, also known as water glass, is the most widely used accelerator because of its efficiency and storage and handling benefits [6]. Although sodium silicate is not necessary for ordinary Portland cement (OPC) hydration, it is frequently used as an accelerator in grouts to promote stability against gushing water [7–9]. Fig. 1 shows the schematic procedure and equipment for grouting.

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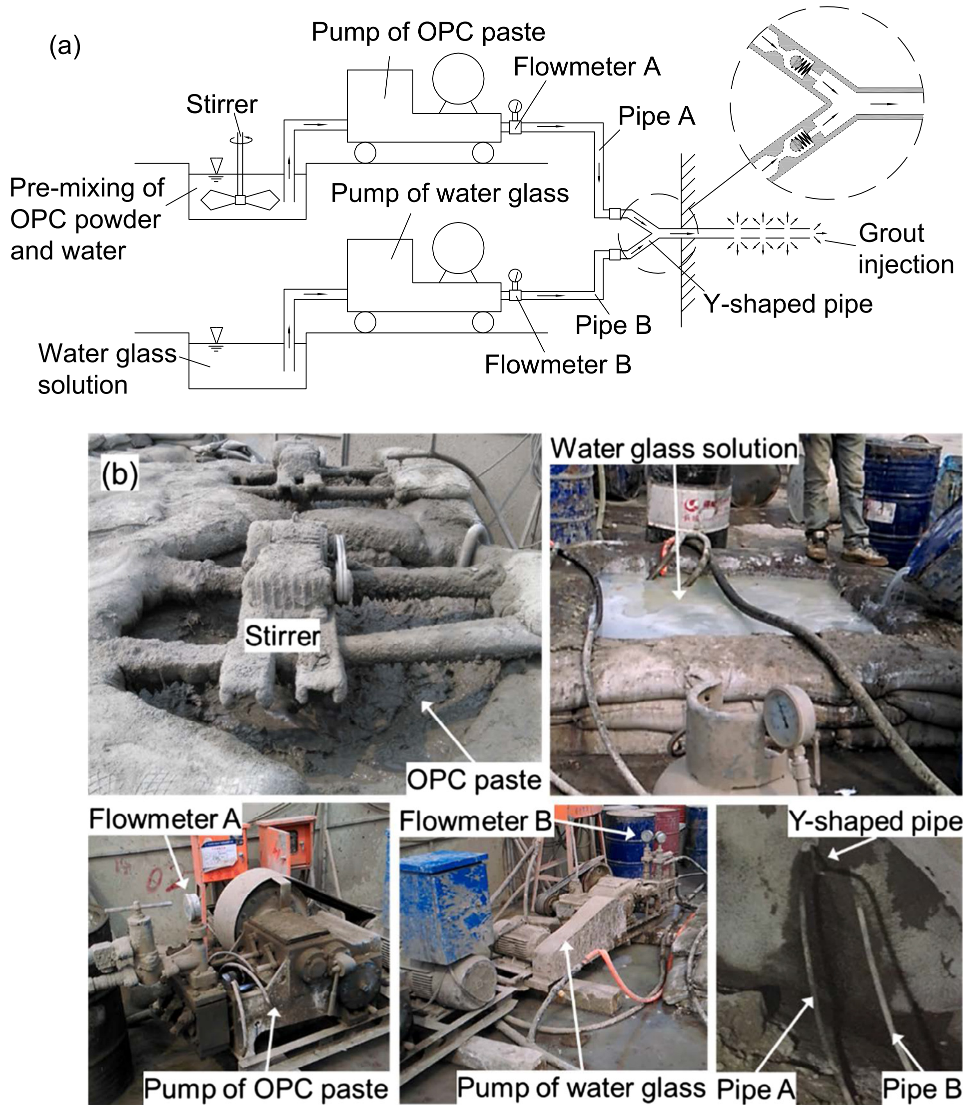

Fig. 1. (a) Schematic and (b) practical grout injection procedure.

Before injection, OPC pastes and water glass are prepared and pumped separately in cases of premature gelation or pipe plugging. Then, the two components of cement-sodium silicate grout (CSG) are pumped together into a Y-shaped pipe and blended immediately before injection into soils and rocks.

The durability of cementitious pastes with various water to binder ratios (*w/b*), dosages and modulus values (M_s, SiO_2 to Na_2O ratio) of sodium silicate has been previously studied [10–18]. However, the *w/b* of grouts used for GSWC in some cases are significantly different from the *w/b* of 0.25–0.55 used in previous studies. For the preparation of CSGs in China, the most widely used *w/b* of OPC pastes ranges from 0.6 to 1 in consideration of fluidity and anti-bleeding during injection [7–9]. Meanwhile, the concentration and M_s of water glass solutions are in the ranges 16–30 wt% and 2–3.75, respectively [5], since lower values may lead to dilution and displacement of grouts under moving water, while higher values always result in instantaneous gelation and pipe plugging [8]. After mixing the OPC paste and water glass in a Y-shaped pipe with a designed volume ratio (*VR*, water glass to OPC paste) in the range of 0.6–1.2, which is accomplished with different pumping speeds for the two components, the real *w/b* and dosage of sodium silicate (*DSS*) of CSGs are in the ranges 0.8–2.5 and 4–8 wt%, respectively. The *w/b* of CSGs adopted in China is significantly higher than that used in previous studies, and sodium silicate is frequently used in CSGs as an accelerator.

The durability properties of grouts are well known to be affected by the *w/b* and *DSS* [6,8,22], but experiments with a high *w/b* have not fully satisfied practical requirements. Dou [7] investigated the microstructure and compressive strength reduction (*CSR*) of CSG (*w/b* = 1.01, *DSS* = 4.4 wt%) after sulphate attack, and the results indicated that the *CSR* of the CSG was 15% after immersion in sodium sulphate for 90 d. Liu [8] studied the *CSR* of CSGs (*w/b* = 0.89–1.63, *DSS* = 6.8–7.7 wt%) and reported that minimal deterioration was observed in specimens with a low *w/b*, while serious spalling and breaking were found in specimens with a high *w/b* after immersion in sodium sulphate for 60 d. Tu [9] demonstrated that the flexural strength reduction (*FSR*) of CSG (*w/b* = 1.49, *DSS* = 3.9) was up to 33% after immersion in sodium sulphate for 28 d. Due to the limited ranges of variables and non-unified experimental procedures, i.e., use of different specimen dimensions, research on the durability properties of CSGs is insufficient, and the existing research cannot be compared to determine an optimal mixture for GSWC, which is urgently needed for subsea and coastal tunnel projects. For instance, a metro tunnel is planned along the coastline of the Yellow Sea in Qingdao, China (Fig. 2a). The concentration of sulphate ions (c_s) in the