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PLA Extrusion Through A Multiplicative Mixer

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1974 -1987 Killion Extruders as Sales Manager, Production Manager, Lab Manager and VP of Development.

1988 to Present: Founder/President of Randcastle Extrusion Systems—a manufacturer of small extrusion equipment. He taught extrusion for SPE for 20 years. He's given many papers on extrusion. Seven patents on extrusion including compounding, pressure stability, pressure control, coextrusion and has an additional patent pending for compounding.

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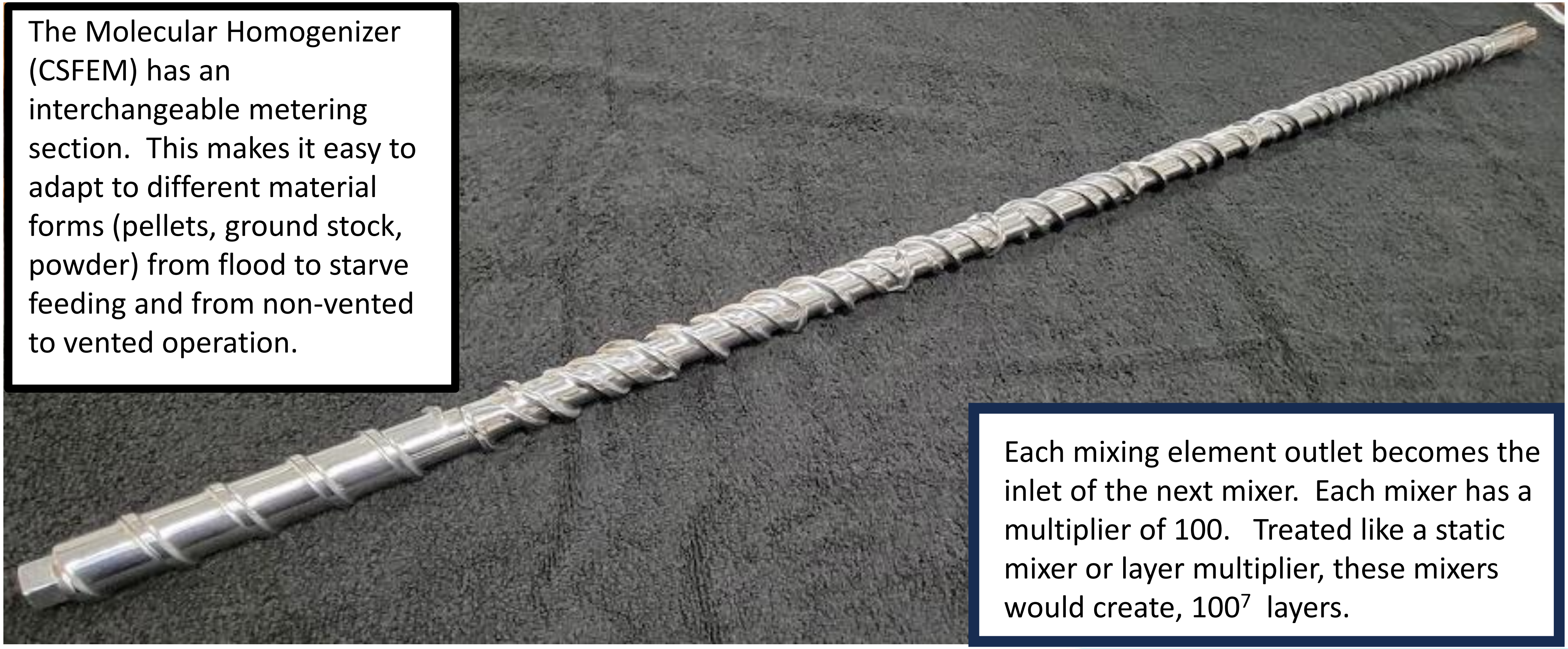
- Examine the process details of the experiments.
- Examine the torsional viscosity curves and implications.
- Conclusions.

The Continuous, Spirally Fluted, Elongational Mixer (CSFEM)

The Molecular Homogenizer (CSFEM) has an interchangeable metering section. This makes it easy to adapt to different material forms (pellets, ground stock, powder) from flood to starve feeding and from non-vented to vented operation.

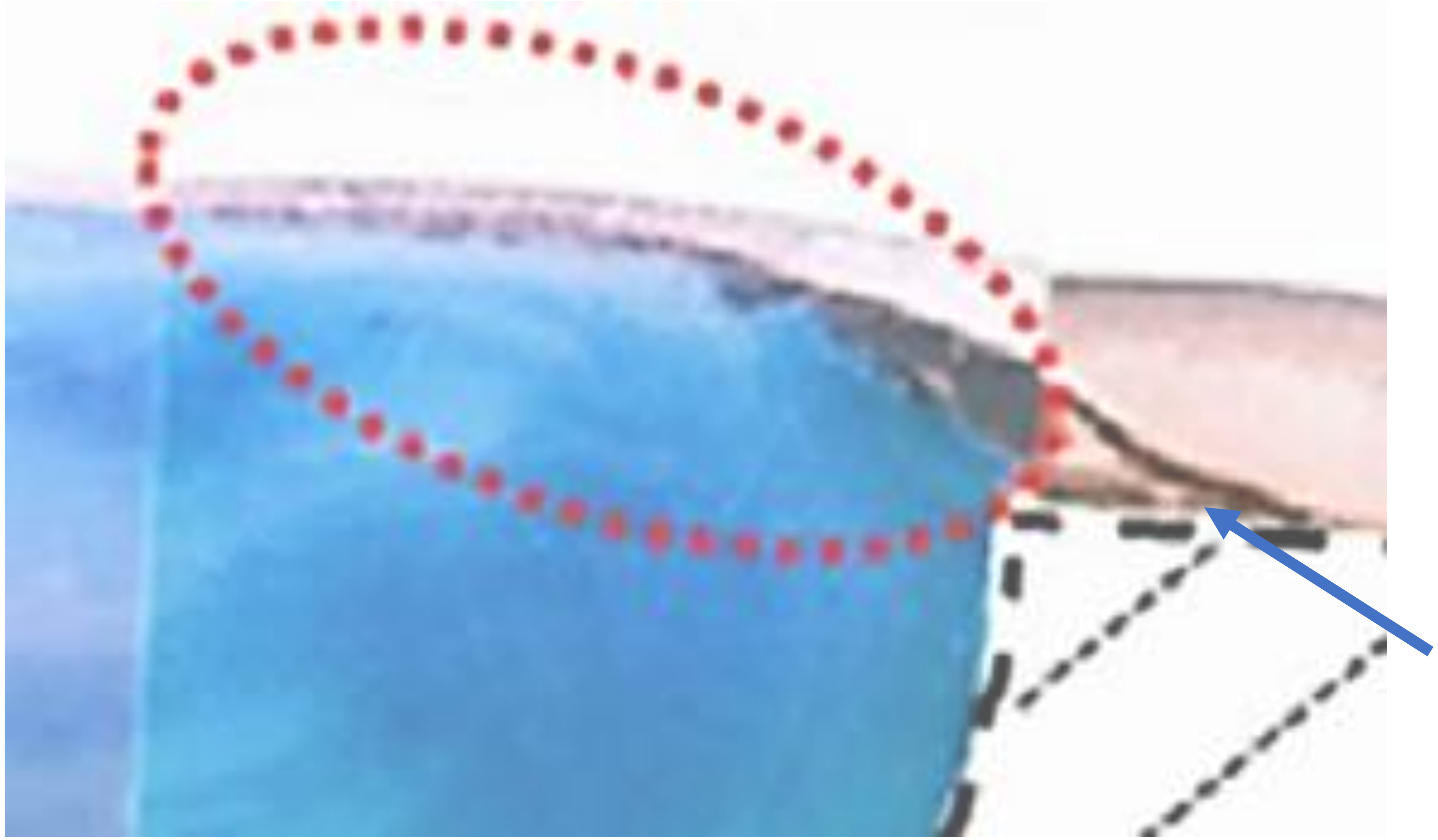


Each mixing element outlet becomes the inlet of the next mixer. Each mixer has a multiplier of 100. Treated like a static mixer or layer multiplier, these mixers would create, 100^7 layers.

Cross-Sectional Elongation In Dynamic Multiplicative Mixer

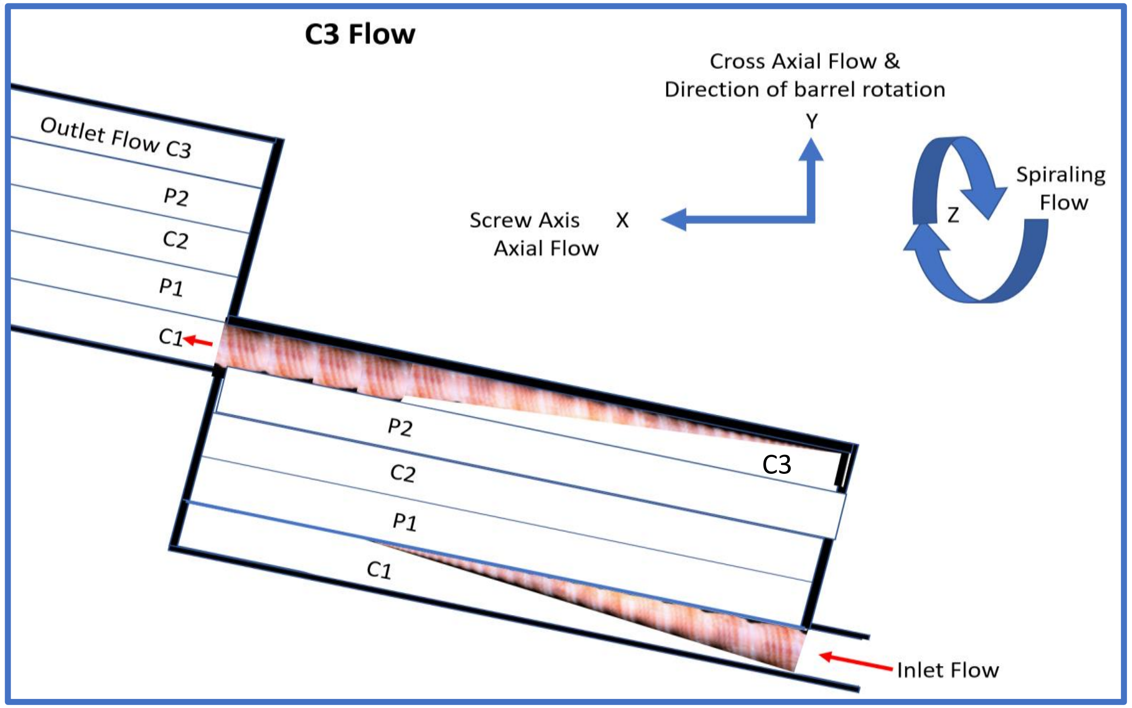
Stretching or elongation within the ellipse is asymmetrical. It elongates more near the pump surface and less at the barrel.

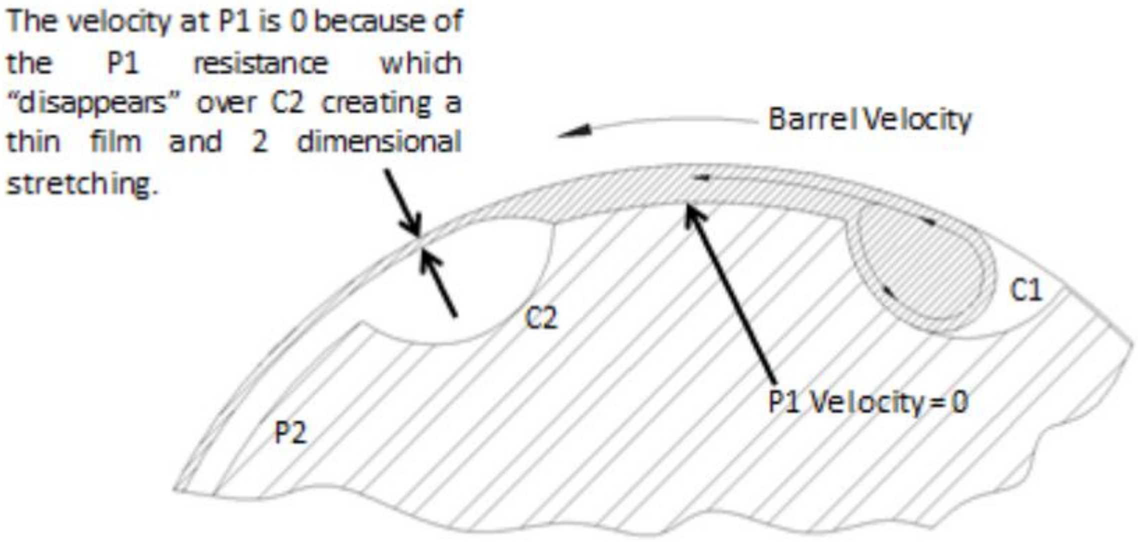
This is the opposite of the shearing action above the pump where low flow exists at the pump surface.



Pump surface the low/zero flow of shear.

The Continuous, Spirally Fluted, Elongational Mixer (CSFEM)





When the outside becomes the inside and enters the next mixing element:

- The asymmetry is reversed and stretches the opposite side.
- The shearing surface is reversed and shears the opposite side.
- When a thin film is created over C2 and C3, heat transfer increases.

The Continuous, Spirally Fluted, Elongational Mixer (CSFEM)

The trade name for this dynamic, multiplicative mixer is the Molecular Homogenizer (MH).

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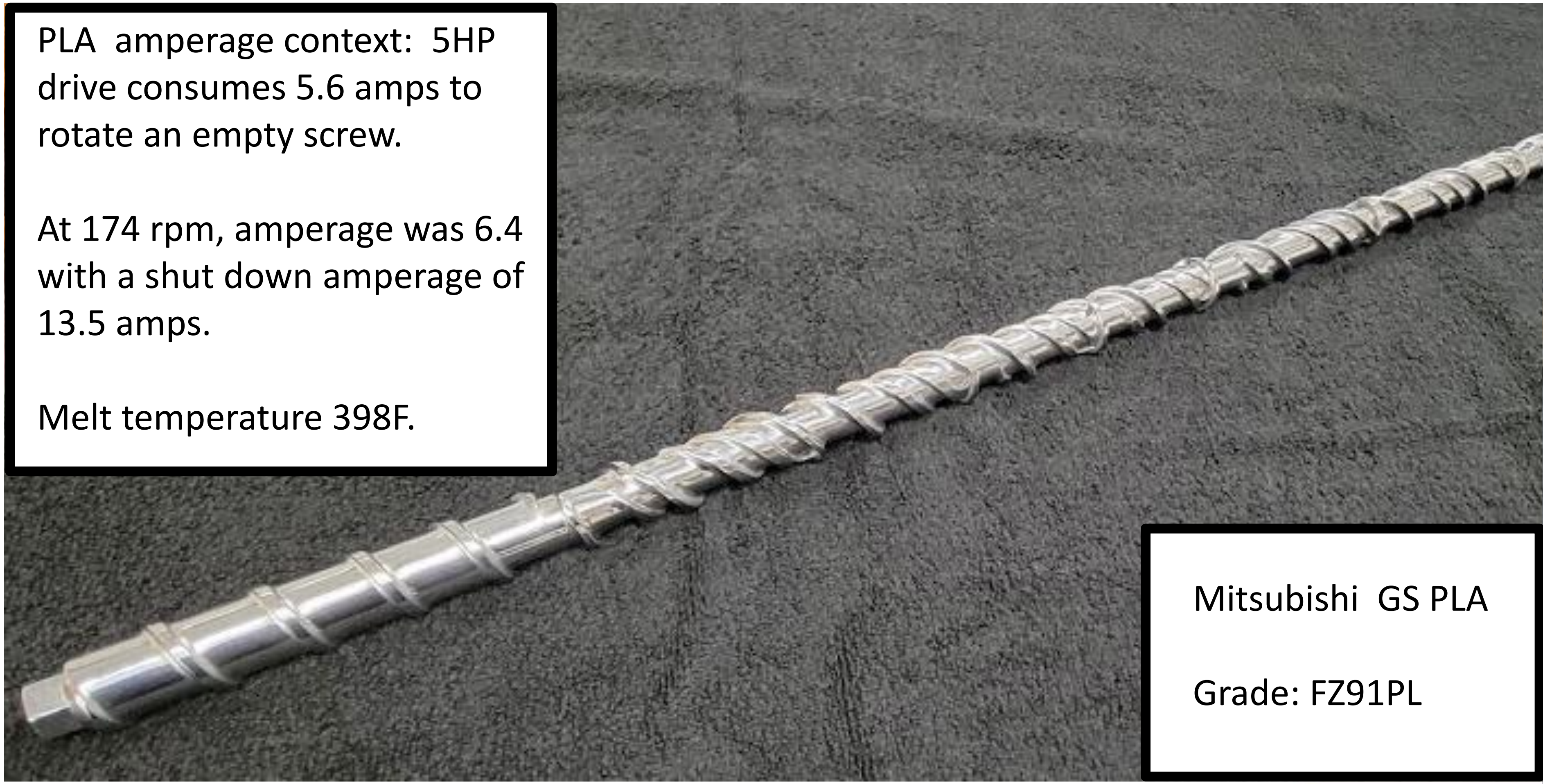


PLA amperage context: 5HP drive consumes 5.6 amps to rotate an empty screw.

At 174 rpm, amperage was 6.4 with a shut down amperage of 13.5 amps.

Melt temperature 398F.

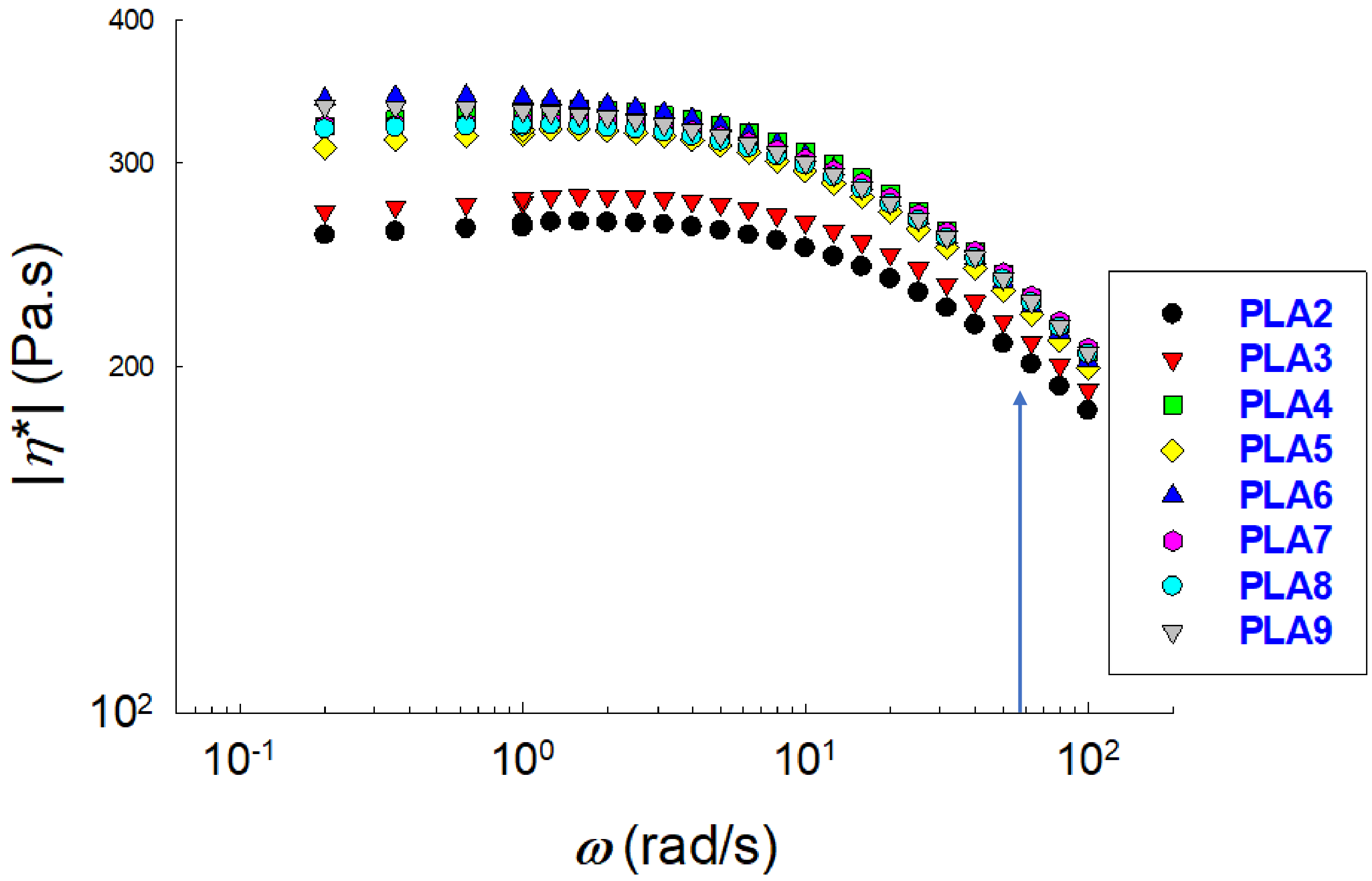
Mitsubishi GS PLA

Grade: FZ91PL

Process Conditions Constant For All CSFEM Experiments

RPM	Barrel	Barrel	Barrel	Barrel	Adaptor	Die	Melt @
	Zn. 1	Zn. 2	Zn. 3	Zn. 4	Zn. 5	Zn. 6	
174	355	375	375	390	360	375	398

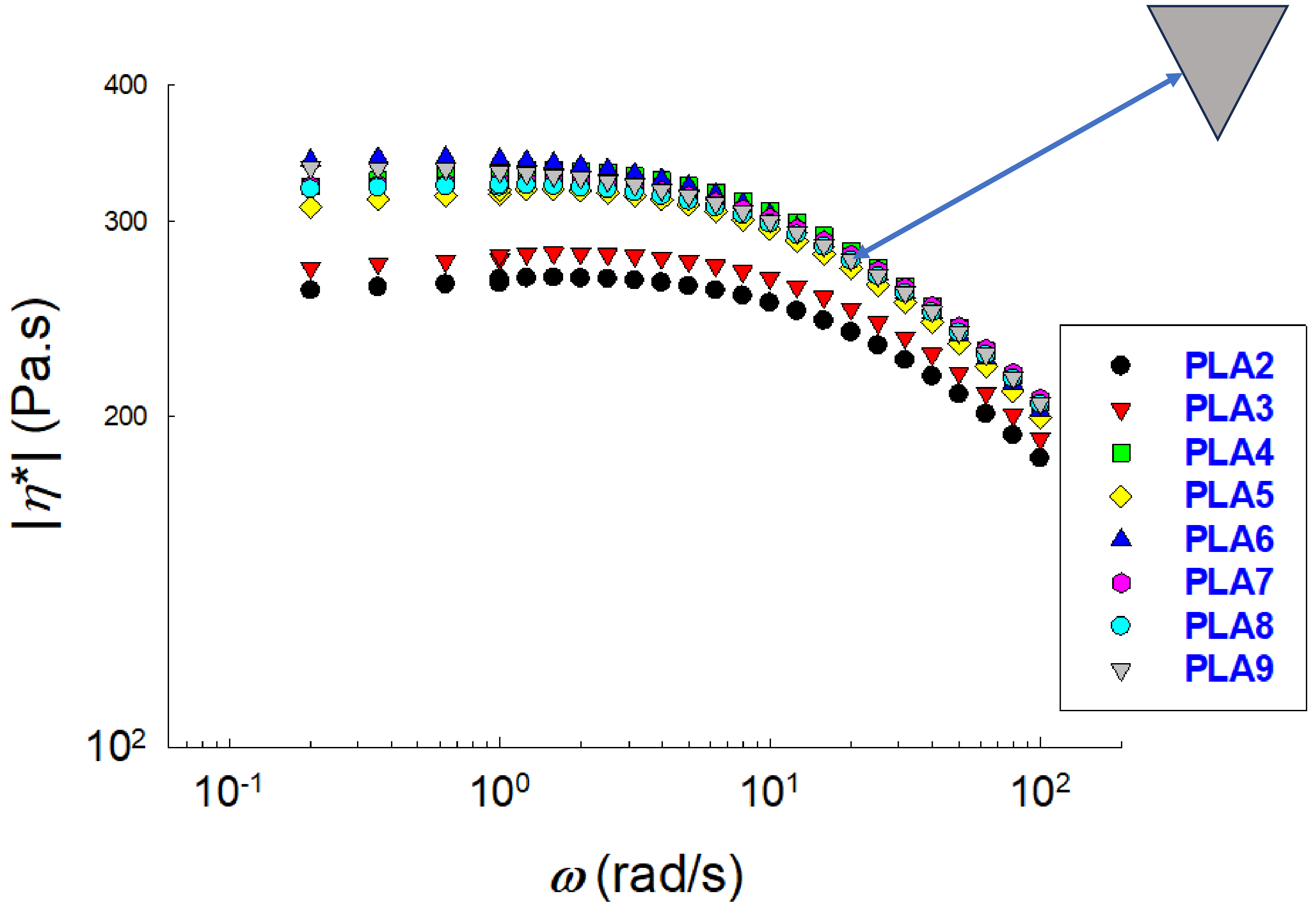
Torsional Rheometer Results:



Given the rotation of the metering section root at 174 rpm, we would have been processing at about 57 (rad/s).

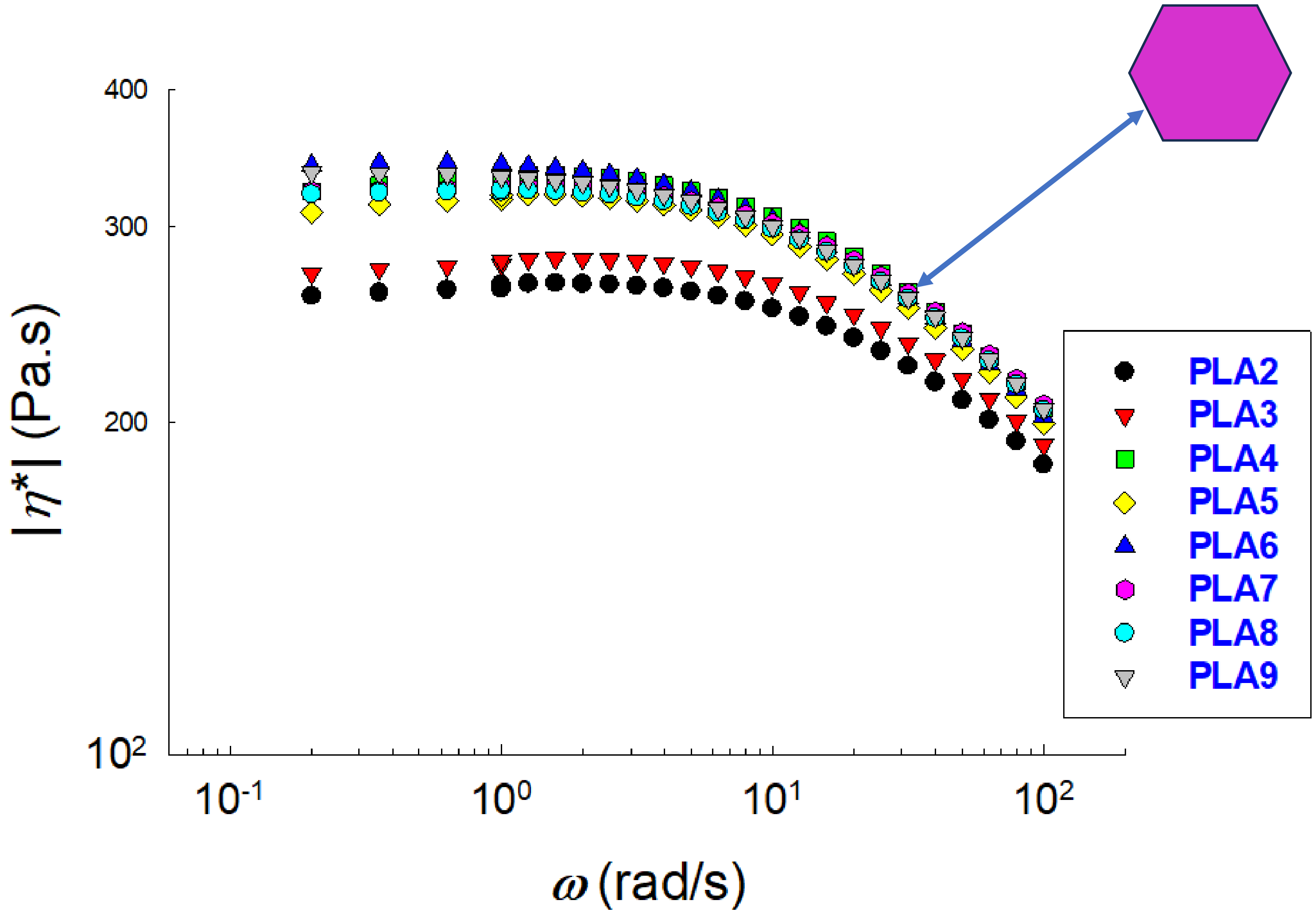
So, we wouldn't expect to see big changes in pressure near the confluence of the curves and we didn't.

Torsional Rheometer Results: PLA9 Virgin



PLA9 is the virgin material. It was not processed and so represents the control to measure everything against.

Torsional Rheometer Results: PLA7 Dried Non-vented

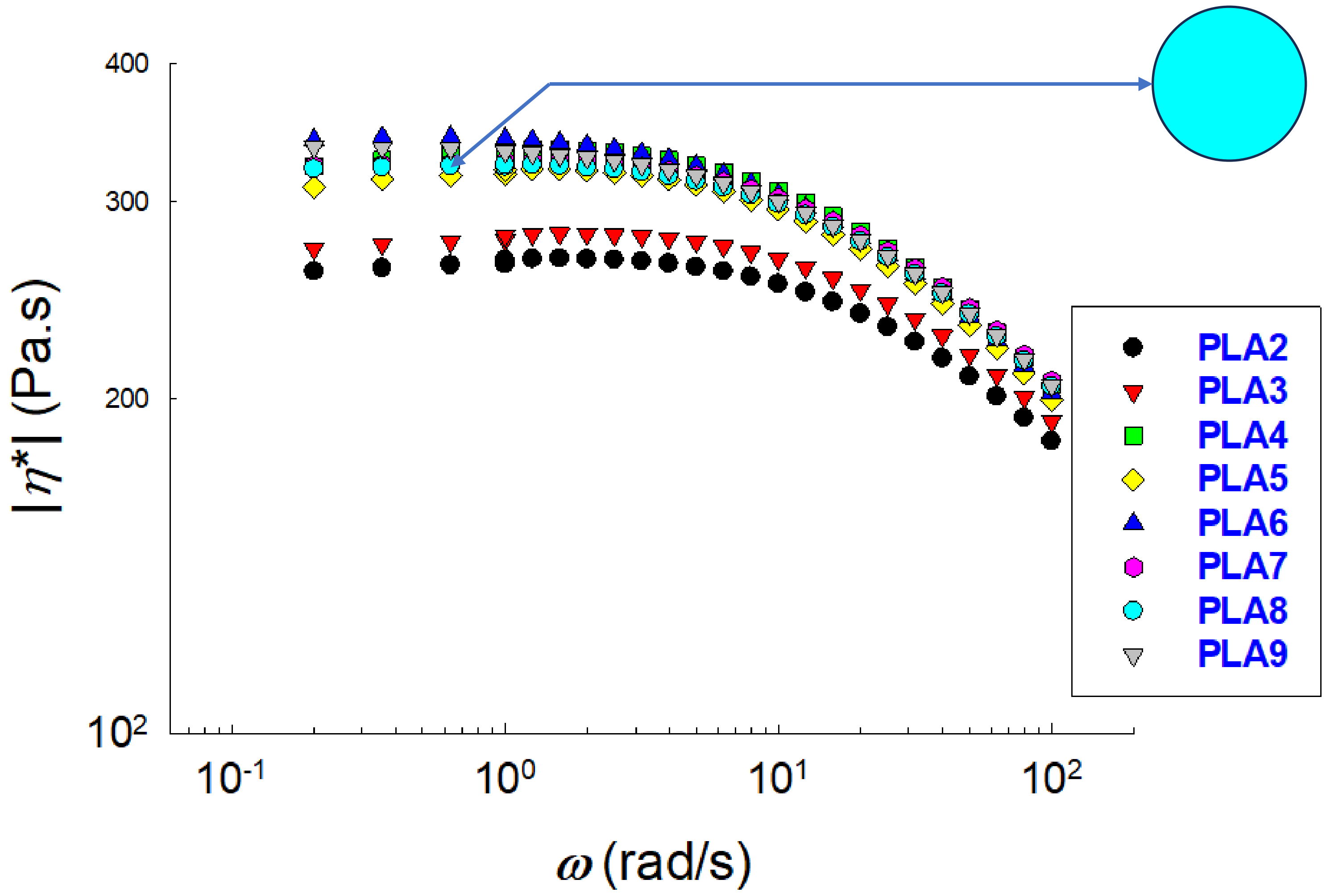


PLA 7 represents typical processing. That is, you normally expect to process dry material. PLA7 is PLA9 (unprocessed dried virgin) now processed into pellets. PLA7 and PLA9 curves are nearly indistinguishable.

Mixing is sometimes exclusively with shear and shear with heat reasoning, *"If it's extremely well mixed, it must be excessively sheared, therefore over heated and degraded.*

Since PLA7's viscosity is nearly unchanged from PLA9, *the screw's various mixing actions have not degraded the material.*

Torsional Rheometer Results: PLA8 Dried & Vented

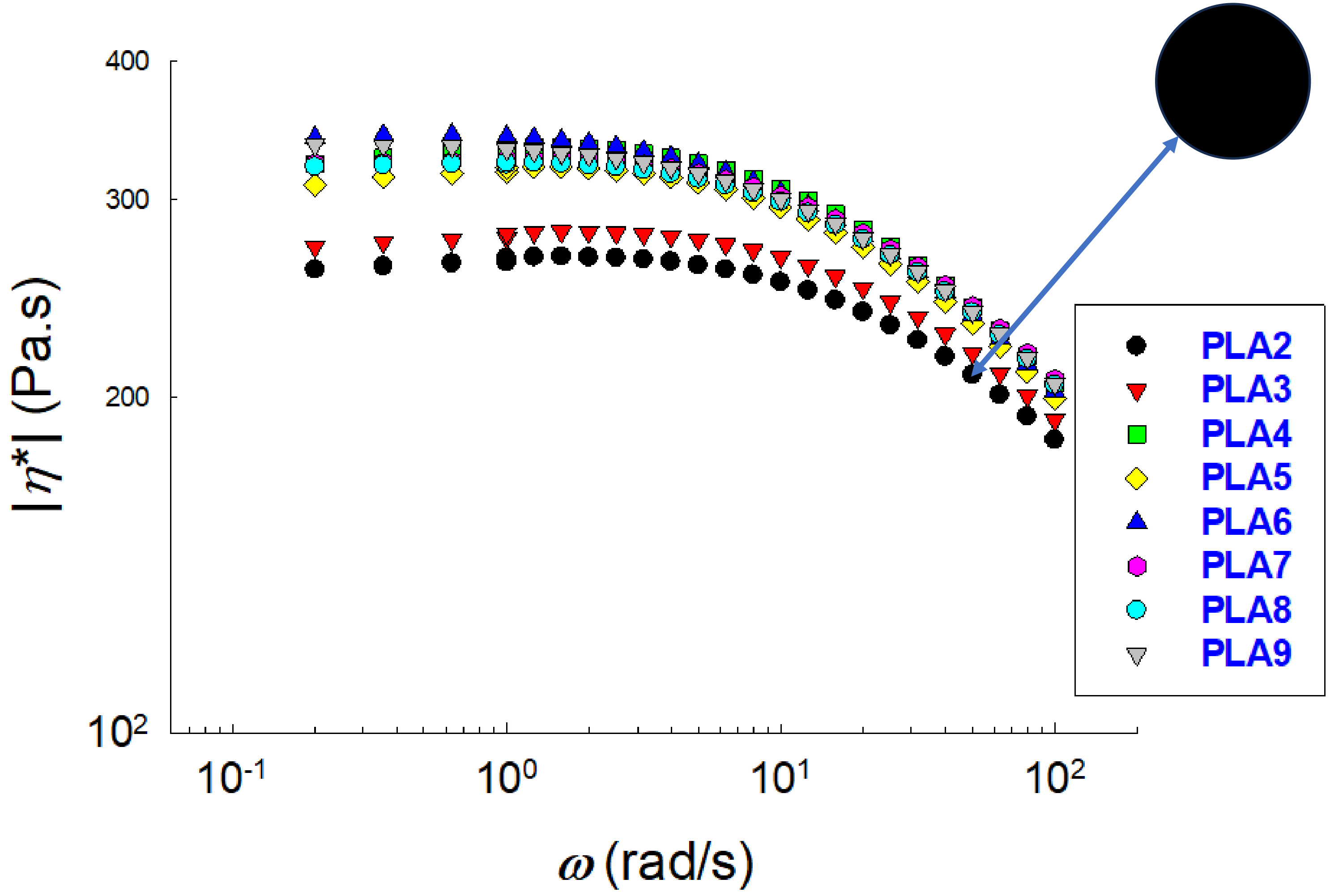


Not surprisingly, this curve is nearly identical to the PLA8 curve. The only processing difference is the atmospheric vent.

Again, we see that the various mixing actions—the 100 trillion distributive layering/mixing and the many dispersive zones—have not degraded the material.

The mixing action is gentle and non-destructive.

Torsional Rheometer Results: PLA2 Undried & Unvented

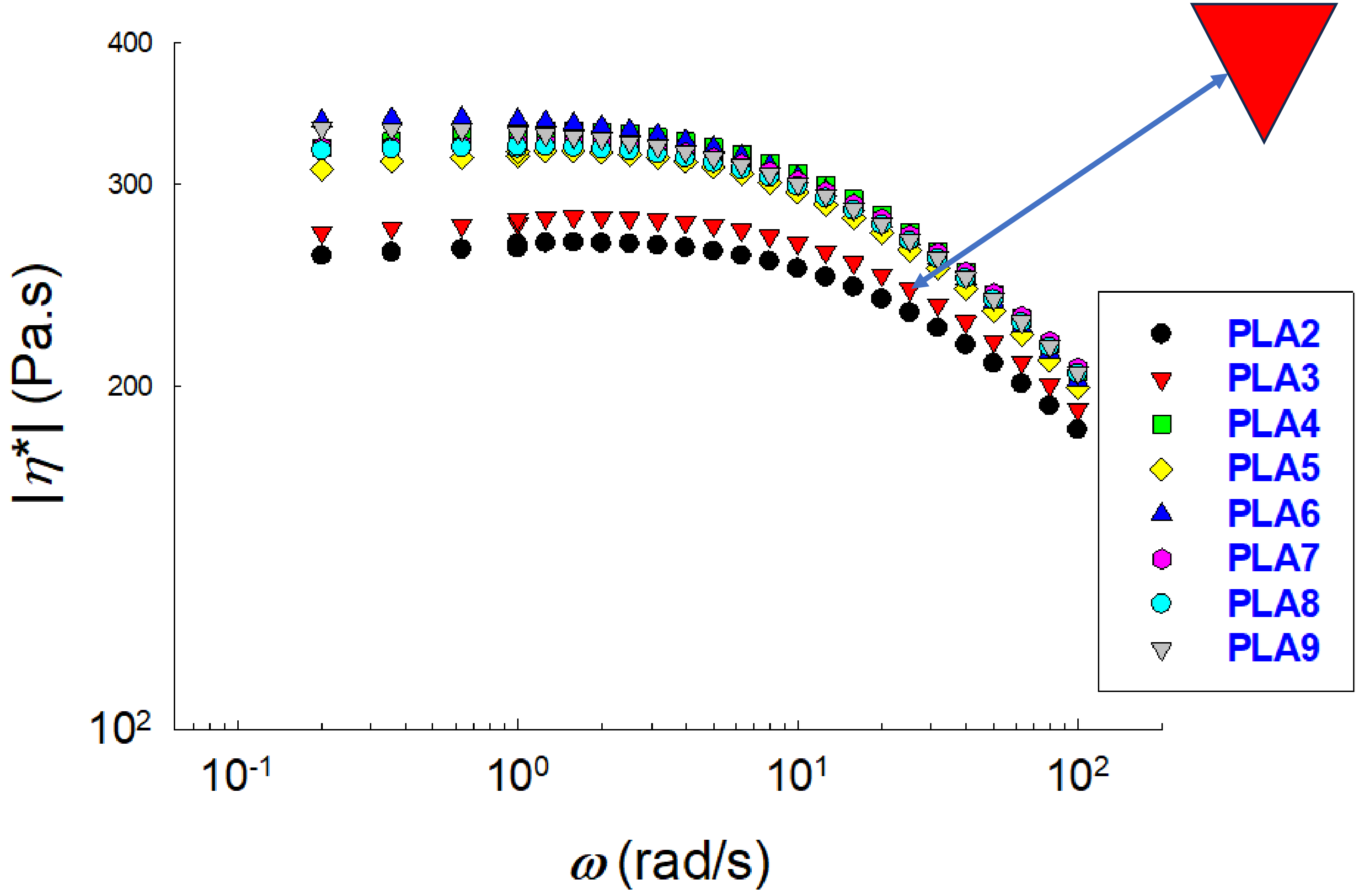


PLA 9, the virgin undried material, was left exposed to atmosphere for 3 weeks.

PLA 9 was then processed undried and unvented and is labeled PLA2.

Clearly the viscosity declined although it is perhaps noteworthy that its curve approaches the virgin material PLA9 at higher speeds.

Torsional Rheometer Results: PLA3 Undried But Vented



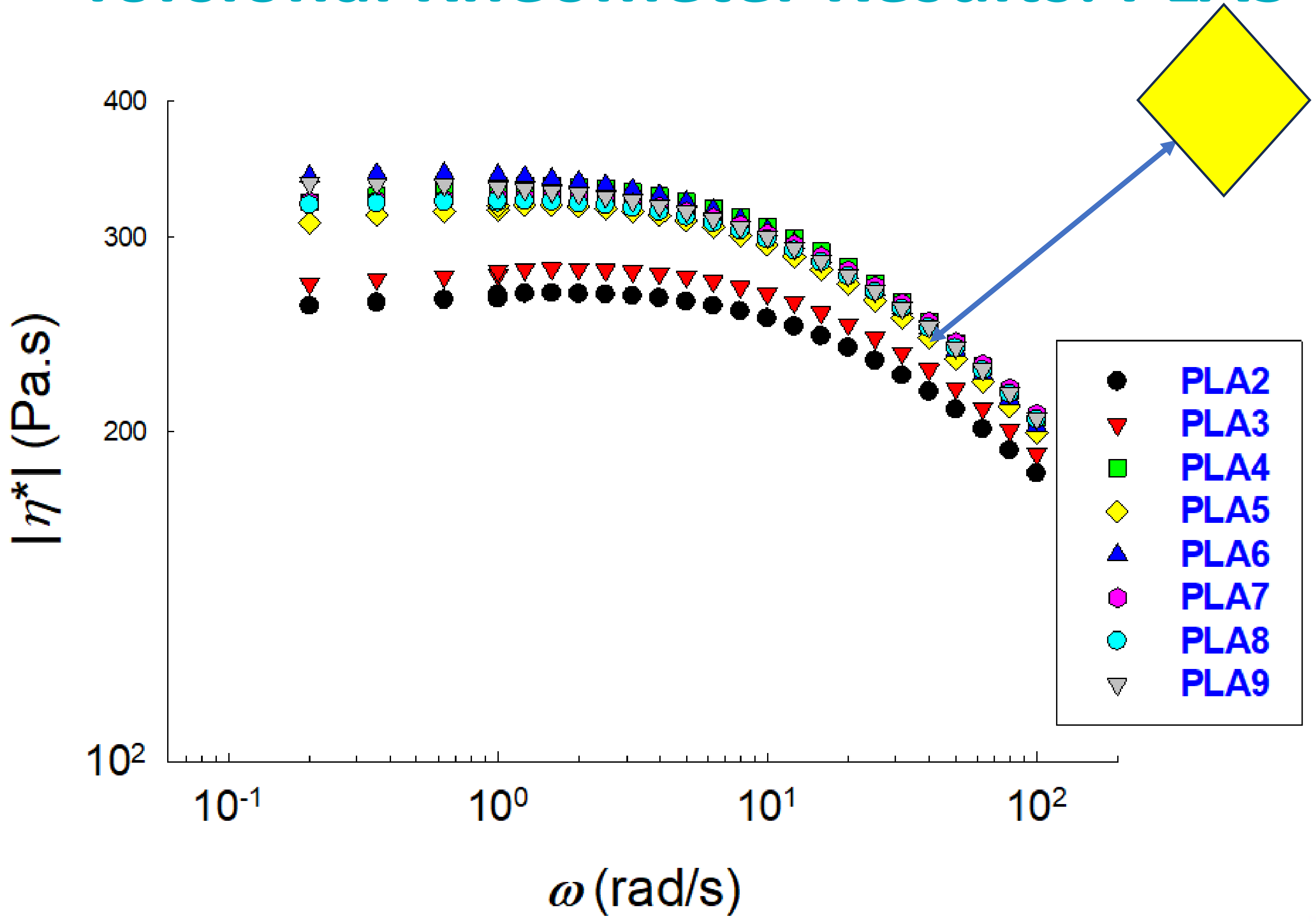
PLA 9, the virgin undried material, was left exposed to atmosphere for 3 weeks.

PLA 9 was then processed undried but vented to atmosphere. It is labeled PLA3. So, the difference between PLA2 and PLA3 is the venting.

Not surprisingly, the venting to atmosphere had an effect, though seemingly minor, on the viscosity. The viscosity declined from the virgin, though not as much as PLA2.

Again, it's noteworthy that the PLA3 curve approaches the virgin material PLA9 at higher speeds.

Torsional Rheometer Results: PLA5 Undried & Unvented



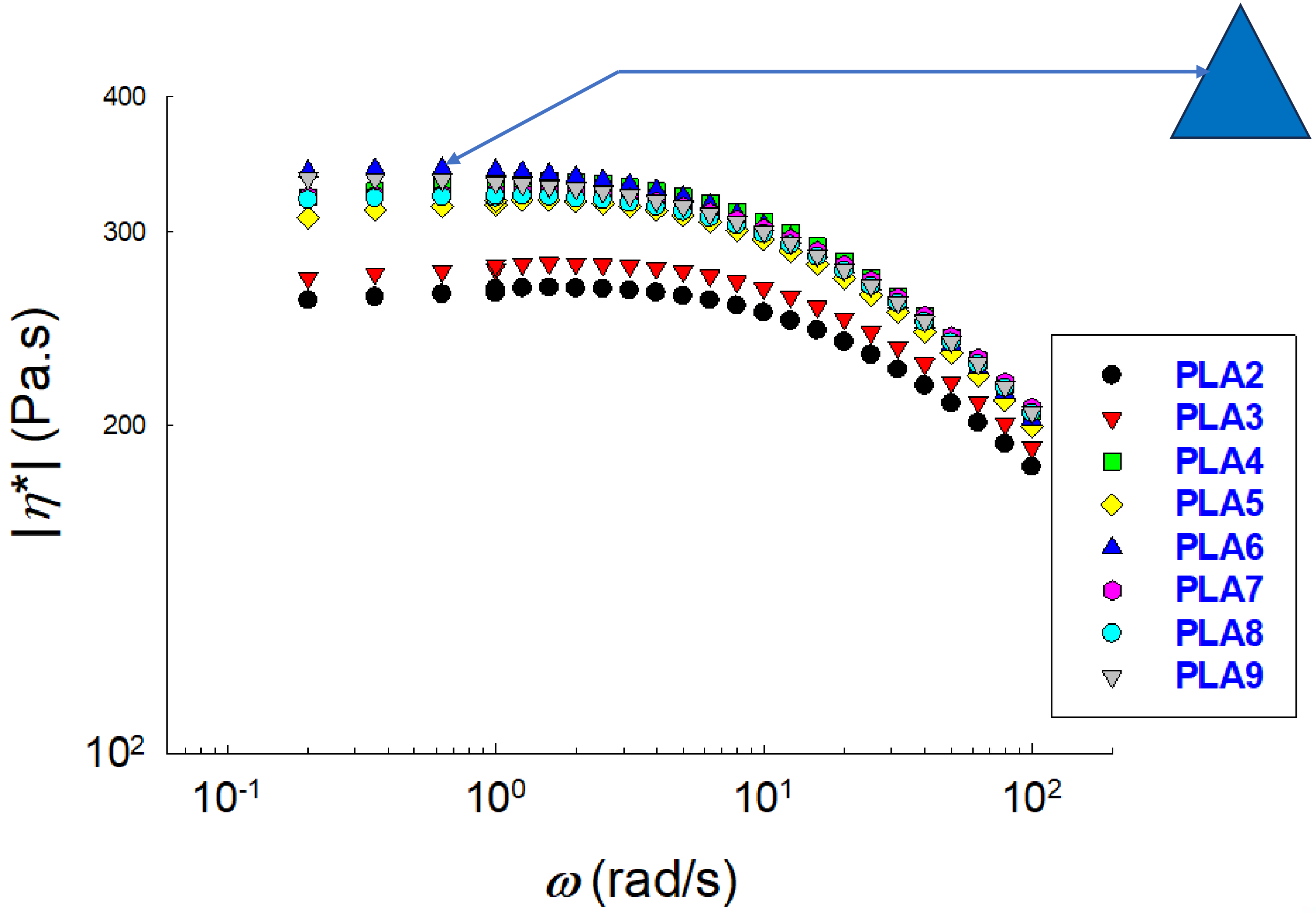
PLA5 is a big surprise. PLA5 was intended to represent the worst-case scenario as undried, unvented recycle. That is, PLA5 is reprocessed PLA2!

It's not clear how the viscosity can increase:

- Perhaps a chemical reaction.
- Perhaps a physical reduction in interstitial space between the polymer chains.

Whatever the cause, the implication is that degraded material, such as PLA recycle can be reprocessed where its viscosity will be like the virgin.

Torsional Rheometer Results: PLA6 Undried & Unvented



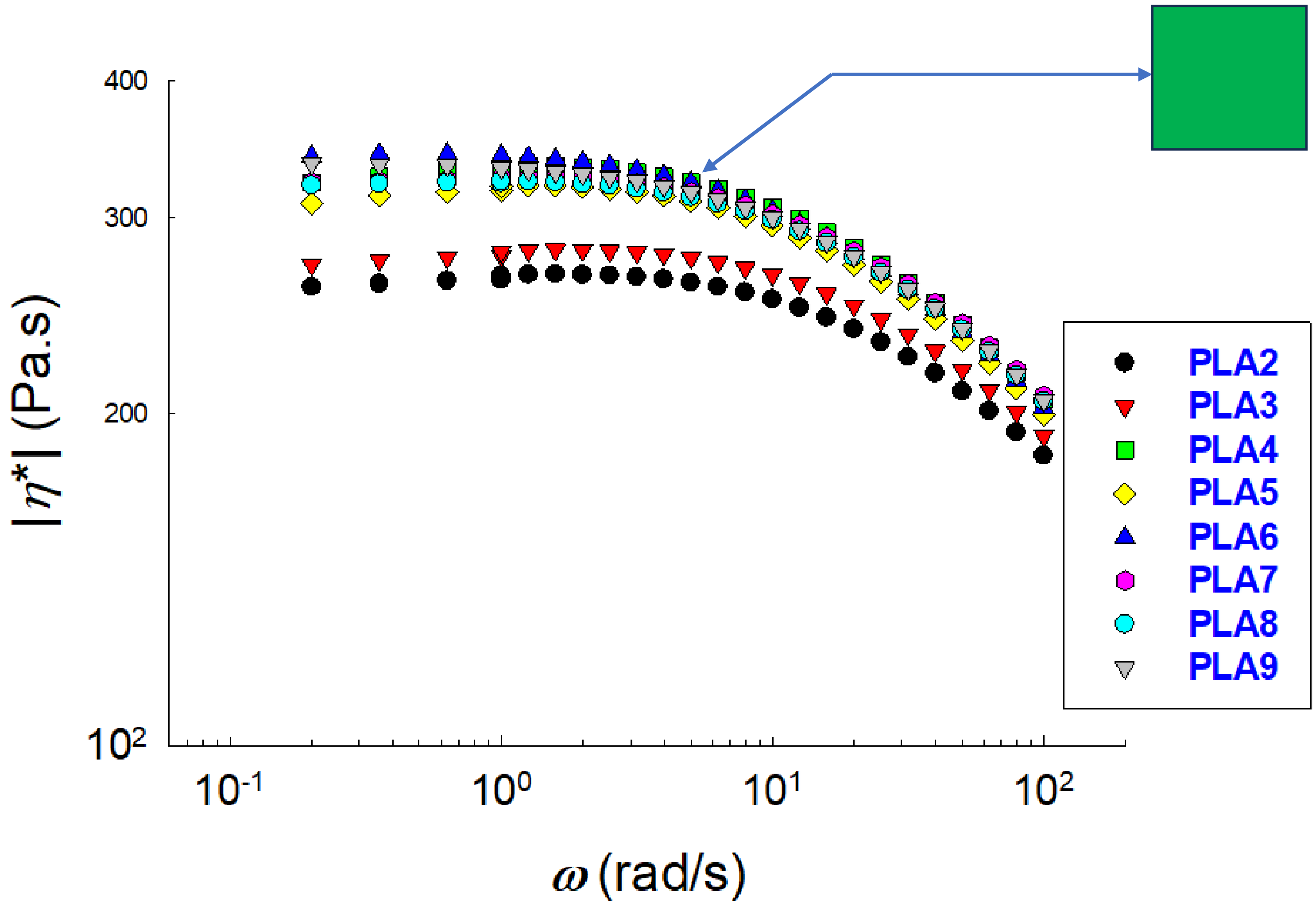
PLA6 is a surprise too. PLA6 was intended to represent the second worst-case scenario as it is PLA3 reprocessed!

Again, it's not clear how the viscosity can increase:

- Perhaps a chemical reaction.
- Perhaps a physical reduction in interstitial space between the polymer chains.

Whatever the cause, the result is consistent with the PLA5 result. That is, that reprocessed material (intending to represent vented recycle) can have improved viscosity—the same as the virgin.

Torsional Rheometer Results: PLA4 Undried & Unvented



PLA4 is the most intriguing surprise. PLA4 was intended to simulate an *undried* 50/50 production mix of virgin and once processed material (PLA8) *where neither was dried for this experiment.*

Again, it's not clear how the viscosity can increase. Whatever the cause, the result is consistent with PLA5 and PLA6 in that the reprocessed combination has improved viscosity—the same as the virgin.

What is wonderfully surprising is that nothing was dried and the viscosity is the same as the virgin! This implies that you don't have to dry PLA with recycle using the CSFEM.

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- The implication of the 50/50 mix—where neither material was dried—is potentially wonderful. After all, not only may drying not be necessary, but that using recycle can be the solution rather than the problem.

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- The dried virgin, i.e. “normal processing,” did not show degradation from the mixing.
- Beside the above, you get the unrivaled mixing where first compounding then extruding becomes unnecessary.

Further Testing:

- There are at least these possible reasons for surprising the increase in viscosity:
  - Crosslinking: This implies that gels would be created that would be obvious in a cast film compared to a virgin cast film. We plan to do this study soon and publish it on our website.
  - Three-dimensional mixing: During previous presentations, we showed X, Y, Z mixing in a single mixing element. Perhaps reorientation of the molecules into three dimensions changes the viscous behavior.
  - Space: It is known that the interstitial space between the polymer chains is uneven. Since space can be divided nearly to infinity, perhaps the space is becoming more uniform (mixed) and this affects the viscosity.
  - Some combination of the above.

Interested parties who would like to mutually investigate should call Keith Luker.

Thanks!

This paper was only possible because of the rheology done by Raj Krishnnaswamy, CJ Biomaterials.

INVESTING IN THE FUTURE OF OUR PLANET AND OUR LIVES

THE CLIMATE. RENEWABLE ENERGY. QUALITY OF LIFE. HUMAN HEALTH.

At CJ Biomaterials, we invent and manufacture biopolymers and bio-based chemicals. We do it because we have a long-term vision to introduce technologies that will help create a more sustainable future, offering true circular solutions to replace many non-recyclable, non-reusable and fossil fuel-based plastics and chemicals.

Professor Kirk Cantor, Phd., Plastics and Polymer Engineering Technology, Pennsylvania College of Technology


Any Questions