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Influence of carbon nanotubes, nanosilica and nanometakaolin on some morphological-mechanical properties of oil well cement pastes subjected to elevated water curing temperature and regular room air curing temperature

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HIGHLIGHTS

- Enhancing mechanical properties of oil well cement (OWC) pastes using different nanomaterials.
- Increasing curing temperature causes a notable increase in the compressive strength.
- 0.1% CNTs causes a good enhancement in the mechanical properties of the hardened OWC pastes.
- Optimum addition of NS to hardened OWC pastes is 1% at 25 and 90 °C.

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ABSTRACT

Nanotechnology has shown great potential in different applications and presents solutions to some of the upstream and downstream challenges in the oil and gas industry. This research work aimed to improve the mechanical properties of oil well cement (OWC) pastes using multiwall carbon nanotubes (CNTs), nano-silica (NS) and nano-metakaolin (NMK). The effect of different curing temperatures, namely; room temperature and elevated temperature (90 °C) on the hydration reaction of OWC pastes admixed with different nano materials was investigated. XRD, TG/DTG, and SEM techniques were used to investigate the phase composition and the microstructure of some selected hardened specimens. The obtained results indicated that all of the nano materials used in this study cause a notable improvement in the mechanical properties of hardened OWC pastes at both curing temperatures. In addition, NMK – OWC hardened pastes present the highest improvement in the mechanical properties among all of other tested mixes.

1. Introduction

Cementing operation is a process an essential during construction of an oil or gas well. Cementing of deep wells requires materials that, not only satisfy the performance specifications but also quite different from those encountered in conventional processes [1]. The main target of the primary cementing process has always been to provide zonal isolation in oil, gas, and water wells [2]. Evidently, a hydraulic seal must be created between the cement and the formation sand then between the casing and cement, while at the same time preventing fluid channels in the cement heath.

Oil well cement is used in different conditions of exposure than cement used in the conventional construction industry. Oil well cement used within large range of temperature, ranges from below zero °C in permafrost to 100 °C n some recovery operations. In addition, in some cases oil well cement must withstand high pressure and must has high resistance to corrosive fluid attacks [3]. The cement quality behind a casing has an essential role during drilling and has an important influence on the secondary cementing, work over and stimulation operation [4]. The poor quality of cement slurry and set cement will increase the cost and time of cementing job. Whereas, the high quality of cement will ensure the long-term durability of burial by providing a high-quality casing [5].

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The American Petroleum Institute Specification for materials and testing for well cement (API Specification 10A, 2002) classifies OWC into nine types [6]. Besides, OWCs are classified into three grades according to their C_3A contents. Recently, nano particles were used to improve drilling, construction and cement properties [7]. Many factors affect the strength of oil well cement, such as period and conditions of curing, slurry design, use of additives and environmental conditions [8].

Nano-materials having a particle size in the range of 1–100 nm, are now being commercially used in numerous applications. The large surface area of nano materials makes them highly reactive with high impact for improving cement slurry properties such as good early strength, reducing permeability, accelerating cement hydration and controlling fluid loss [9]. Actually, the chemical reactions necessary to produce a dense and compact structure with more calcium silicate hydrates (CSH) and less calcium hydroxide content were facilitated in presence of nano-particles as a result of their large surface area, as well as their abundance due to their small size [10,11].

Evidently, many researchers reported that addition of nano materials such as nano-clay and nano-silica causes a significant increase in the compressive strength of the cement and prevents strength deterioration at high temperature [1,12–23].

Nano-silica is one of the most common and important cement admixtures both in the oil field and in construction and civil engineering industries. Nano-silica is extremely fine silica particle; it is composed of highly fine vitreous particles with nearly about 1000 times smaller than the average cement particles, besides it has high pozzolanic activity. So, nano- silica is widely used to improve slurry impermeability and the mechanical properties of the hardened material [24,25]. Besides, the incorporation of nano-silica in cement slurries results in reducing the setting time; therefore, it has been used as a popular additive in the oil field industry.

Carbon nanotubes, graphene, and nano-fibers are ones of the most important nano materials that have recently attracted tremendous scientific interest due to their remarkable superior properties, such as exceptional tensile strength, elastic modulus, electrical and thermal conductivity. The use of these materials is very promising for production a next-generation high-performance structural and multi-functional nano-composite materials [26–28].

The addition of carbon nanoparticles to the cementitious materials provide extraordinary strength increase as well as controlling cracks prevention [29–35]. Many investigations indicated that the incorporation of carbon nanotubes into cementing matrices causes a notable improve in their mechanical properties [36–40]. Carbon nanotubes (CNTs) are graphene sheets rolled up to form cylinder sort tubes. A single walled CNT is a single sheet rolled up into a tube with diameter range from 1 to 3 nm, while multiwall CNTs are multiple sheets rolled into a series of tubes, one inside the other with diameter range from 10 to 40 nm [30,41].

Carbon nanotubes have tensile strength and Young's modulus values ten times greater than steel and a density five times smaller [42]. Also, CNTs have a very high length to diameter ratio and could be distributed widely and densely at the microscopic scale that covering longer lengths. These characteristics can be utilized in cement composites to bridge cracks and prevent its increase. So, that CNTs can be basically used to develop a new generation of crack-free cement materials [38,41,43].

The thermal activation of kaolin (dehydroxylation) at a certain temperature, causes the breakdown or partial breakdown of the crystal lattice structure, forming a phase transition (metakaolin) which has highly amorphous and disordered characters having a good pozzolanic activity [44]. Upon firing kaolin to temperature above the dehydroxylation temperature it will cause the recrystallization of metakaolin to form mullite with less pozzolanic activity [45]. A small part of octahedral aluminum oxide is maintained, while the remaining part is transformed to more reactive tetra- and penta-coordinated units [46]. Evidently, nano-metakaolin particles have high pozzolanic activity, act as nuclei for cement hydration, can fill the pores in the cement matrix, so, incorporation of nano-metakaolin in the cementitious materials, causes notable improvements for strength and permeability of the hardened composites.

This study aimed to utilize some nano materials such as CNTs, nano-silica, and nano-metakaolin for improving the microstructure and the mechanical properties of oil well cement hardened pastes. Also, to investigate the effect of temperature on the hydration process of OWC when admixed with these nanomaterials.

2. Experimental

2.1. Materials

Oil well cement (OWC) used in this study is high sulphate resistance (class G) according to American Petroleum Institute specification (API)with a specific gravity of 3.15 g/cm^3, it was supplied from Lafarge cement company, Suez, Egypt. The chemical oxide composition of OWC and its mineralogical phase composition as calculated from Bogue equations [47,48] are given in Table 1.

Multi-walled carbon nanotubes (CNTs) with a surface area of 93.81 m^2/g and purity >90% was used. The estimated outside length and diameter of CNTs ranged from 5–10 μm to 10–40 nm, respectively, with about 2.1 g/cm^3 density and their electrical conductivity was higher than 100 S/cm. CNTs were delivered by Egyptian Petroleum Research Institute (EPRI), Cairo, Egypt, Fig. 1 shows the morphology and microstructure of CNTs.

Nano-kaolin with 1.8×10^4 cm^2 g^{-1}, Blaine surface area, was supplied from Middle East Mineralogical (MEMCO), Egypt. Nano-metakaolin (NMK) was obtained by firing nano-kaolin for three hours at 750 °C, Table 2 shows the chemical composition of both nano-kaolin and nano-metakaolin.

Fig. 2 shows the SEM micrograph of NMK, the figure indicates the presence of NMK particles with an almost hexagonal shape with varying particle sizes ranging from 50 to 950 nm with the predominance of NMK particles having sizes of 50–200 nm.

Nano-silica used in this investigation was prepared from rice husk (RH) according to the method described in previous publications [49,50]. XRD, TEM, and SEM of NS are given in Fig. 3a–c, respectively.

The surfactant used to assist the good dispersion of CNTs, NS and NMK was polycarboxylate (PC) based superplasticizer (Sika Viscocrete 5230 L) with specific gravity 1.08 g/ml and solid residue ~40%, was supplied by Sika Company, Elobour City, Egypt.

2.2. Sample preparation and characterization

2.2.1. Preparation of the hardened cement pastes

Different OWC blends were prepared by admixing it with different amount of the nano materials used in this investigation. Table 3 shows the percentage composition of the different OWC blends and their designations.

Table 1
Chemical oxide and mineralogical phase composition of OWC.

Item	Mass (%)
SiO2	21.80
Al_2O_3	2.90
Fe_2O_3	4.81
CaO	64.90
MgO	1.30
SO_3	2.80
K_2O	0.33
Na_2O	0.09
LOI (Loss On Ignition)	0.80
Mineral composition according to Bogue calculation (%)	
C_3S	63.70
C_2S	13.50
C_3A	0.00
C_4AF	14.60