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Depressurization damage of oil well cement cured for 3 days at various pressures

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HIGHLIGHTS

- High curing temperature increases the 3-day splitting tensile strength of cement.
- Pressure has little effect on the 3-day splitting tensile strength of cement.
- A mechanism for depressurization-induced cement specimen damage is proposed.
- High C_3A content in cement increases its risk to damage during depressurization.

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ABSTRACT

A variety of different types of oil well cement were tested with a newly developed test apparatus under different curing conditions to study the effects of curing temperature and pressure on their tensile test behavior. Specimens were cured at temperatures ranging from 24 to 60 °C and pressures ranging from 0.69 to 51.7 MPa. Tensile tests were performed at the age of 72 h. The capability of the test apparatus to record system deformation during pressurization and depressurization also allows study of cement–water interactions at different curing stages. Both splitting tensile tests and water pressure tensile tests were conducted after depressurization for assessing possible damage induced by the pressure change. A potential damage mechanism of set cement during depressurization is proposed in this study by analyzing the system deformation and tensile strength test data.

1. Introduction

Cementing is one of the most important phases of oil and gas well construction, the purpose of which is to create a cement sheath in the annulus between the steel casing and the wellbore. The cement sheath primarily acts as a seal to isolate different zones of the formations and prevent the migration of hydrocarbons or water from one layer to another. In addition, it also serves to protect the casing from corrosion as well as from shock loads due to further drilling. As both temperature and pressure increase with the depth of the wellbore, oil well cements are subject to wide ranges of temperature and pressure. For the purpose of modeling long-term performance of the cement sheath, oil well cements are routinely cured in high temperature and high pressure autoclaves in cementing labs to simulate the downhole conditions in oil wells. However, cement specimens cured in autoclaves have to be returned to the ambient temperature and pressure for mechanical property determinations and it is not well known how the properties are affected by temperature and pressure changes. Past laboratory experiences had indicated that a high pressure gradient during depressurization can cause extensive specimen cracking.

This study employs a newly developed test apparatus to evaluate the effect of curing temperature and pressure on the properties of different oil well cements. The test device allows the determination of water pressure tensile strength of cement by fluid pressure (or hydraulic fracture) test method, where the water pressure on the curved surface of a cylindrical specimen is increased linearly until the specimen fractures in tension [1,2]. The tensile strength obtained from fluid pressure tests can be very close to that obtained from traditional tests, especially when nitrogen gas (whose viscosity is about two orders of magnitude lower than that of water) is used as the pressurizing medium. Clayton [3] was among the first to

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study correlations between fluid pressure and splitting tensile test results. The correlation factor (α), defined here as the ratio between fluid pressure tensile strength (f_{fpt}) and splitting tensile strength (f_{st}), was found to decrease with decreasing loading rate, which ranged from 12 to 0.012 MPa/min. For nitrogen-pressure tests, α appeared to have reached a plateau ($\approx$1) when loading rate was reduced to the range between 1.2 and 0.12 MPa/min. Similar correlation factors were obtained by Mindess [4] using a loading rate of 0.6 MPa/min. However, for water pressure (hydraulic fracture) tests, α continued to decrease (from 1.89 to 1.25) with decreasing loading rate, suggesting that a plateau has not been reached. Preliminary studies using the test apparatus developed in this study showed that α was approximately equal to 1 when water pressure tests were performed on more permeable materials such as Leuders limestone at a loading rate of 0.69 MPa/min (100 psi/min); and that f_{fpt} of hardened cement tested with oil (which has a higher viscosity than water) as the pressurizing medium was much higher than that tested with water at the same loading rate. Therefore, the fluid pressure tensile strength of a material appeared to decrease with decreasing loading rate until a threshold rate was reached, below which test results seemed to be independent of loading rate and approximately equal to splitting tensile strength. For tests performed with a fixed loading rate above the threshold value, the correlation factor α would probably decrease with decreasing fluid viscosity and increasing specimen permeability. Fluid pressure testing of cement has not been widely adopted due to complexities of the fracture mechanism, however, as will be shown in this study, this test method can be very useful in assessing the susceptibility of set cement to depressurization damage.

Cement develops its properties by hydration in the presence of water to form a complex series of hydrates that bind cement grains together and form a continuous matrix. The most dramatic property change that a cement experiences during hydration is the solidification process known as setting, which transforms the cement from a workable plastic slurry into a rigid solid. In oil well cementing, the property of a plastic cement paste is typically quantified by its viscosity or consistency, while the property of a hardened cement may be quantified by its ultrasonic acoustic property, permeability, compressive strength, tensile strength, modulus of elasticity, Poisson's ratio, etc. As a result of the progressive cement hydration reactions, these various properties also vary with time. The overall degree of hydration of cement, defined as the total extent or percentage of cement that has reacted, is one of the most important parameters in modeling the evolution of these properties with time. For a given cement, the effect of curing temperature and pressure on the progress of its overall degree of hydration can be modeled fairly accurately based on chemical kinetics theories [5,6]. The dependency of the cement paste's certain physical and mechanical properties on curing temperature and pressure can be modeled in a much similar way if one assumes that the evolution of these properties has a direct correlation with the overall degree of hydration of the cement [7,8]. Similar concepts have also been adopted as a nondestructive method to estimate concrete strength at different curing temperatures [9]. The assumption is generally valid for properties such as viscosity, setting time and early-age compressive strength, when the total degree of hydration of cement is low [7,10–14]. However, the correlations between mechanical properties and degree of hydration become poor at later ages [15–18], primarily due to the fact that the microstructure developments of cement pastes also vary with curing conditions [14,19].

The purpose of this study was not to track or model the progress of various properties of cement over time at different curing conditions, as such work has been reported in other studies [5–8,20]. Tests were conducted primarily for qualitative assessment of the effect of curing temperature and pressure on the properties of set oil well cement after curing for 72 h and depressurized. It appears that while curing temperature (24–60 °C) may have a small effect on the final density and effective w/c ratio of the set cement due to its strong effect on the setting time, curing pressure (up to 51.7 MPa) has negligible effects on these properties. The unique set-up of the test device allows the system deformation behavior to be closely monitored during the depressurization process such that the cement–water interactions can be analyzed. After depressurization, the tensile strength of the cement was determined at in-situ curing temperature by water pressure test and then at ambient temperature by splitting tension test. The system deformation test data, coupled with the tensile strength test results by two different test methods, reveal critical insight with regard to the damage mechanism of set cement during depressurization.

2. Materials and methods

2.1. Materials

A total of four different classes of oil well cements, including Class A, C, G, and H were investigated in this study. The main compound compositions of these different cements, derived from the oxide analysis (conducted by X-ray fluorescence spectroscopy) test results using the Bogue calculation method [21], are presented in Table 1. Class H-P cement was a premium Class H cement, while Class H-I and Class H-II cements were two different lots of a standard Class H cement from the same manufacturer. All cement slurries (or pastes) were prepared with de-aerated water and cement only, with no additives. The particle size distributions (PSD) of the cements were measured by the laser scattering technique with dry dispersion methods (at least 10 measurements were performed on each type of cement). Class H-I cement was not measured as it should be similar to Class H-II cement. The specific surface areas calculated from the PSD data (assuming spherical particle shape and a cement density of 3150 kg/m^3) for Classes A, C, G, H-P and H-II cements were 356 m^2/kg, 565 m^2/kg, 327 m^2/kg, 394 m^2/kg, and 323 m^2/kg, respectively.

2.2. Experimental apparatus and test program

The apparatus developed in this study consists of three syringe pumps and four steel pressure cells, within which cylindrical cement specimens can be cast. A schematic illustration of the test system is shown in Fig. 1. The pressure cell was designed to allow different pressures to be applied to different regions of a hardened cylindrical cement specimen during a water pressure (hydraulic fracture) test. During the curing period, one can use either one of the three syringe pumps to apply a uniform hydrostatic pressure (i.e. end pressure = center pressure = seal pressure) to all pressure cells. The syringe pump can be programed for different pressurization and depressurization rates. The total system volume (primarily consists of the pressure cells and the syringe pump being used) is approximately 1800 mL and its change with time

Table 1
Estimated main compound compositions (by mass percentage) of the different cements.

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	$CaSO_4$	Free lime
A	61.7	12.0	8.4	9.4	0	4.7	1.4
C	72.2	5.2	2.2	11.8	0	4.7	0.2
G	62.6	15.9	4.8	10.9	0	3.8	0.2
H-P	47.9	27.5	0	16.2	2.0	4.2	0.3
H-I	66.5	11.7	0.3	13.4	0	4.5	0.3
H-II	70.3	8.5	0	12.8	0.0	4.8	0.3