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Experimental exploration of the waterproofing mechanism of inorganic sodium silicate-based concrete sealers

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HIGHLIGHTS

- No detectable new composition is introduced into the concrete treated with a sealer.
- The formed C–S–H gels only partially fill the defects of concrete structures.
- The concrete sealers reduce the sizes of micro-pore and micro-crack in the concrete.
- The sealers improve the compactness and the water impermeability of the concrete.
- Sodium silicate-based concrete sealers are surface hydrophilic agents.

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ABSTRACT

The precise waterproofing mechanism for sodium silicate-based concrete sealers was experimentally explored using a Leeb hardness tester, a Fourier transform infrared spectroscopy, an X-ray diffraction microscopy, a thermal-gravimetric analysis, a surface area and porosity analyzer, a scanning electron microscope and an optical contact-measuring device. After treating the concrete surface with a sodium silicate-based concrete sealer, the new substance-sodium hydroxide-introduced into the concrete structure is undetectable most likely because of the quite low concentration and its migration to the concrete surface. The surface hardness of the concrete specimens impregnated with the sodium silicate-based concrete sealer is found to be increased by approximately 11.9% relative to the untreated concrete specimens. The content of the calcium hydroxide in the concrete structures decreases whereas the content of the calcium silicate hydrate (C–S–H gel) in the concrete structures increases compared with the untreated concrete structures. Sodium silicate-based concrete sealers are essentially surface hydrophilic agents, yet they do reduce the velocity of water ingress into the concrete structures, because the expansive and insoluble C–S–H gels partially fill the micro-pores, micro-voids and micro-cracks in the concrete structure to form smaller micro-pores, micro-voids and micro-cracks and improve the compactness and water impermeability of the concrete.

1. Introduction

In recent years, sodium silicate-based concrete sealers have frequently been used in civil engineering to prevent water from penetrating both new and existing concrete structures to extend their durability [1], because water and aggressive water-soluble agents (e.g., chloride ions, carbon dioxide, sulfur dioxide and sulfates) are the main factors that result in the deterioration of reinforced concrete structures [2,3]. Consequently, this type of concrete surface protection treatment has aroused increasing interest in both academia and industry.

When sodium silicate-based concrete sealers permeate into concrete, it is widely accepted that the active sodium silicate reacts with portlandite in the cement matrix to yield calcium–silicate hydrates (C–S–H gels), which block the concrete pores, enhance its surface hardness and increase its structural impermeability and durability [1,4–12]. Therefore, sodium silicates are generally

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Table 1
The composition of the modified sodium silicate-based concrete sealer.

Materials	Weight content (wt%)
Sodium silicate solution	91.75
Deionized water	6
Catalyst solution	0.2
Sodium hydrate	2
Fluorocarbon surfactant	0.05

viewed as pore-blockers [9]. While the performance of sodium silicate-based concrete sealers has been systematically investigated [1,4–9,12], the exact mechanisms through which they improve the concrete performance are still unclear [1,4–6]. One argument is that sodium silicates are effective and efficient sealers because SiO_2 precipitates in the pores [10]. Another theory is that the silicates react with excess calcium hydroxide near the concrete surface to yield relatively insoluble calcium–silicate hydrates [11]. A third standpoint is that the silicates form an expansive gel similar to that formed during alkali silicate reactions to fill the concrete voids by swelling [4]. In addition, one of the earliest studies on sodium silicate-based concrete sealers [4] found silicates act as sealers via a combination of mechanisms, and which mechanism determines the sealer performance most likely varies from application to application. Clearly, the investigations on the waterproofing mechanism of sodium silicate-based concrete sealers have not yielded a universal conclusion. Accordingly, exploring the exact mechanisms by which sodium silicate-based concrete sealers improve the waterproofing performance of concrete structures is of great significance.

Therefore, we systematically explored the waterproofing mechanism of inorganic sodium silicate-based concrete sealers combining quantitative and qualitative approaches. This paper presents the test data obtained from a Leeb hardness tester, a Fourier transform infrared spectroscopy (FTIR), an X-ray diffraction microscopy (XRD), a thermal-gravimetric analysis (TGA), a surface area and porosity analyzer, a scanning electron microscope (SEM) and an optical contact-measuring device. Based on these experimental results, the precise waterproofing mechanisms of sodium silicate-based concrete sealers are outlined.

2. Experimental section

2.1. Materials

A sodium silicate-based concrete sealer, modified from the sodium silicate-based concrete sealer previously developed in our laboratory [12], was composed of sodium silicate solution (8.2 wt% Na_2O, 26 wt% SiO_2 and SiO_2/Na_2O ratio of 3.1–3.4 by mole), deionized water, specific catalyst solution (a complex compound with a molecular structure consisting of $Ca^{2+}\cdots A^{2-}$, whose exact composition has not yet been disclosed by any manufacturer due to commercial confidentiality [12]), sodium hydrate and fluorocarbon surfactant (grade RB-802). The sodium silicate solution, the specific catalyst solution and the fluorocarbon surfactant were purchased from Beijing Sodium Silicate Factory, Hangzhou Lotech Corporation and Guangzhou Reborn Chemical Co., Ltd., respectively. The weight content of each ingredient of the modified sodium silicate-based concrete sealer is summarized in Table 1.

The performances of the modified sodium silicate-based concrete sealer measured in the National Research Center of Testing Techniques for Building Materials which is the national independent third party, along with the corresponding requirements specified by China's construction materials industrial standard JC/T 1018-2006(water-based capillary inorganic waterproofer), are presented in Table 2.

2.2. Preparation of specimens

Twelve truncated cone-shaped concrete specimens, each with a C30 strength grade and $\varnothing 175 \times \varnothing 185 \times 150$ mm geometry, were manufactured according to standard procedures. The composition of the concrete specimens is listed in Table 3. The cement, the fineness module of the medium sand and the maximum particle size of the crushed stone used in the concrete composition are type 1/42.5 R, 2.3–3.0 and 40 mm, respectively [12].

To control micro-crack sizes in the concrete structures, the concrete was sufficiently vibrated for approximately 30 s during the preparation process of the truncated cone-shaped concrete specimens. Subsequently, all of the specimens were cured under standard conditions [(20 ± 2) °C, relative humidity ⩾95%] for 28 days. The composition and mixture ratio of the concrete specimens, particularly the water–cement ratio, significantly influence the effects of sodium silicate-based concrete sealers on the concrete structures. Generally speaking, as the strength grade of concrete increases and the water–cement decreases, the compactness of concrete is improved and thus the effects of sodium silicate-based concrete sealers on the concrete structures become more pronounced. Because the concrete with a C30 strength grade is most commonly used in buildings and it is specified by China's construction materials industrial standard JC/T 1018-2006, the effects of concrete composition and its water–cement ratio on the experimental results are not considered in this paper.

Six truncated cone-shaped specimens were used as controls, and the other six were used as the test substrates whose bottom surfaces that were in contact with the formworks were dipped into the sodium silicate concrete sealer bath for 24 h. The immersion depth was over 10 mm. The impregnated specimens were then cured under the standard conditions (20 ± 2 °C, relative humidity 50 ± 5%) for 6 days prior to testing.

In accordance with Chinese national standard GB/T 50082-2009 (standard for test methods of long-term performance and durability of ordinary concrete), which is comparable with EN 123908-2000 [21], ASTM C6421997 [22] and DIN 1048 part 5-1991 [23], water impermeability measurements were performed on six impregnated specimens and six reference specimens using the concrete impermeability tester (HP-4.0, Shanghai Le Ao Test Instrument Co., Ltd., China) [12]. The hydraulic pressure was adjusted to 1.2 MPa and kept there for 8 h. Subsequently, the specimens were broken and the depth of penetration values were measured at 10 points. The results reported are based on the mean of six parallel measurements. Note that the reference specimens should be impermeable at a hydraulic pressure of 0.8 MPa for 8 h, or else all of the measurements should be repeated.

After the water impermeability measurements, the bottom surfaces of reference samples and testing samples were broken using appropriate tools. The broken pieces were used to prepare specimens for the following different measurements.

2.3. Surface hardness measurements

It is widely accepted that treating concrete structures with sodium silicate-based concreter sealers may increase their surface hardness [1,4,5]. However, to our knowledge, the experimental data to date on the improvements of the surface hardness of concrete structures caused by sodium silicate-based concrete sealers are quite limited. Therefore, it is of particular relevance to analyze quantitatively the extent to which the surface hardness of the concrete structures impregnated with the sodium silicate-based concrete sealers may be increased due to the treatment.

Table 2
The measured pH, density, viscosity, surface tension, initial gelation time, final gelation time, water impermeability and storage stability and the corresponding requirements specified by China's construction materials industrial standard JC/T 1018-2006.

Testing parameters	Measured values	Specifications	Testing methods
pH	13	13 ± 1	GB/T 8077-2012 [13]/ISO 4316-1977 [14]
Density (g/cm^3)	1.37	⩾1.1	GB/T 8077-2012/ISO 1675-1985 [15]
Viscosity (s)	10.2	11 ± 1	GB/T 1723-1993 [16]/ISO 2431-1993 [17]/ASTM D 5125-10-2014 [18]
Surface tension (mN/m)	23.25	⩽26	GB/T 8077-2012/ISO304-1985 [19]
Initial gelation time (min)	145	120 ± 30	JC/T 1018-2006
Final gelation time (min)	205	180 ± 30	JC/T 1018-2006
Depth of impermeability (mm)	11	⩽30	GB/T 50082-2009 [20]
Storage stability (10 cycles)	No change in appearance	No change in appearance	–