Mechanical Behavior of Cement

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Introduction

Understanding cement mechanical behavior allows oil and gas wells to be better designed for long-term integrity. This document outlines the terminology and common test procedures used to evaluate the mechanical behavior of cement. Testing protocols were compiled from several laboratories within the industry. Cooperative testing helped to check repeatability of testing techniques. Testing was also partially used to guide specifics within any recommended procedures. Curing conditions are dependent on the expected downhole conditions and testing temperature was only considered at atmospheric conditions. Only test methods that are widely used at this time are presented here, such as:

— uniaxial compression test,

— direct and indirect tension test,

— triaxial test,

— acoustic test.

The parameters derived from these tests include:

— unconfined compressive strength,

— Young's modulus,

— Poisson's ratio,

— bulk modulus,

— tensile strength,

— shear failure envelope,

— dynamic Young's modulus,

— dynamic Poisson's ratio.

Cement is used in wellbore construction to provide structural support and prevent annular fluid flow. Cement slurry is pumped in the annulus outside of the tubular. This slurry hydrates into a porous solid. It is important that cement placement is designed and executed successfully for the cemented annulus to initially protect and support the tubular string as well as provide zonal isolation. It is also important that the cement's hardened properties be designed correctly for it to continue to perform long-term. An initially good cement sheath can become compromised when subjected to stress changes experienced in a well (Thiercelin et al., 1998; Bosma et al., 1999; Bois et al., 2012). Changes in stress can result from changes in pressure, temperature, and other fluctuations such as formation compaction and creep caused through wellbore operations (drilling, stimulation, workover, etc.) and production (reservoir depletion). Therefore, it is important to characterize the hardened cement's properties to facilitate estimations of the stress–strain responses of the cement during wellbore operations. These estimates can provide the information necessary for designing a cement system that can withstand the thermal and mechanical stresses the cement sheath may have to endure during its useful life.

There are two common ways to determine the properties of hardened cement. One technique is via "static" measurements using a load frame that yields values of static Young's modulus, static Poisson's ratio, compressive strength, and tensile strength; the second technique uses acoustic measurements that give values of dynamic Young's modulus and dynamic Poisson's ratio. There is not a general correlation between static and dynamic measurements over a wide variety of cement compositions. However, correlations may be established for a limited range of compositions (Reddy et al., 2007). The two methods will be addressed separately with emphasis on the "static" method.

Mechanical Behavior of Cement

1 Scope

The mechanical testing described in this document will provide the necessary cement property data for use in cement sheath integrity simulations. The compressive strength tests and nondestructive sonic determination of compressive strength of cement defined in API 10B-2 do not provide suitable data for cement sheath integrity simulations. The methods of API 10B-2 provide information on the strength of cement to ensure that the cement is suitable for general well construction applications and to determine when sufficient strength is developed to allow well operations to continue.

2 Normative References

This document contains no normative references. For a list of documents and articles associated with this publication, see the Bibliography.

3 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1
effective stress
The part of stress that impacts the mechanical behavior of a material body. Effective stress is calculated by subtracting the pore pressure from the total stress.

3.2
elasticity
The ability of a material to change its form as a result of an applied stress and return to its original form once the stress is removed.

3.3
failure criteria
The prediction or estimation of the failure of a material and the conditions under which it fails under the action of external loads.

3.4
isotropic
Identical properties in all directions.

3.5
load frame
A fixture used to test a material and measure its properties in compression or tension.

3.6
Mohr's circle
The two-dimensional graphical representation of the stresses in a material body.

3.7
Poisson's ratio
$\boldsymbol{\nu}$
A measure of a material's tendency to expand when it experiences compression in a perpendicular direction and can be further described as the negative ratio of transverse strain to axial strain.

3.8
stress
An applied pressure or system of pressures that strains or deforms a body.

3.9
strain
The measure of the relative deformation that results from applied stress.

3.10
tensile strength
$\boldsymbol{\sigma}_{\mathbf{T}}$
The maximum stress a material can withstand before failing, while being stretched.

3.11
triaxial
Involves three axes. In the context of this document it refers to a material's response in three dimensions.

3.12
unconfined compressive strength
$\boldsymbol{UCS}$
The maximum stress a material can withstand before failing, while being compressed without confining pressure.

3.13
Young's modulus
modulus of elasticity
$\boldsymbol{E}$
Property of a linear elastic solid material that represents the material's stiffness, which can be further described as the ratio of stress to strain.

4 Expansion and Explanation of Defined Terms

4.1 General

To facilitate communication and avoid confusion, it is important to provide clear definitions to the mechanical parameters discussed in this report. Note that only the parameters directly related to mechanical testing of cement are provided here. More details about the principals discussed in this document can be found by referring to a book on solid mechanics (Timoshenko and Goodier, 1970) and, more specifically, on rock mechanics, such as Jaeger et al. (2007), Fjaer et al. (2008), or Aadnoy and Looyeh (2011).

4.2 Stress

4.2.1 General

At a point located in a solid, stress is defined by a force, F, and the surface, A, through which the force is acting on the solid.

First, define the load vector, p, which is defined as the ratio of the force, F, to the area, A, as given by:

$$p = \frac{1}{A} F \tag{1}$$

Second, look at what occurs at a specific point on the surface. The area is allowed to shrink down to the point, so that the magnitude A goes to zero. The load vector at that point can be defined by:

$$p(x, n) = \lim_{dA \to 0} \frac{1}{dA} F \tag{2}$$