

## Shear bond strength of oil well cement in carbonic acid environment

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### ABSTRACT

Shear Bond Strength (SBS) is an important property of cement that determines the life of oil and gas wells. This paper presents the results of an experimental study on the effect of carbonation on the SBS of cement under high-pressure high-temperature (HPHT) condition. The study is aimed at examining the effects of CO<sub>2</sub> concentration, temperature, and pressure on SBS of cement containing 35% of silica flour. The study was conducted by aging two types of specimens (i.e. cement cores and SBS samples made of steel pipe and cement). After curing, the specimens were aged for 14 days in an autoclave. The autoclave was 80% filled with brine saturated with mixed gas containing CO<sub>2</sub> and CH<sub>4</sub>. Aging pressure (21–62 MPa), temperature (38–221 °C) and CO<sub>2</sub> concentration (10–100% CO<sub>2</sub>) were varied. After aging, the specimens were recovered, and their SBS, porosity and mineralogical composition were determined to assess the level of carbonation and degradation.

To identify the most dominant factor affecting the SBS of cement, measurements were analyzed applying the Analysis of Variance (ANOVA) method. The analysis showed that temperature has a more prominent effect on the carbonation process than pressure and CO<sub>2</sub> concentration. Furthermore, results showed strong interaction effect among the main influential factors (pressure, temperature and CO<sub>2</sub> concentration). SBS increased with the carbonation. Medium-range temperatures (107 and 177 °C) caused high levels of carbonation as manifested by huge improvement in SBS and a significant reduction in porosity after exposure to a carbonic acid environment.

### 1. Introduction

The establishment of reliable zonal isolation is one of the principal objectives of primary oil well cementing. The development of strong bonding between cement and casing is essential for maintaining zonal isolation for a prolonged time. Cement degrades gradually and loses its mechanical and sealing performance when it is exposed to carbonic acid environment. When a cement bond fails, it allows the flow of formation fluid from one zone to other zones or even to the surface, creating health and safety issues.

Understanding the effect of CO<sub>2</sub> on cement degradation is essential to expand the applications of CO<sub>2</sub> Enhanced Oil Recovery (EOR) and CO<sub>2</sub> sequestration activities. A number of studies [1–16] have been conducted on degradation behavior of oil well cement in presence of CO<sub>2</sub> environment. The studies were focused on investigating the compressive strength, permeability, and porosity of cement at low and intermediate pressures (up to 30 MPa). Studies [17–19] on the shear bond strength of cement are very limited. Shear bond strength (SBS) represents the maximum wall shear stress that the interfacial bond between cement and casing can withstand without failure.

Setting or hardening of cement is a chemical reaction in which

binding components of cement (calcium hydroxide and calcium silicate hydrate) are formed to maintain structural integrity and create a bond between cement and surrounding solid surfaces (casing and borehole). The hydration process is necessary to build a structure and develop a competent bond. The bond strength depends on how effectively the cement in the annulus is filled up with binding components. Also, the bond strength is affected by other factors such as wettability and roughness of the casing surface, the degree of hydration, the structural and expansive behavior of cement [17] and the presence of fibrous material in the cement slurry [20]. Intensive cleaning and wetting the contact surface with a surface active material can improve bond strength. Surface roughness, wall friction, and mechanical interlocking also enhance shear bond strength [18]. The wall friction could develop because of the swelling of cement during carbonation. The swelling causes expansion-induced normal stresses, and consequently, frictional forces between pipe and cement improve. The structure of hardened cement at interface influences the mechanical behavior of cement bond. At the interface, there is a continuous thin layer of calcium hydroxide (CH), which is supported by calcium silicate hydrate (C-S-H) gel that helps the adhesion between cement and casing [21].

The degradation process of cement in the carbonic acid

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## Nomenclature

### Symbols

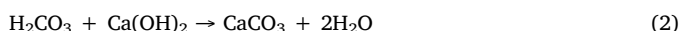
$A_c$	Contact area of cement with the pipe
$A_{cy}$	Area of the hydraulic cylinder
$P_{max}$	Maximum hydraulic pressure
$P$	Hydraulic pressure
$T$	Temperature

### Acronyms

ANOVA	Analysis of variance
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API	American Petroleum Industry
ASTM	American Society for Testing and Materials
BWOC	By the Weight of Cement
CH	Calcium hydroxide
C-S-H	Calcium silicate hydrate
DAQ	Data acquisition
FTIR	Fourier Transform Infra-Red
HEC	Hydroxyl ethyl cellulose
HPHT	High-pressure High-temperature
HS	Class H cement containing silica flour
SBS	Shear bond strength

environment is complex due to the involvement of different natural phenomena, including hydration of cement, dissolution of CO<sub>2</sub> in surrounding fluids, dissolution and carbonation of binding components of cement, bi-carbonation of calcium carbonate, and diffusion of chemical species in porous cement. Carbon dioxide is a highly soluble gas which rapidly dissolves in water or aqueous solutions such as formation fluid. The dissolution of CO<sub>2</sub> in an aqueous environment results in the formation of carbonic acid. Temperature, partial pressure of CO<sub>2</sub> and other ions present in surrounding fluid influence acid concentration and pH. When cement is exposed to aqueous fluid saturated with CO<sub>2</sub>, the acid penetrates into cement matrix and reacts with the main hydration products or binding materials (CH and C-S-H) of cement. The degradation process involves three steps. First, carbonic acid is produced when CO<sub>2</sub> gas dissolves and reacts with water to form carbonic acid. Then, calcium hydroxide and C-S-H dissolve and react with acid and creates calcium carbonate. In the presence of excess carbonic acid, calcium carbonate reacts with acid and forms easily leachable calcium bicarbonate. Thus, the degradation process is described as a series of chemical reactions as [11,12]:



The formation of carbonic acid (Eq. (1)) is strongly dependent on the solubility of carbon dioxide in aqueous solution. At high pressures (greater than 20 MPa), carbon dioxide exhibits abnormal solubility (Fig. 1). Due to the high reactivity of calcium hydroxide to acids, under ambient condition, the second reaction (Eq. (2)) is considered faster than the third one (Eq. (3)). Hence, the kinetics of CH carbonation is likely controlled by ionic transport or dissolution of CH. Under the atmospheric condition, the solubility of CH in pure water varies approximately linearly with temperature: 0.185 g/100 g H<sub>2</sub>O at 0 °C and 0.077 g/100 g H<sub>2</sub>O at 100 °C [23]. Under high pressure and temperature condition, the carbonation mechanism of C-S-H is more complex than that of CH. Depending on pressure, temperature and pH, C-S-H can form different types of intermediate carbonation products such as scawtite (Ca<sub>7</sub>(Si<sub>3</sub>O<sub>9</sub>)<sub>2</sub>CO<sub>3</sub>·2H<sub>2</sub>O) and spurrite (Ca<sub>5</sub>(SiO<sub>4</sub>)<sub>2</sub>CO<sub>3</sub>) that have diverse properties [24–26]. In the presence of acid, the intermediate products react with acid and form calcium carbonate. The formation of calcium carbonate and intermediate products and their subsequent precipitation in pore space results in expansion of cement, and reduction of porosity, permeability and ionic diffusion [12,27,28]. The produced CaCO<sub>3</sub> further reacts with the remaining acid (Eq. (4)) to form soluble calcium bicarbonate, which can be leached out from cement matrix. The reaction of CaCO<sub>3</sub> with carbonic acid (Eq. (4)) is also referred as bi-carbonation. The leaching tends to increase porosity and permeability and degrades mechanical and sealing properties of

cement. If degradation stops after the formation of CaCO<sub>3</sub>, it would improve compressive strength and will reduce permeability [7].

## 2. Previous studies

Evans and Carter [47] reported the existence of a relationship between compressive and shear bond strength of cement. However, Parcevaux and Sault [48] later found that the shear bond strength is more related to cement shrinkage/expansion and elasticity than its compressive strength. Moreover, shear bond strength varies significantly with the surface condition of the casing. It can be improved by cleaning the contact interface [17]. Enhanced bonding characteristics were observed in the field when casing surface was sand-blasted before cementing [29]. Not correctly cleaning of casing surface and removing mud film before cementing results in weak shear bond [47]. Furthermore, application of a resin-sand coating on casing surface dramatically improves shear bond strength [30].

Temperature is the critical parameter that determines cement property, including shear bond strength. Temperature considerably influences different natural phenomena involved in cement degradation such as ionic diffusion, solubility of gas and solids, and C-S-H phase transformation. Carter et al. [19] reported the existence of critical temperature (110 °C) at which shear bond strength becomes sensitive to temperature variation. They observed a considerable bond strength reduction above this temperature. However, Becker and Peterson [17] noted the improvement of bond strength with temperature (less than 121 °C). Temperature induces structural transformation of C-S-H to different crystalline forms including Tobermorite gel, which develops when the temperature is between 60–150 °C and C/S (CaO/SiO<sub>2</sub>) ratio is approximately 1 (Fig. 2). It is the most prominent form of C-S-H that exhibits good bonding property [31,32]. With increasing temperature, other C-S-H phases that have different bonding property develop.

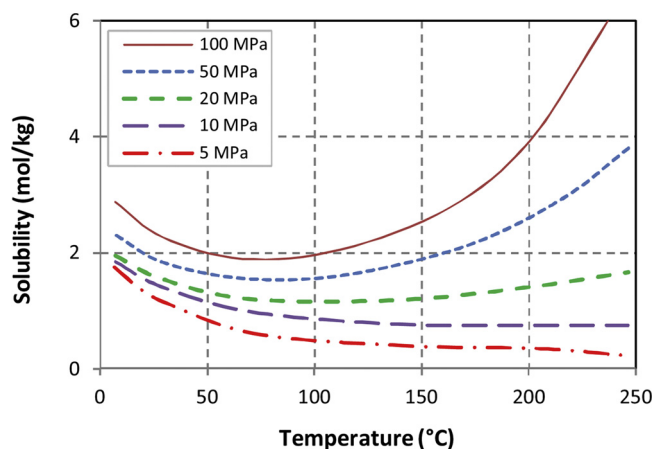


Fig. 1. Solubility of CO<sub>2</sub> in pure water (redrawn from Duan and Sun [22]).

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