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Structure and debonding at cement–steel and cement–rock interfaces: Effect of geometry and materials

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HIGHLIGHTS

- Cementing is an essential part of well construction in oil and gas industry.
- Interfacial transition zone develops along convex and concave interfaces in cement.
- Lubrication force can explain the development of the zone during cement casting.
- A discontinuity (a fracture) runs within this zone along concave wall.
- A weak zone also develops along convex wall, with fractures normal to interface.

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ABSTRACT

The interfacial transition zone (ITZ) is a weak region developing in cement when it hardens in contact with a solid wall. Its existence is well-known to construction engineers, and is used e.g. to determine the optimal size distribution of aggregates in concrete. The concept of the ITZ has, however, not been thoroughly explored in the context of well cementing yet. This is the case even though cement bonding to rock and steel pipe can be a crucial factor controlling leakage both in active and abandoned wells. In the present work, laboratory experiments were conducted to visualize the impact of the ITZ on well cement integrity. It was found that fracturing and debonding of cement in the ITZ can occur – and that the exact failure mode depends on the curvature of the interface. Samples with a convex interface between cement and steel (cement surrounding a steel hollow cylinder) displayed radial fractures oriented normal to the interface. Samples with a concave interface (cement plug inside a rock/steel hollow cylinder) displayed discontinuities (fractures) running within the ITZ, along the interface. The discontinuity developing along a concave interface between cement and porous rock was found to be more irregular than the one developing along a concave cement–steel interface. A theoretical study was also performed in the paper, concluding that the mechanism behind tensile stresses inducing fractures along the interface and normal to it is likely to be cement shrinkage.

1. Introduction

Cementing is an essential part of well construction in the oil and gas industry. After an interval of the subsurface has been drilled, a steel casing pipe is set in place and cemented, whereby cement is injected into the annulus from the bottom up. The quality of the resulting annular cement sheath is crucial for well integrity, and must prevent leakage along the well. Ensuring cement integrity is also a crucial part in underground CO_2 storage, where injected CO_2 must be prevented from escaping into the upper horizons along wells penetrating the storage site. As noted by the Intergovernmental Panel on Climate Change, "injection wells and abandoned wells have been identified as one of the most probable leakage pathways for CO_2 storage projects" [1].

Bulk cement as well as interfaces between cement and casing and between cement and rock are likely weak spots in wells with regard to leakage [2]. The so-called interfacial transition zone (ITZ) is known to be present along interfaces between cement and other materials. The properties of ITZ are different from the bulk cement [3–5]. In particular, a high-porosity zone of fine-grained material builds up at the interface because it is not possible to pack large particles as densely in the near-wall region as they are packed in the bulk cement ('near-wall' refers here to either cement–steel or

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cement–rock interface). Elevated porosity of the near-wall region leads to increased permeability [6]. Moreover, strength and stiffness of hardened cement vary with distance from the wall within the ITZ, passing through a minimum at a distance of 10 to 20 μm from the wall [7]. It has been observed in earlier studies that the change of structure and hydraulic properties with distance from the wall in the ITZ occurs gradually, over a distance of 15–50 μm from the wall. This distance increases as cement ages. There is usually a gradual transition in structure and properties from the wall to the bulk cement [3].

Experimental studies suggest that fracturing and eventual debonding might occur not exactly at the interface but at some distance into cement. The discontinuity would then run subparallel to the interface, within the relatively weak fine-grained material of the ITZ [4]. A plausible reason for the fracturing inside the ITZ rather than at the very interface is the strength variation inside the ITZ in the direction normal to the interface. Experimental measurements using the microindentation technique revealed that both Young's modulus and microstrength have a minimum inside the ITZ, at a distance of 10–30 μm from the wall [7]. Both parameters increase toward the wall and toward the bulk cement. Since the strength is higher at the very wall than at some distance into the cement, failure is more likely to occur inside the ITZ rather than at the very wall. The complex structure and possible failure/fracturing in the ITZ suggest that cement–steel interfaces should be treated as so-called 'imperfect interfaces' well known in the mechanics of composite materials [8–11]. Some of the classical stress and displacement continuity conditions, developed for 'ideal' or 'perfect' interfaces, may be violated at such 'imperfect' interfaces.

Understanding the mechanism of debonding is crucial for assessment and improvement of cement performance in wells, either producing or plugged and abandoned. Debonding can be caused by e.g. thermal stresses due to thermal cycling induced by injection of a relatively cold or hot fluid down the well [12]. It may also be caused by mechanical loads due to changing in-situ stresses (caused by e.g. reservoir depletion or CO_2 injection); by chemically active fluids [13]; or by a combination of the above factors.

Cement is used in wells in different geometrical configurations. In particular, when placed in the annulus between the casing pipe and the rock, cement is in contact with the steel surface that is convex, and the rock surface that typically has a rough landscape due to asperities, washouts and breakouts induced during drilling. During well plugging and abandonment, cement plugs are placed inside the casing or rock to create a permanent barrier after the well has stopped producing. In this case, cement is in contact with a concave steel or rock surface. Thus, the geometry of the contact between cement and steel or rock can be concave, convex, or rough and irregular. It should be noted that the absolute majority of experimental and theoretical studies of interfaces between cement and steel or aggregate materials have been carried out with the steel or aggregate surface being either flat or convex (e.g. [3]).

The first objective of our work was thus to look into the effect of different geometry (concave vs convex) of the interface on the development and structure of the ITZ, and on fracture development in it. Another aspect that was investigated, which is not commonly addressed in cement interface studies, is the interface between cement and porous rock. In particular, hydraulic properties of porous sedimentary rocks are different from steel. Detailed investigations of rock–cement interfaces are rare, with a few exceptions [13]. Sandstone, which is one of the most common reservoir rocks in oil and gas industry, was chosen in this work to compare differences in cement bonding to steel and rock.

2. Experiments

2.1. Setup

Two types of specimens were prepared, both with pure Portland G cement:

1. Specimen A, with cement inside and outside a steel pipe.
2. Specimen B, with cement inside a hollow cylinder of sandstone.

The arrangement of different materials is schematically shown in Fig. 1a and b for specimens A, B, respectively. The cement was mixed according to API 10A specification.

In terms of the interface geometry, specimen A (Fig. 1a) was representative of both well plugging (cement inside a steel pipe) and annulus cementing (cement outside a steel pipe). Cement was in contact with a concave steel wall inside the pipe and a convex steel wall outside the pipe. A 3 mm thick piece of steel pipe was first placed in about 5 mm thick plastic ring. The outer diameter of the steel pipe was equal to 10 mm, while its thickness was 1 mm. The outer diameter of the plastic ring was approximately 20 mm. The cement was poured over carefully so that it filled the steel ring and plastic ring. The steel ring was moved around with tweezers and then centralized to ensure good contact with cement paste. The level of the cement paste was slightly over the edges of the plastic ring to account for shrinkage during curing. During cement hardening, the samples (there were several with this geometry) were kept in a furnace within a pressure cell at a temperature of 66 °C and 15 bar pressure of nitrogen gas for 7 days. There was no water added during the curing process, and the cement cured only with the initial water content. The cement paste level was still higher than pipe walls after curing, so

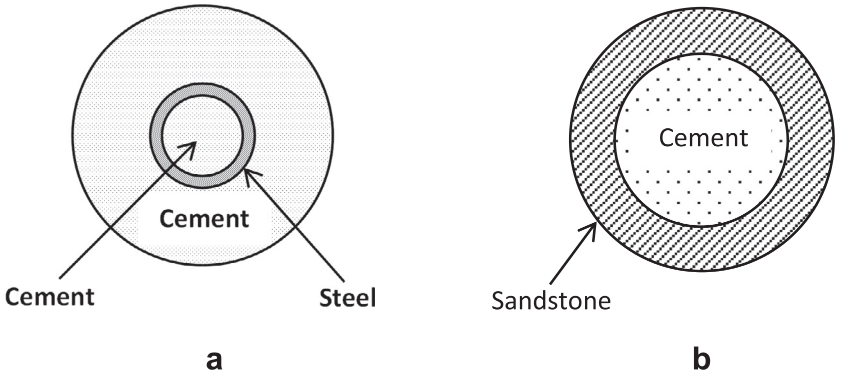

Fig. 1. Schematic illustration of material arrangements in specimens A (a) and B (b). Not to scale.