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Effect of colloidal nanosilica on early-age compressive strength of oil well cement stone at low temperature

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HIGHLIGHTS

- Early-age microstructural properties of oil well cement paste containing nanosilica at 4 °C.
- Colloidal nanosilica enhances the early-age strength of hardened cement paste significantly.
- Colloidal nanosilica consumes calcium hydroxide and promote the hydration of cement.
- Nanosilica modifies the internal structure of the hardened paste.

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ABSTRACT

The compressive strength of cement stone rises slowly when cementing marine shallow section at low temperature, resulting in increased drilling cost and risk. This paper presents results of experimental study that was conducted to investigate the effect of low temperature on early-age compressive strength of cement stone admixed with colloidal nanosilica. The compressive strength of cement stones was measured after aging at 4 °C for 1, 3, and 7 days respectively. The hydration products of different aging cement stone were analyzed by X-ray diffraction and Fourier Transform infrared spectroscopy, and the microstructures were observed by scanning electron microscopy. In addition, the hydration exotherm of colloidal nanosilica modified cement slurry during hydration process was tested at 20 °C. The results indicated that the compressive strength of cement stone significantly improved by colloidal nanosilica. Interestingly, colloidal nanosilica retarded the initial hydration, and then promote the hydration process afterward. The mechanism of colloidal nanosilica to improve the compressive strength of cement stone was that colloidal nanosilica consumed calcium hydroxide to produce additional calcium silicate hydrate, filling large pores and cracks inside cement stone. More importantly, nanosilica particles provided nucleation sites of cement hydration and modified the internal structure of the hardened stone. The improvement of early-age compressive strength of oil well cement stone is beneficial to saving costs and reducing risk.

1. Introduction

With the consumption of conventional land oil and gas reservoirs, people move their eyes towards to the marine resources. It has brought challenges to well drilling, especially cementing. Marine environmental protection and hydrocarbon safety mining propose a high demand to cementing quality. However, the temperature is low at marine shallow section, around 4 °C at seabed [1]. Temperature reduction will cause a decrease in the early-age strength of cement stone [2], and the value rises slowly with time. This is because the low-temprature delays the hydration of cement slurry.

Many studies were committed to improve the mechanical strength of oil well cement stone at low temperature, and had made quite a few achievements [2,3]. Soriano et al. [2] replaced 15% cement by catalyst and metakaolin while preparing cement stones at 5 °C, and the compressive strength increased compared with that without replacement. Fumed silica is a good pozzolanic material because it presented a small particle size with high packing ability [4]. Liu et al. [5] studied the influence of fumed silica on the compressive strength of cement stone cured at −5, 0 and 5 °C. In general terms, it has been observed that low-temperature hindered the hydration of the binary system and inhibited the pozzolanic activity of the fumed silica. However, the compressive

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strength and the flexure strength of the mortars with fumed silica were higher than the control mortars at −5, 0 and 5 °C after aged for 3, 7 and 14 days.

In recent years, a new pozzolanic material containing nanosilica particles has been available on the market, and has been used in cement and concrete in order to enhance the mechanical, physical and durability of cement-based materials [6–10]. It is believed that nanosilica has much smaller particle size and higher pozzolanic reactivity than fumed silica [7]. Qing et al. [6] reported that the setting time of cement slurry added nanosilica decreased, compared with that added fumed silica. In addition, the compressive strength of nanosilica modified cement stone was obviously higher than fumed silica modified cement stone, especially at early ages. In another work, Pang et al. [11] found that in lightweight slurry, the effectiveness of nanosilica acceleration can be much stronger than that of $CaCl_2$ at 15 °C.

However, most of the studies were carried out at room or high temperature, and there were few studies on the influence of nanosilica on cement stone at low temperature. In addition, the effect of nanosilica on the microstructure of cement stone was not studied. Therefore, it is important to understand the details of Portland cement containing nanosilica at low temperature from the perspectives of microstructure development and product changes. Nanosilica is available in the form of compacted dry powder or colloidal suspension. While preparing cement slurry, colloidal nanosilica is more convenient than powder nanosilica [12]. So in this study, colloidal silica was used to modified cement slurry.

In this paper, the compressive strength of colloidal nanosilica modified cement stones was measured after aging at 4 °C for 1, 3, 7 days respectively. X-ray diffraction (XRD), Fourier Transform infrared spectroscopy (FT-IR) were used to analyze the hydration products, and scanning electron microscopy (SEM) tests were conducted to observe the microstructure. In addition, the hydration exotherm of colloidal nanosilica modified cement slurry during hydration process was tested at 20 °C.

2. Materials and methods

2.1. Materials

API class G oil well Portland cement was obtained from Shandong Shengwei Enterprise Company (Linqu, China). The chemical composition and physical properties are shown in Table 1. Colloidal nanosilica (CNS) was bought from Zhejiang Yuda Chemical Company (Shangyu, China). The chemical composition and physical properties of CNS are shown in Table 2. X-ray diffraction (XRD) diagram and scanning electron microscopy (SEM) micrograph of the dried CNS are shown in Figs. 1 and 2. Dispersing agent FHJZ-1 obtained from Fuhai Industry Development Company (Dongying, China) was employed to achieve the desired rheology of cement slurry and better dispersion of nanoparticles. The primary composition of dispersing agent is sulfonated ketone/aldehyde poly-condensate.

2.2. Methods

2.2.1. Manufacturing process

Oil well cement slurry was prepared according to Standard API PR 10B-2-2013. The rheology of the cement slurry deteriorates due

Table 2
Chemical composition and physical properties of CNS.

Color	Density, (g/cm^3)	SiO_2 content (%)	Viscosity (mPa · s)	pH
White	1.242	35.1	12.7	10.2

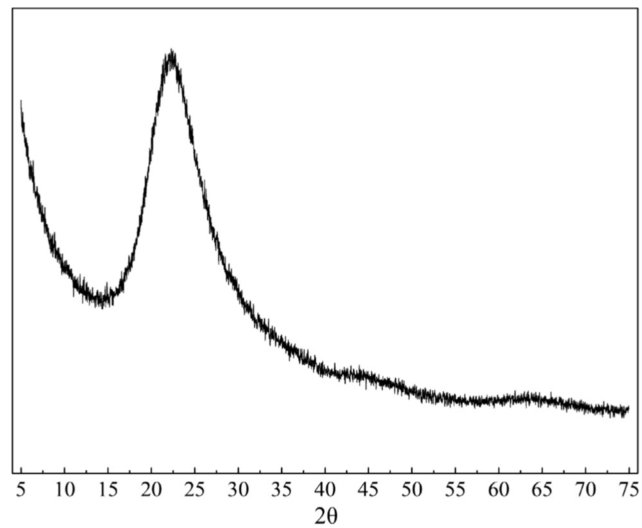

Fig. 1. XRD analysis of dried CNS.

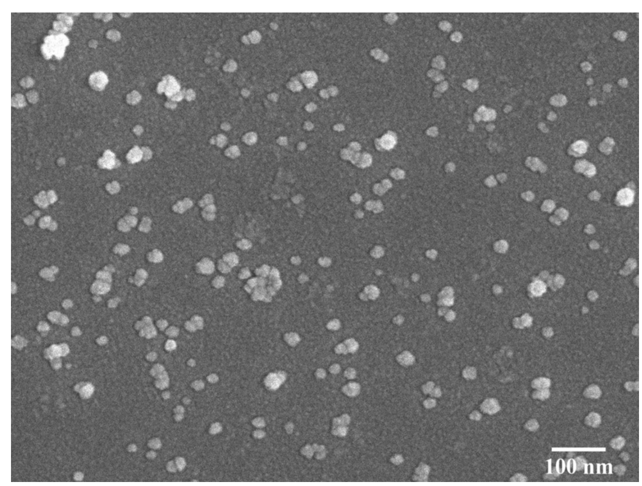

Fig. 2. SEM micrograph of dried CNS.

to the large surface area of CNS particles. So the water to solid rato (w/s) was set to 0.5 (the water in CNS was taken into account), and FHJZ-1 dispersing agent was employed to enhance the workability of cement slurry. The dosage of dispersing agent was 0.5 wt.% to solid. The formulations of cement slurry are shown in Table 3. Firstly, dispersing agent and CNS were dissolved in the water and transferred into the cup of the blender. Next, the cement was added within 15 s to the aqueous solution at a stirring rate of 4000 rpm, and then the mixer speed increased to 12,000 rpm immediately and stirring for 35 s.

Table 1
Chemical composition and physical properties of oil well Portland cement.

CaO (wt.%)	SiO_2 (wt.%)	Fe_2O_3 (wt.%)	Al_2O_3(wt.%)	Density, (g/cm^3)	Specific surface area, (m^2/kg)
64.2	19.4	5.5	4.5	3.15	336