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

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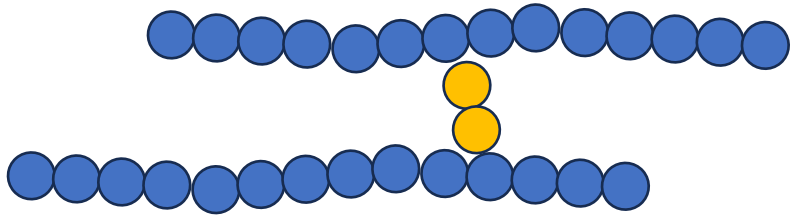
Inverse Vulcanization: A Path to Sustainable Roadways?

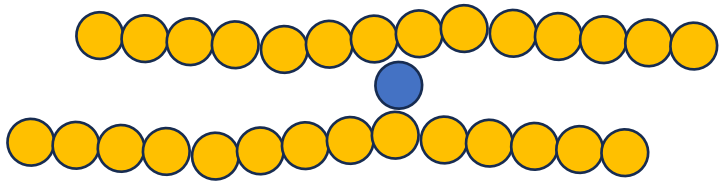
- A binder produced from a cheap, pure, readily available materials feedstock? A flexible platform? Potential for a circular economy?
- Apologies, it isn’t bitumen!
- *Elemental sulfur* is the potential feedstock we will explore today

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



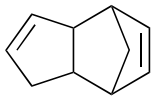


Vulcanization

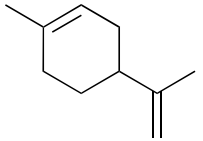
- Used to produce ‘vulcanized rubber’ – a strengthening process
- Small (<10% wt) amounts of sulfur are used to crosslink polymer chains (butadiene rubber)
- This produces an *elastomeric* polymer network
- Technically, vulcanized rubber is **1 molecule** (a big one!)
- Poorly understood from a chemical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

Inverse-Vulcanization

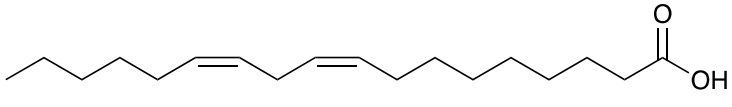
- A newer concept, in which sulfur is used as a *majority component*
- Able to generate and control the properties of the produced material (elastomeric, brittle, viscous, self-healing, vitrimers)
- Poorly understood from a chemical perspective (great work is being done – especially here in Phoenix!)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



dicyclopentadiene



limonene



linoleic acid

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

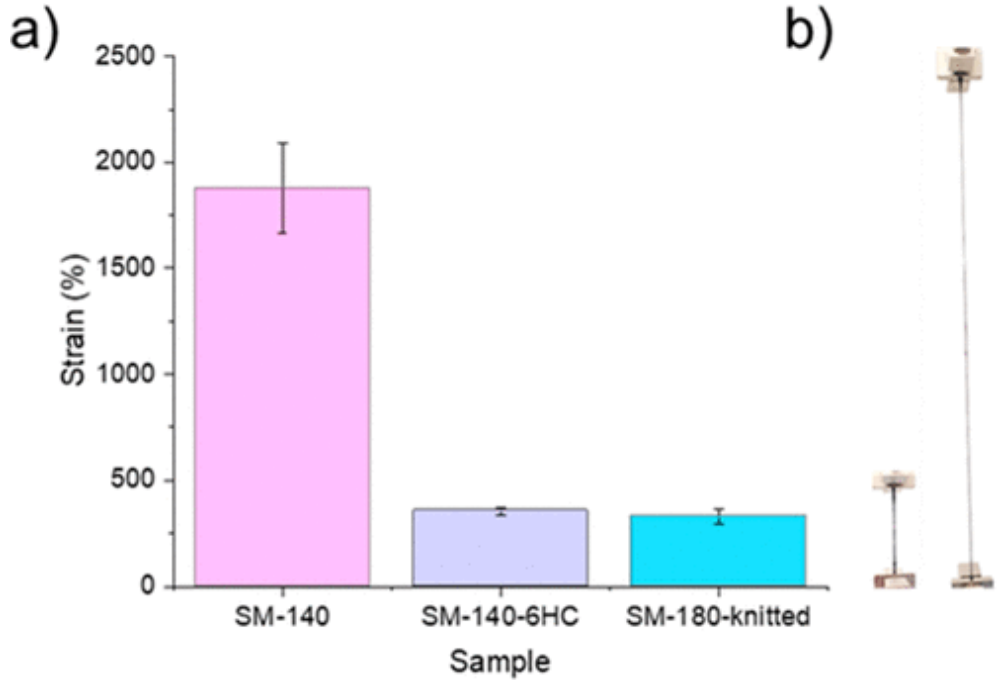
Tuning Materials Made From Elemental Sulfur With Additives

0 hours

12 hours

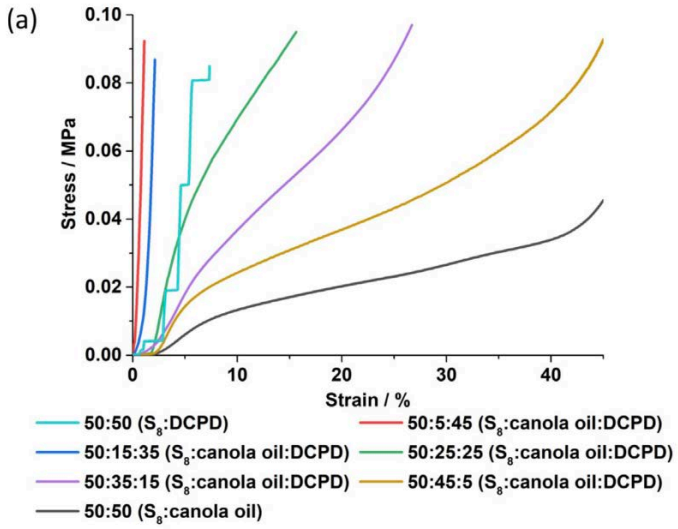
24 hours

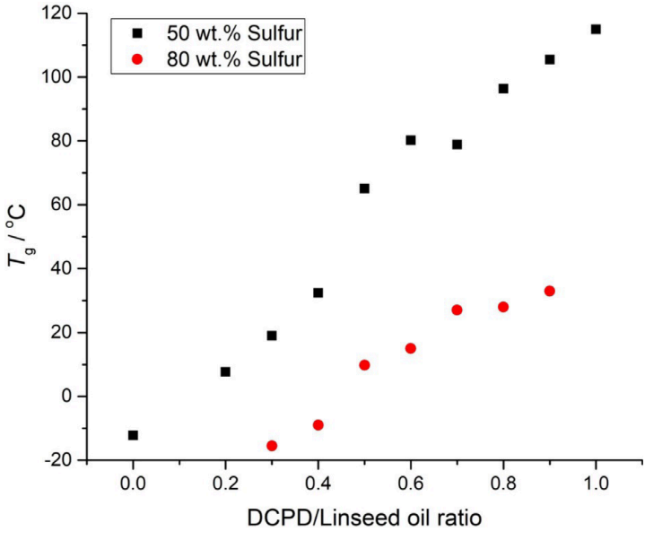
Increasing “catalyst” concentration (0, 1, 5% wt)

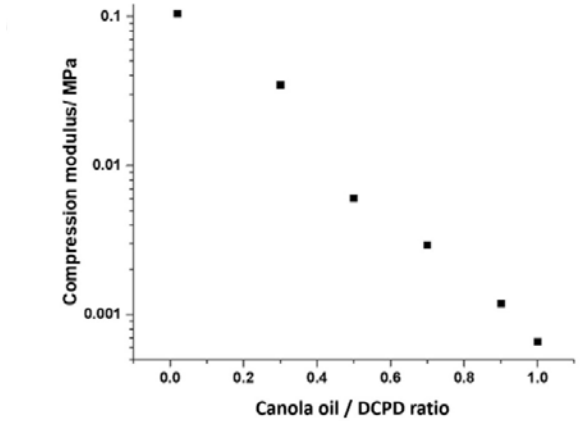


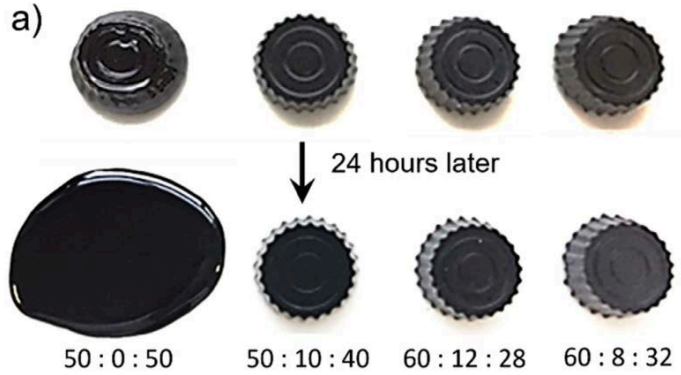
A post-synthetic “knitting” using an $AlCl_3$ catalyst

Altering the Physical Properties of Inverse Vulcanized Materials By Blending Monomers









Opportunities in ‘Inverse Vulcanization”

- There are plentiful opportunities in inverse vulcanization for innovation:
  - 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. (*Chemical)*
  - There is *potential* in certain systems for H_2S release during reaction, which is particularly malodourous. Easily scrubbed from effluent gas streams by bleach. (*Engineering*)
  - The convergence of policy, engineering, and science. Bringing a radically different technology to market is not as simple as finding a good material. (*Commercialization*)

Conclusions

- Polymeric materials generated from elemental sulfur demonstrate exceptional promise in a variety of applications
- Researchers first developed ‘inverse vulcanization’ type chemistry over 30 years ago, we are the 2nd wave of researchers
- Increased appetite in sulfurous materials is driving a revolution in sulfur chemistry
- Thank you for listening, apologies in advance for any poor engineering knowledge!

* Happy to discuss at any point