

Breakthrough Innovation in Material Science with Specific Regard to Sulfur and Inverse Vulcanisation

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Inverse Vulcanization: A Path to Sustainable Roadways?

- A binder produced from a cheap, pure, readily available materials feedstock? A flexible platform? Potential for a circular economy?
- I apologize, it isn't bitumen!
- *Elemental sulfur* is the potential feedstock I am going to discuss today

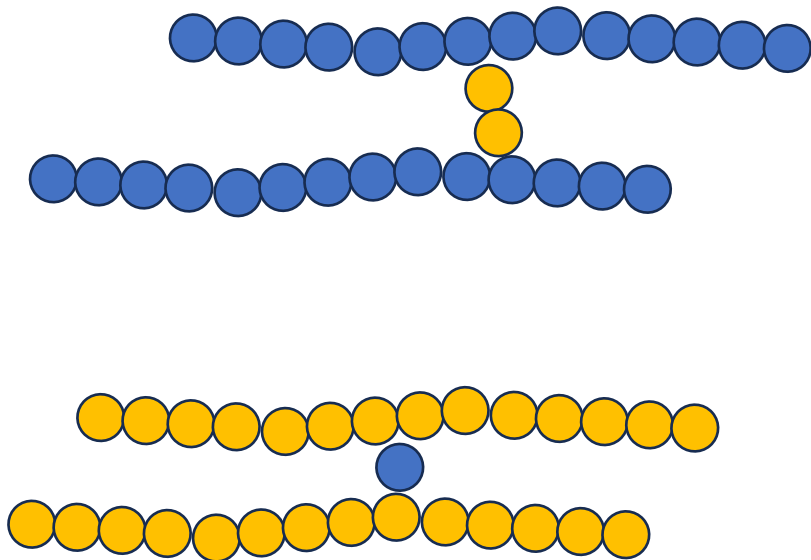


Inverse Vulcanization: Why sulfur?

- Supply exceeds demand
- Exceptional (99.5%+ purity)
- Low cost (~ \$150 / tonne)
- Supply is projected to **increase**
- Alignment with circular economy & reduction of environmental impact



Understanding Inverse Vulcanization: Process and Importance

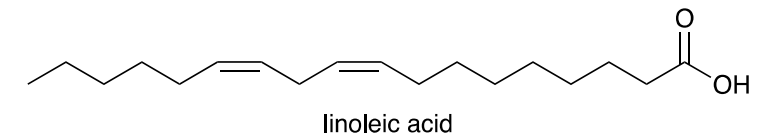
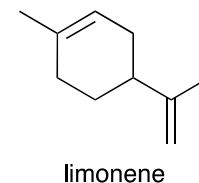
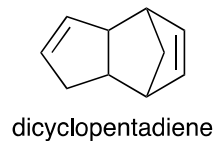


Vulcanization

- Used to produce 'vulcanized rubber'
- Small (<10% wt) amounts of sulfur are used to crosslink polymer chains (butadiene rubber)
- This produces an *elastomeric* polymer network
- Technically, vulcanized rubber is **1 molecule** (a big one!)
- Poorly understood from a chemical perspective

Inverse-Vulcanization

- A newer concept, in which sulfur is used as a *majority component*
- Able to generate and control the properties of the produced material (elastomeric, brittle, viscous, self-healing, vitrimers)
- Poorly understood from a chemical perspective (great work is being done – especially here in Phoenix!)



So...why aren't we building roads out of sulfur already?



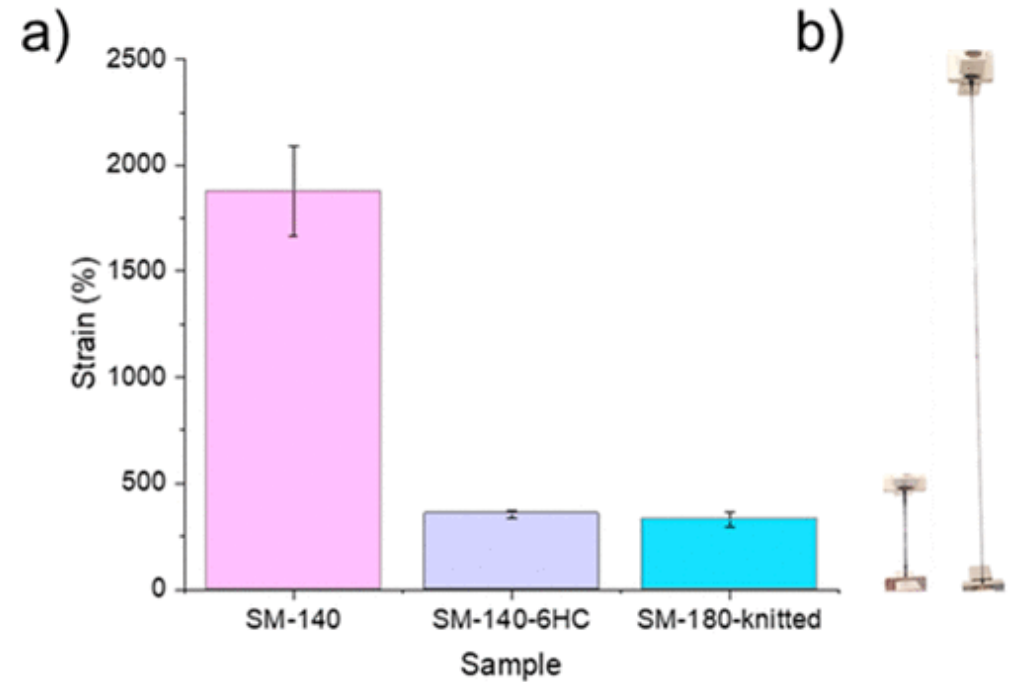
1. Materials chemistry is a 'hard' problem, there is no single environment, no simplified system. There is no 'big data' for us material chemists.¹ Progress is slow, and when a superior material is successfully commercialized it spreads like wildfire. (A race to the bottom)
2. Previously, there was little motivation to produce roads from sulfur. The potential for resource scarcity is driving science policy towards waste valorization, and market trends are driven by new materials.

¹ The caveat being that there is big data, but not for researchers of sulfur polymers sadly

Tuning Materials Made From Elemental Sulfur With Additives

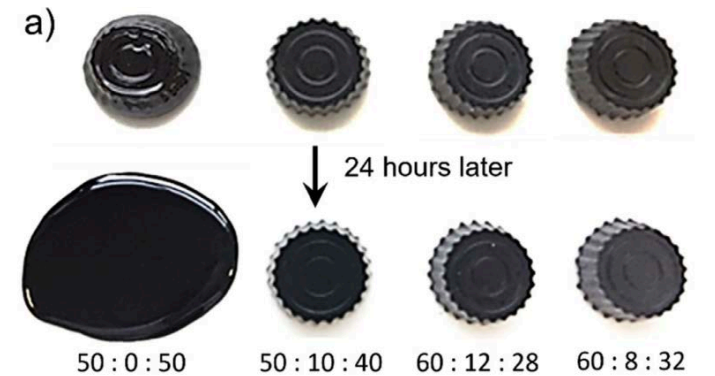
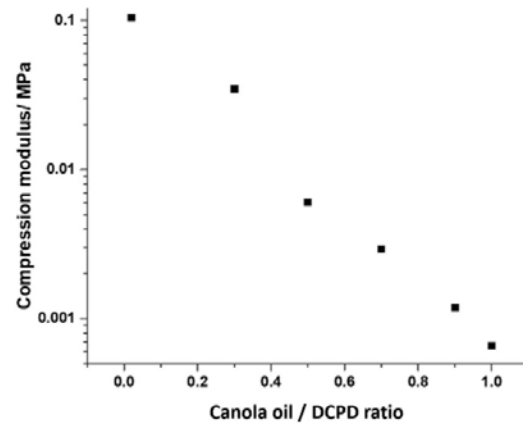
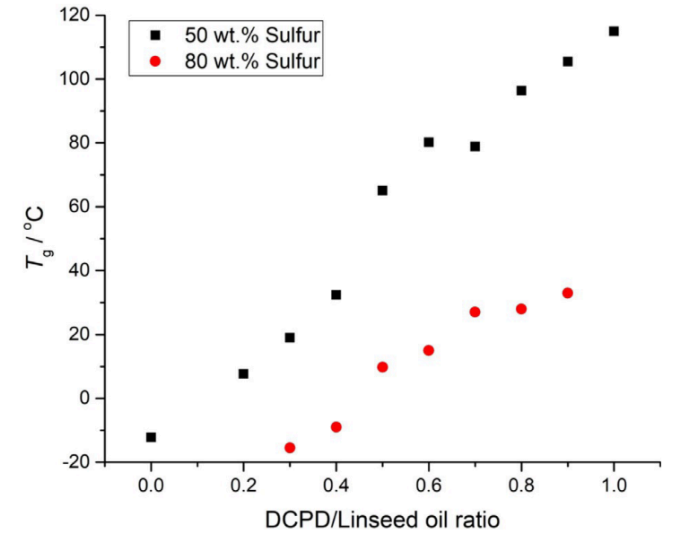
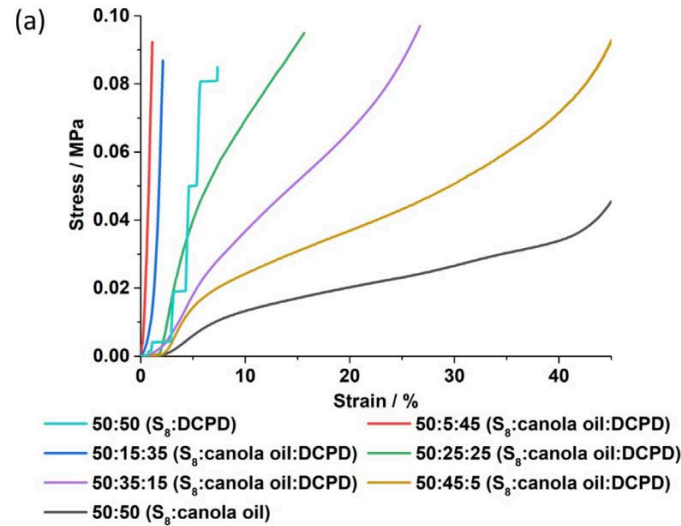


Increasing “catalyst” concentration (0, 1, 5% wt)



A post-synthetic “knitting” using an AlCl_3 catalyst

Altering the Physical Properties of Inverse Vulcanized Materials By Blending Monomers



Challenges in ‘Inverse Vulcanization’

- There are challenges
 - In principle the sulfur can be recovered from the polymer, and there are already hints at this in the literature* but nobody has gone as far as trying this.
 - There is *potential* in certain systems for H₂S release during reaction, which is particularly malodourous. Easily scrubbed from effluent gas streams by bleach.
 - The convergence of policy, engineering, and science. Bringing a radically different technology to market is not as simple as finding a good material.

* Happy to discuss at any point

My Call To Action (Conclusions)

- Inverse vulcanized polymers, sulfur polymer, thiopolymers, all one and the same. Extreme promise as a novel material.
- We first stumbled upon this process a while back and forgot about it
- We're looking at them again, and we're finding promising results every year
- If you want to develop, explore, understand, or even just chat about these materials I am always here. Nothing would make me happier than seeing an inverse vulcanized polymer commercialized.
- My question to the audience: **What can I, as a polymer chemist, do to help engineers and policy makers get these materials on the market?**
- Thank you for listening, I apologize in advance for my poor engineering knowledge!

* Happy to discuss at any point