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Silica content influence on cement compressive strength in wells subjected to steam injection

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ABSTRACT

High temperatures cause deleterious changes in hydrated products of Portland cement, compromising its physical properties, mainly, the compressive strength. This phenomenon is known as strength retrogression and occurs when the CaO/SiO_2 ratio is close to 2.0. To deal with this condition, silicon dioxide (SiO_2) rich materials are added to cement. In this study four slurries with 0%, 30%, 35% and 40% BWOC of silica flour were formulated and tested under conditions of 38 °C and 300 °C for 7 and 28 days to cure it. The highest temperature was chosen to represent the one employed in thermal cycles, when an oil well is subjected to steam injection, seeking to increase the production - Enhanced Oil Recovey (EOR). In order to investigate the influence of temperature on the behavior of the compressive strength on the samples, a uniaxial compression test and crystallographic characterization of the material tested through the technique of X-ray diffraction (XRD) were performed. Research has shown that the SiO_2 reacted at high temperature for the two periods evaluated, forming the xonotlite phase and improving the mechanical behavior, especially in the slurries with 35% and 40% BWOC. The standard slurry, without silica, was heavily damaged by the strength retrogression phenomenon after the heat cycle of 300 °C for both 7 and 28 days. For the slurries that were submitted to 38 °C (low temperature) for both periods, the silica flour basically acted as a load in mixes with cement. Also, it was noticed some mechanical strength loss of the samples with silica when compared with the standard sample, without silica.

1. Introduction

The primary cementing of an oil well provide mechanical stability, isolate the rock formations drilled, preventing communication between them, and protect the casing from the contact with any formation corrosive fluid. In this type of operation, one or more slurries are pumped into the annular space between well bore/casing. It is expected that the slurries are going to be able to meet the purposes mentioned, throughout the life of the well, without any or minimal corrective interventions. In order to achieve these goals, the cementing project must be well evaluated, discussed, planned and executed.

During the design of cementing operation it is imperative to properly consider the temperature that the cement slurry will be exposed. It is necessary to evaluate its effect on both the fluid phases, when the slurry flows in the annular space, as well as in its solid state (hydrated), when the matrix will need to provide the physical and chemical properties required throughout the life of the well. High temperature environments are considered critical and capable of causing adverse effects on the hydrated Portland cement products, resulting in an alteration of their mechanical properties. These scenarios typically occur in deep wells that exhibit High Temperature (HT), geothermal wells and wells subject to steam injection for Enhanced Oil Recovery (EOR). The steam injection is applied to reduce the viscosity of the heavy oil, increasing its mobility and increasing its production. Thermal heavy oil recovery methods are widely used in many projects around the world, as for example: Kern Field in California, USA, Mene Grande in Venezuela, the Athabasca Oil Sands in Alberta, Canada, the Surplacul de Barcau Field in Romania and Northeast Region in Brazil (Ichim and Teodoriu, 2017 apud Curtis et al., 2002; Panait-Patricia et al., 2006).

When exposed to a high temperature condition, the Portland cement hydrated products suffer a chemical and microstructure deleterious transformation process to the material. This phenomenon is known as strength retrogression transformation and it occurs from the temperature of 110 °C, intensifying with the addition of temperature (Taylor, 1990;

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Luke, 2004; Nelson and Guillot, 2006). In this phenomenon, calcium-rich phases are formed in the cement matrix and there is a decrease of mechanical properties and an increase of permeability of the material.

Slurries that were exposed to high temperatures should contain in their composition SiO_2 concentrations ranging between 30% and 40% or even higher. This concentration range allows the reaction of SiO_2 with $Ca(OH)_2$ leading to new phases that confer better mechanical properties to the cement, such as tobermorite, trucostite and xonotlite (Eilers and Root, 1976; Taylor, 1990; Nelson and Guillot, 2006; Richardson, 2008; Iverson et al., 2010). Materials that are rich in SiO_2 are known as anti-retrogression agents, being silica sand and silica flour the most used.

The chemical reaction between SiO_2 and hydrated cement products is called pozzolanic reaction, and consist of the reaction between $Ca(OH)_2$ (CH, formed by the hydration process of the minerals C_3S and C_2S) and pozzolan (silica-rich material) forming a calcium silicate hydrated species (C-S-H) (Taylor, 1990; Bezerra et al., 2011). The Table 1 presents the silicate cement hydration reactions and the CH reaction with the pozzolan, as well as the reactions velocities.

2. Methodology

The study considered the exposure of cement samples at different temperatures and subsequent analysis of physical behavior and crystallographic characterization. In summary, the methodological application of the study was structured in the followig topics:

- Preparation of four slurries compositions with different concentrations of silica.
- Exposure of all samples to specific times and temperatures.
- After exposure periods, uniaxial compression test was performed and characterization by XRD diffraction of all samples.
- Evaluation of the results for correlation between the mechanical behavior and the crystallographies of the samples.

2.1. Materials

The slurries were formulated using Special class Portland cement, fresh water and silica flour in different concentrations. The Special class Portland cement was developed to meet the cementing operations of wells in onshore scenario at Brazil and follows the standard NBR 9831 (NBR 9831, 2006). It is a type of cement for oil well cementing similar to class A.

The silica flour is a rich material in SiO_2, with approximately 99% of silicium oxide in the chemical composition (Shahab et al., 2015; Li et al., 2015). This is the material most used as anti-retrogression agent in oil well cementing industry.

2.2. Samples preparation

Cement slurries were prepared to achieve a density of 1.87 g/cm^3 (15.6 ppg) and tests was performed under the American Petroleum Institute procedure (API, 2013). The Special class Portland cement used had a specific gravity (SG) of 3.15 g/cm^3, silica flour SG of 2.64 and fresh water 1.0 SG.

Four slurries were prepared with different concentrations of silica by weight of cement (BWOC): 0% (standard), 30%, 35% and 40%. The compositions of the slurries are presented in Table 2.

Table 1
Pozzolan reaction description (Bezerra et al., 2011).

Reaction	Velocity of reaction
$2C_3S + 6H \rightarrow$ C-S-H (61%) + CH	Fast → hours and days
$2C_2S + 4H \rightarrow$ C-S-H (82%) + CH	Fast → days
Pozzolan + CH + H → C-S-H (pozzolanic reaction)	Slow → days and months

Table 2
Slurries compositions.

Slurries	Water (mL)	Special Portland cement (g)	Silica source - BWOC (%)	Silica flour (g)	Factor Water/Cement
S0%	354.28	767.27	0	0	46.17
S30%	339.31	601.72	30	180.52	56.39
S35%	337.42	580.83	35	203.29	58.09
S40%	335.66	561.35	40	224.54	59.80

After preparation, each slurry was poured into metallic molds with a 50.8 mm edge submitted in thermostatic bath at 38 °C for specific times. Each formulation described in Table 2 was evaluated in two distinct scenarios, low temperature (38 °C) and high temperature (300 °C). The lowest temperature was the reference and also because it is the same applied for cement specifications for the Brazilian standard NBR 9831 (NBR 9831, 2006). The temperature of 300 °C was chosen to represent the average temperature in wells subjected to steam injection cycles for EOR. In this case, the samples were subjected to 300 °C and 2000 psi in the last 3 days of the 7 and 28 days of curing. The procedure of curing time are presented in Table 3.

In the case of this study, 1 thermal cycle was applied. The cycle comprises the last 3 days where the samples were subjected to 300 °C, simulating situations of wells that are subjected to steam injection.

For the low temperature samples remained for 7 and 28 days in the thermostatic bath at 38 °C. The high temperature thermal cycle in the last 3 days was performed in a curing pressurized Chamber, model Chandler 1910.

2.3. Uniaxial compression test

The mechanical compression test was conducted based on the American Petroleum Institute procedure (API, 2013). After 7 and 28 days cure periods, uniaxial compression tests were performed in 3 samples of each composition and for each temperature, using a universal mechanical testing machine from Shimadzu, model AG-I 100 kN.

2.4. Materials characterization: X-ray diffraction (XRD)

After uniaxial compression tests samples were selected as bodies-of-proof to XRD characterization. The X-ray analyses were performed using an equipment from Bruker, Eco D8 ADVANCE, with CuKα radiation X-ray tube. The scan was done at a range of 5°–80° with an increase of 0.02°, a step time of 0.2 s and a rotation of 15 rpm was applied on sample holder. The software used in the identification was the EVA from Bruker, aimed on the determination the presented phases. After the uniaxial compression test, each sample was crushed and pulverized using mortar and pestle.

3. Results and discussions

3.1. Compressive strength analyses

3.1.1. Comparing cure times: 7 and 28 days

The Portland cement hydrated products are formed since the first contact between cement and water and continue to form over time. The

Table 3
Procedure of curing time.

Temperature	Procedure: curing time
38 °C	7 days in thermostatic bath
	28 days in thermostatic bath
300 °C	7 days, being 4 days in thermostatic bath and more 3 last days in curing chamber at 300 °C (thermal cycle)
	28 days, being 25 days in thermostatic bath and more 3 last days in curing chamber at 300 °C (thermal cycle)