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The scratch test for strength and fracture toughness determination of oil well cements cured at high temperature and pressure

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ABSTRACT

Recent advances in scratch test analysis provide new ways to relate measured scratch test properties not only to strength properties but fracture properties of materials as well. Herein, we present an application of such tools to oil well cements cured at high temperatures and pressures. We find a concurrent increase of strength and toughness of different oil well cement baseline formulations which we relate to the water-to-binder ratio for a series of cementitious materials prepared with cement and silica flour. The scratch test thus emerges as a self-consistent technique for both cohesive–frictional strength and fracture properties that is highly reproducible, almost non-destructive, and not more sophisticated than classical compression tests, which makes this 'old' test highly attractive for performance-based field applications.

1. Introduction

The primary objective of well cementing, or the placement of cement in the annulus between the pipe or casing and the rock formation, is zonal isolation. That is, the annular cement sheath must isolate zones containing pressurized fluids from each other and from the surface and maintain this isolation even when the cement sheath is subjected to changes in stress and strain during the operating life of the well. From a mechanics point of view, this objective needs to be met by an appropriate cementitious material that can withstand high temperatures and pressures which are typically encountered in downhole applications. The key to choosing the appropriate material is a method that allows the control of an appropriate material parameter. As in the construction materials industry, the classical parameter in use has been the compressive strength of the material, which is part of the cultural baggage of engineers, be this in infrastructure applications of concrete, or in well-cementing applications. On the other hand, given the objectives of well cementing, one can arguably make the case that the material parameter that controls sealing and stability of the in-situ material does not relate to a limit in strength but rather to a risk of cracking and fracture. A performance-based design of such functions would thus need to consider fracture properties, for instance fracture energy or fracture toughness. The main challenge of fracture toughness properties is that their determination typically requires a much more sophisticated test setup that can deal with fracture size effects inherent to fracture phenomena in brittle and quasi-brittle materials [1], which need to be taken into account in the determination of concrete's fracture properties [2-5]. Presenting such a method that can be used to characterize fracture properties of oil well cements is the focus of this paper. More precisely, using a recently developed fracture approach to analyze the scratch test [6], the aim of this paper is to shed light on the effect of high temperature and pressure on the fracture toughness of a series of baseline oil well cement formulations.

2. Materials and methods

2.1. Materials

The materials considered here are made of class G cement (for composition, see Table 1). As reference, we consider a class G cement hydrated at ambient conditions with no mixed additives. The slurry density of 1.9 g/cc corresponds to a solid volume fraction of 41.5% and a water-to-cement mass ratio of $w/c = 0.44$. With respect to high temperature and pressure applications, two further base-line cement mixes in frequent use in oil well application are investigated. These mixes contain in addition 35% of silica flour (by weight of cement), which is known to react at high temperature and pressure. Silica flour is crystalline silica, containing at least 98% silicon dioxide and with a mean particle size around 20 μm. It is formed by grinding of quartz sand in ball or vibration mills. For comparison with the reference sample the two materials were designed either at the same water-to-cement mass ratio or the same water-to-binder mass ratio. Sample A of slurry density 2.03 g/cc contains 70 vol.% of class G cement and 30 vol.% of silica flour. This corresponds to a solid volume fraction of 50% representative of a water-to-binder mass ratio of $w/b = 0.33$, at a

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