One potential issue to think about is connected to the complexity of shrinkage itself. It is perhaps tempting to think about shrinkage or contraction similar to how a metal contracts when it cools down – a temperature change induces a bulk volumetric strain. When we are discussing a hardening cement, we are dealing with a complicated chemical process instead. The transition to a solid, and associated volumetric changes, are now related to fluid saturation, temperature, drained or undrained conditions, confinement etc. – cement *chemistry*.

What I am getting at, is that there might **not** be a simple link between cement **shrinkage** and the **contact pressure** at the inner cement-casing interface. If cement was like a steel, and shrinkage was similar to cooling down of steel, then I would be inclined to think that we could link the contact pressure to a volumetric *eigenstrain* in the steel. All we need is the empirical thermal expansion coefficient of steel. But what about cement and cement chemistry? What types of stresses and strains are developed in the cement as it transitions from slurry to a porous material? How does this vary with curing conditions and geometry, and does it contract volumetrically in the same way as cooling of steel?

My point at this in the introduction – i.e. it is uncertain if the inner portion of cement will contract as a result of shrinkage. I attach two papers by a group in the US that have been working on modelling cement shrinkage in collaboration with Schlumberger. I have not been able to digest this to any appreciable degree, but I do think there are some relevant insights to take away from this work in the continuation.

The theory I outlined in my document is too basic.  This is material from Boresi (Mechanics of Materials) chapter 11 that I focused on in the early part of my research work looking at the elastic behavior of hard materials and how these radial circular elements interact.  The big unknown is what happens as the cement cures.

A broader title in my paper could be ‘An analytical and numerical study of cement curing in annular geometry’.  The key issue I believe is that the final hardened cement develops its properties depending upon the environment it is cured under.  Being contained between two strong steel containers it seems that the cement is the ‘weak part’ and will cure under influence of this confinement.  This aspect is not taken into consideration using the elastic Boresi equations.  Instead of free expansion and high porosity, it seems natural to expect reduced porosity under confinement.  How pressure and temperature affect the steel you have a good understanding of using the Boresi equation.  Questions that comes up: How does free expansion relate to confined expansion?  What is a sensible parameter to introduce in your model to capture what is happening while the cement cures?

My suggestion is to dig deeper into the mathematics of other researchers in this or similar fields, followed by postulating a more advanced model than the one I currently have.

What is really at the heart of the matter, as I see it, is to develop an improved understanding of stresses and strains within the cement and at the cement/casing/formation interfaces during hydration. Cement shrinkage is probably one of the dominant contributors to micro-annulus generation and loss of zonal isolation in wells, yet there is still no satisfactory understanding of this process nor the underlying mechanisms. This is unfortunate, given the considerable industrial/operational importance of this question. This question is equally relevant for traditional oilwell cements and companies that seek to develop new materials for zonal isolation.

Work that can contribute to an improved understanding of *eigenstresses* and *eigenstrains* as function of the degree of hydration, and relate that to isolation performance.

Again I suggest of going into the current state-of-the-art in the field. I attach some references that I think could be useful.

* SPE 139668: This paper describes a cement integrity model developed by CurisTec, a French company, in collaboration with Total’s well integrity/cement experts in France. I think this work is an example of current practices within the petroleum industry, using a similar mechanistic approach as I am outlining.
* ARMA 22-254: The experimental work Meng Meng, William Carey et al. at Los Alamos is probably the most sophisticated attempts so far at characterizing stresses in cements during/after curing. In this paper, from last year, they discuss annulus cement in section 3, and I think this section is very relevant. In sec. 3.2 they state: “In reality, this effect [inward shrinkage of annulus cement] will be restrained by the stiffness and thickness of the casing and also the outer formation stiffness. Restrained cement shrinkage under well conditions is necessary to be measured in the future.” I attach several other very recent papers by the same group.
* For a state-of-the-art modelling perspective of cement curing, one can do no better than having a look at this PhD thesis from MIT: [https://dspace.mit.edu/handle/1721.1/99577](https://eur03.safelinks.protection.outlook.com/?url=https%3A%2F%2Fdspace.mit.edu%2Fhandle%2F1721.1%2F99577&data=05%7C01%7Cpayam.allahvirdizadeh%40technipfmc.com%7Caa86b900b85242e066b608daf09f03a4%7C0804c95193a0405d80e4fa87c7551d6a%7C0%7C0%7C638086864026565542%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000%7C%7C%7C&sdata=%2BYntvBysNMfyOP2sJskXU25WVJ9hPiigfJotbLvVBQ8%3D&reserved=0).

A challenge to be aware of, is the difficulty of validating model results. As such, it is probably better to try to compare model results to published data, for instance experimental data in the attached Meng Meng et al. Cement and Concrete Research (2021) paper.

Thanks