SME 2022: Lagging - Beyond the Capstan Equation

A deeper look into how the lagging and belt interact

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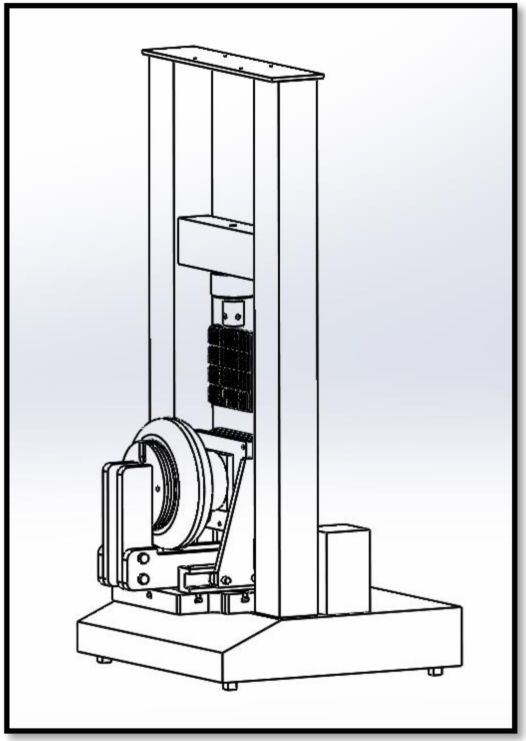
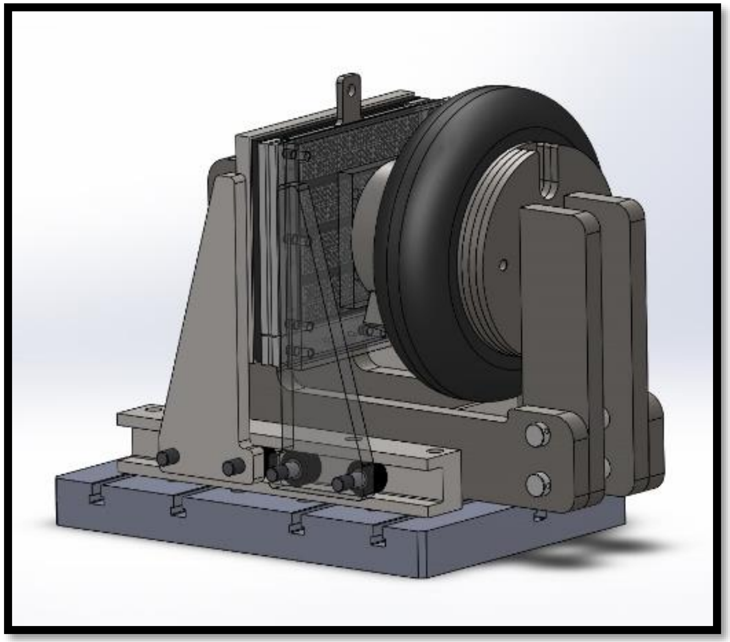
Background

- **Friction was measured for several lagging types using the below fixture**





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Background

- **These were the lagging samples**

Full ceramic	Medium ceramic	Diamond rubber ceramic	Diamond rubber	Plain rubber
				

- **Focus on three types**
  - Diamond rubber
  - Medium ceramic
  - Full ceramic

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Testing

- **Test goal was to observe the influence of increasing pressure on static and dynamic friction**

- **Record static & dynamic friction factors**

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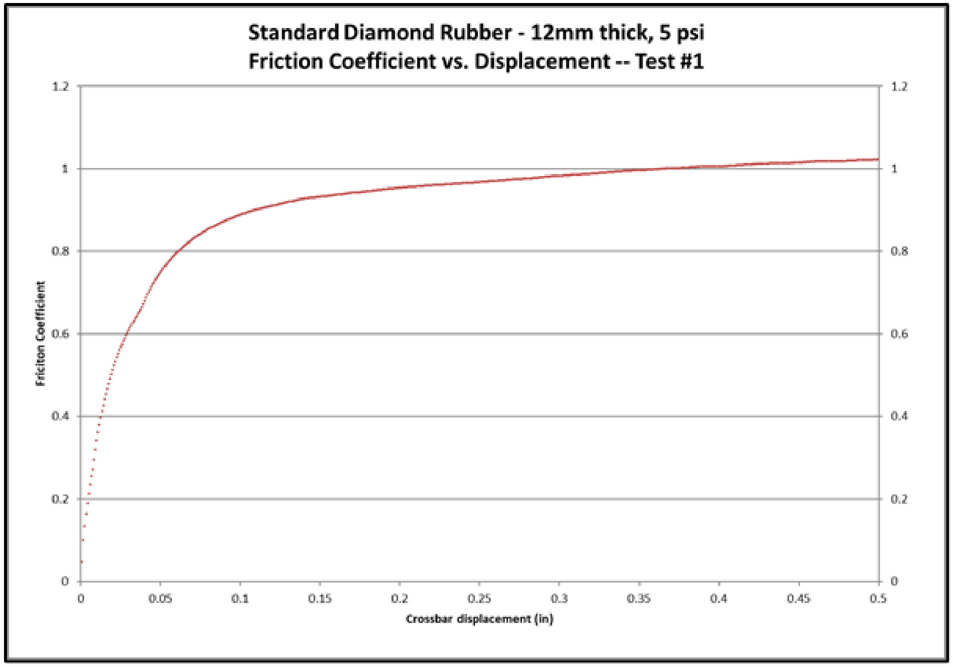
Testing

- **At 5 psi applied pressure, the data plotted as expected**



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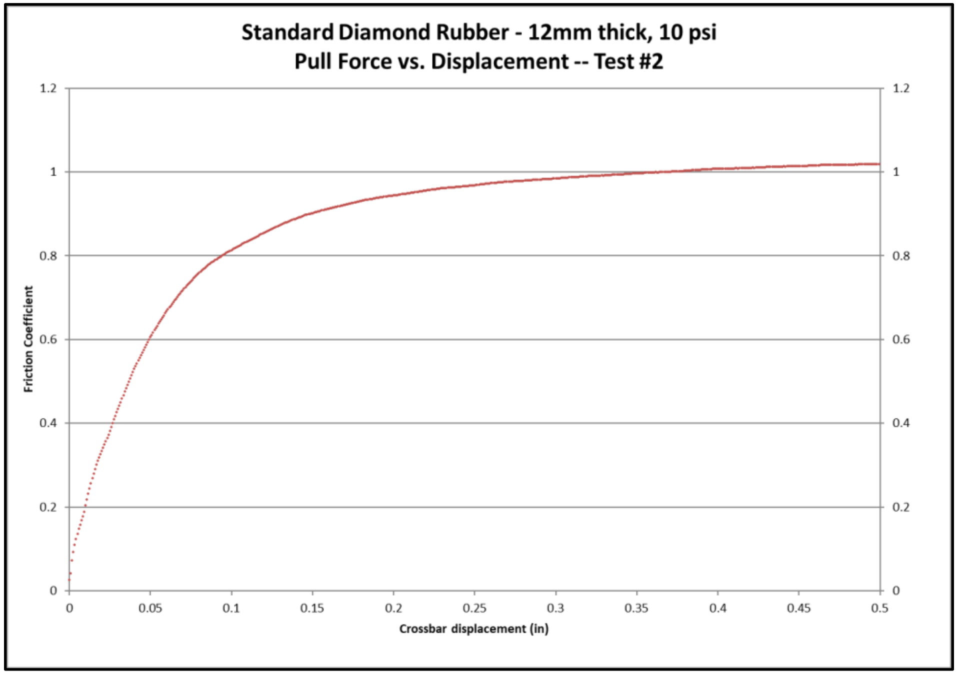
Testing

- 10 psi, the high friction took longer to develop, onset is getting fuzzy



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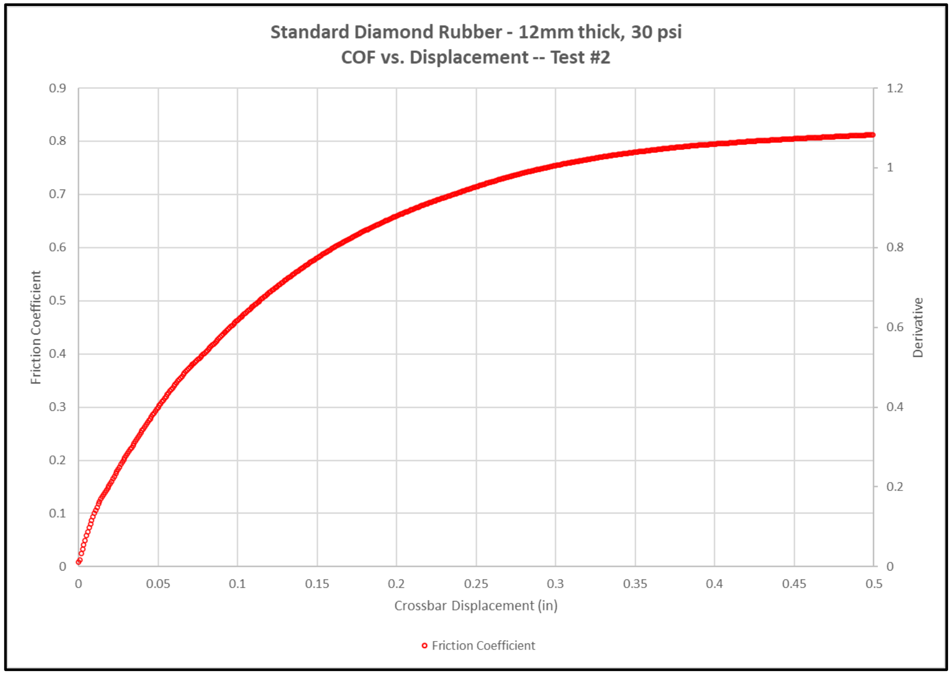
Testing

- **By 30 psi, it is very difficult to define a static or dynamic COF**



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Discovery

- **Other friction experts asserted that rubber friction was a function of slip history. (B.N.J Perrson)**
- **Is there an equation to predict friction as a function of crosshead displacement?**

- **Analysis found that:**

$$\mu = Ax\ln(x) - bx$$

Where *A* & *b* are pressure-based constants

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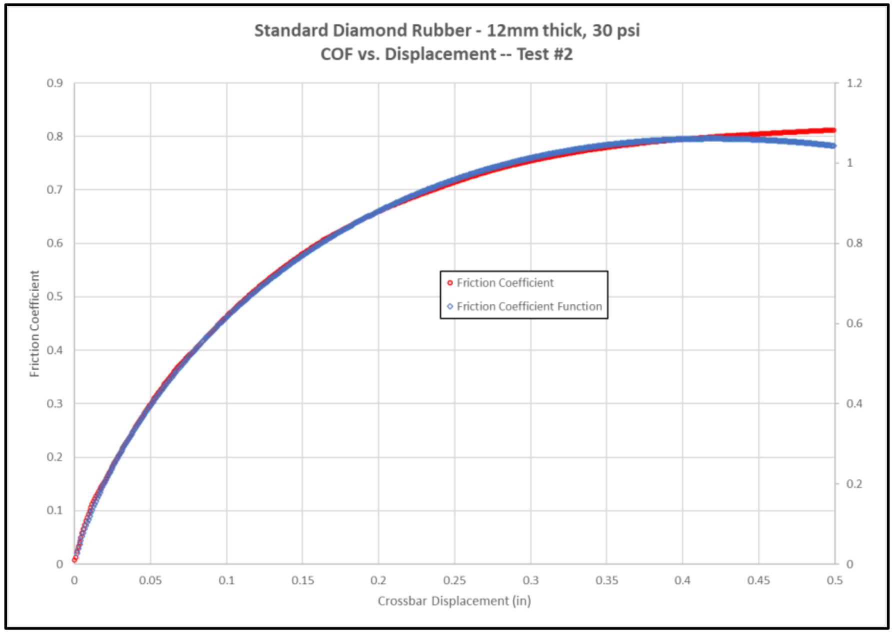
- **The function is a very good fit before 10mm of travel**

A = -1.896; b = -.251



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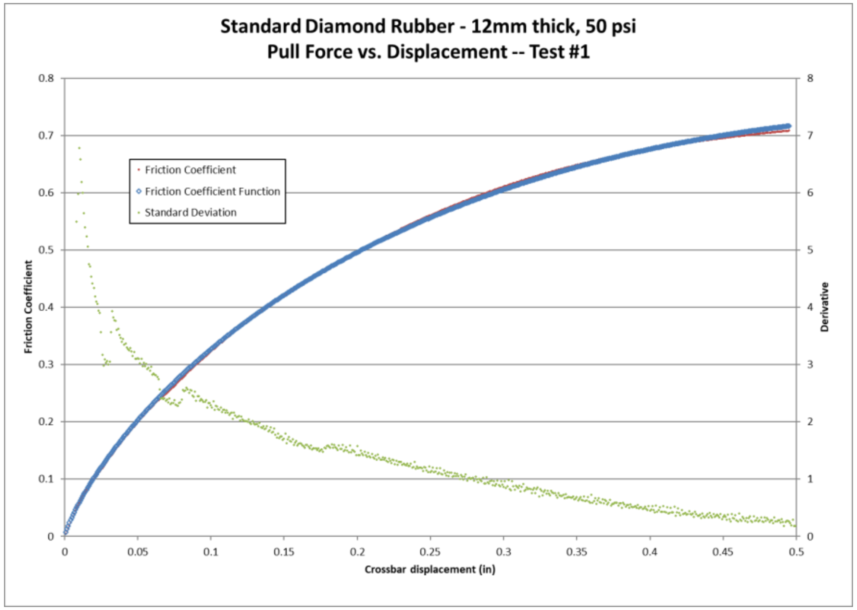
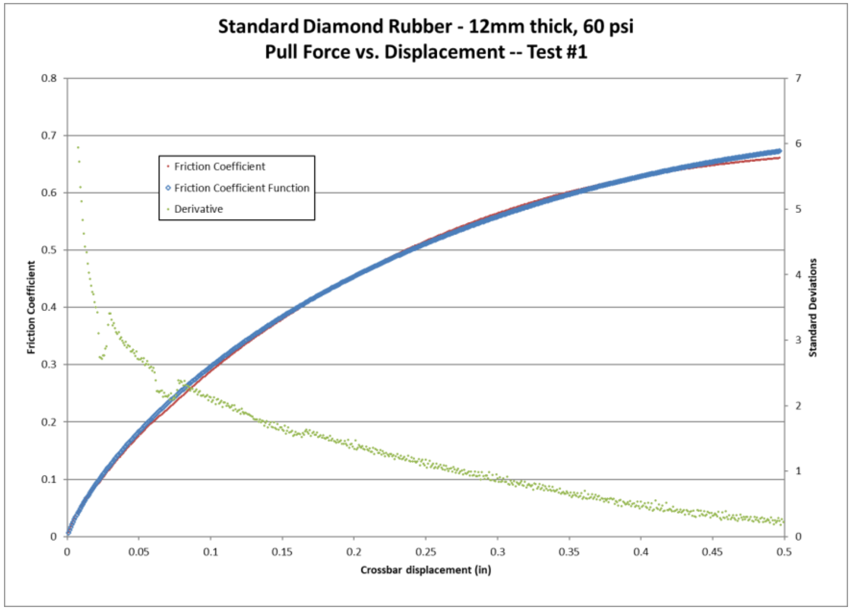
Discovery

This curve fitting (finding A & b) was repeated for other pressures





Looking good for 50 & 60 psi

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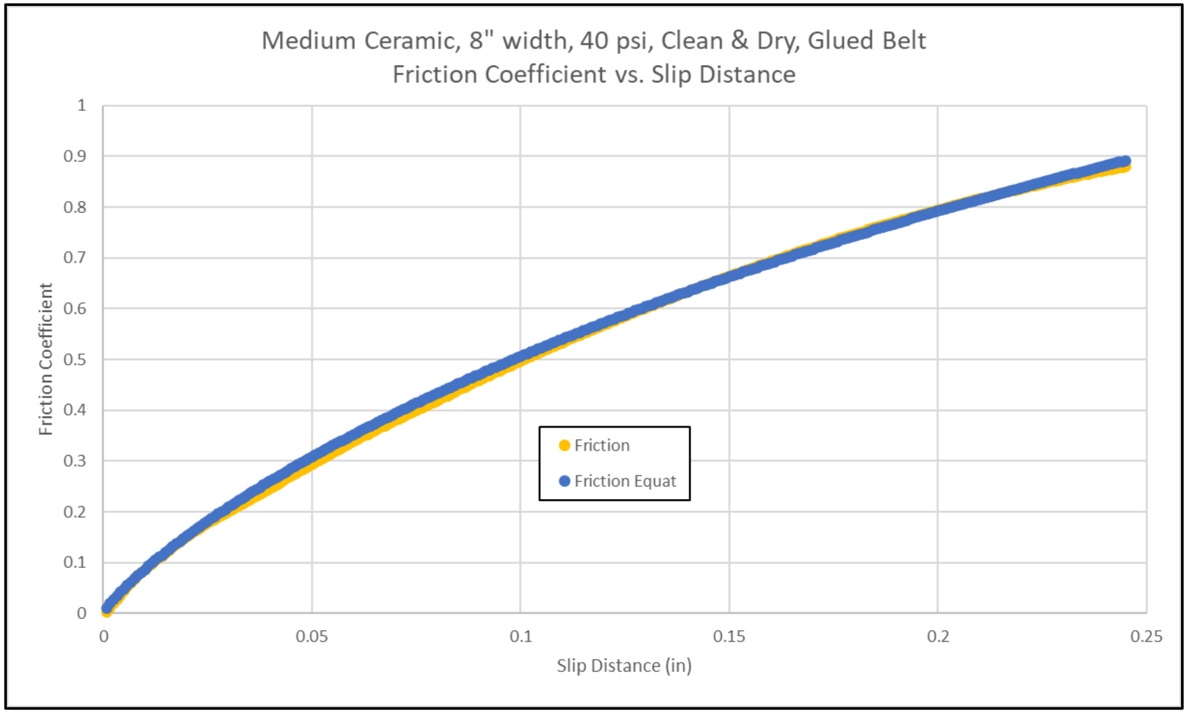
Discovery

This equation and curve fitting (finding A & b) holds true on medium ceramic



Looking good at 40 psi

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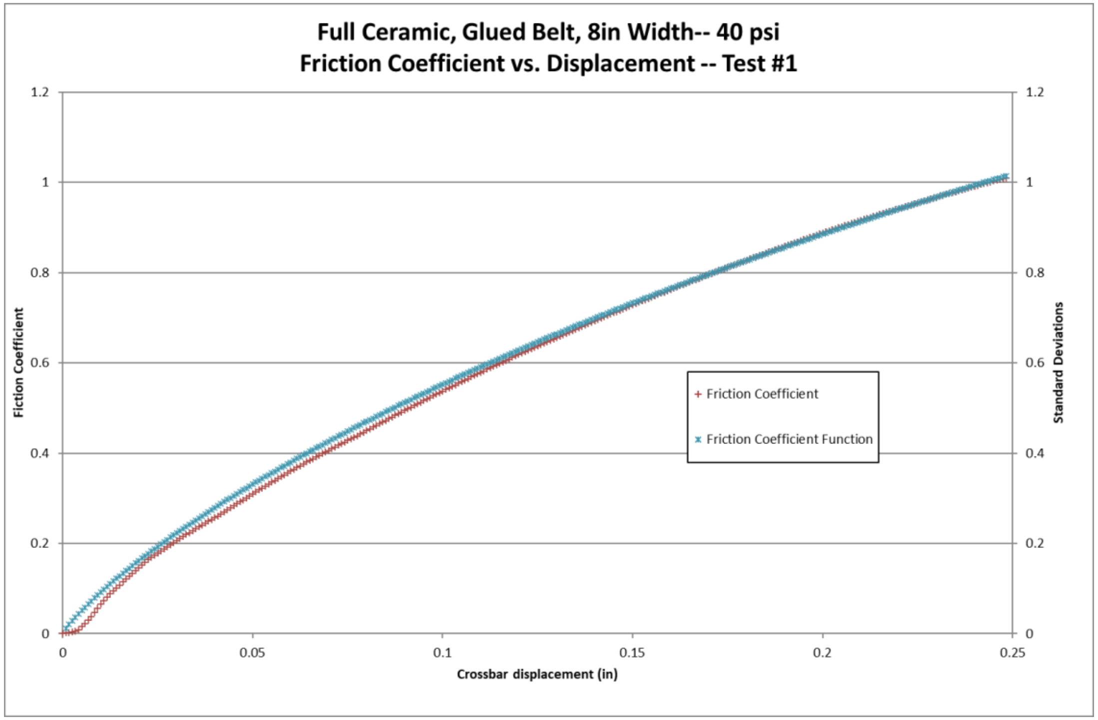
Discovery

This equation and curve fitting (finding A & b) also holds true on full ceramic



Looking good at 40 psi

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The constants

Application

- A & b have been found for all three lagging types at various pressures
- Next would be to find equations for A & b for each lagging type as a function of pressure
- With these equations, a model of a conveyor pulley would be able to instantaneously calculate wrap pressure at any location based on the local belt tension and then provide the A & b constants to create a local friction coefficient calculation

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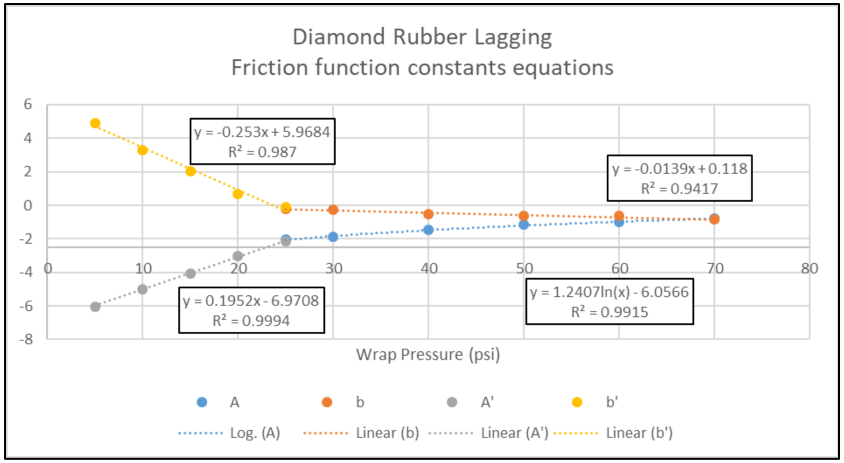
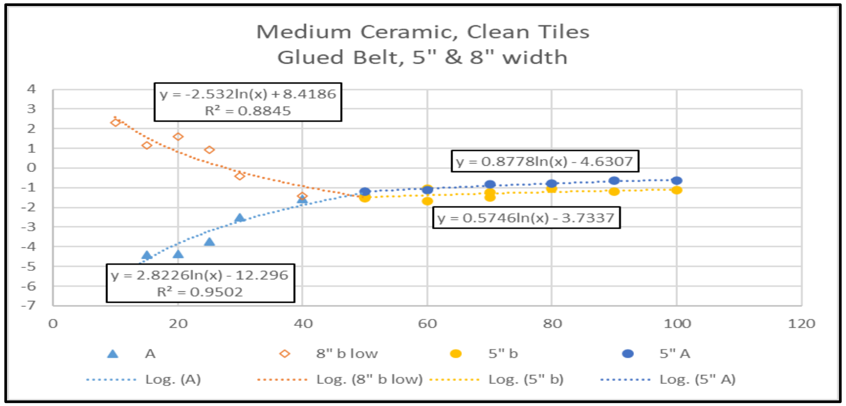
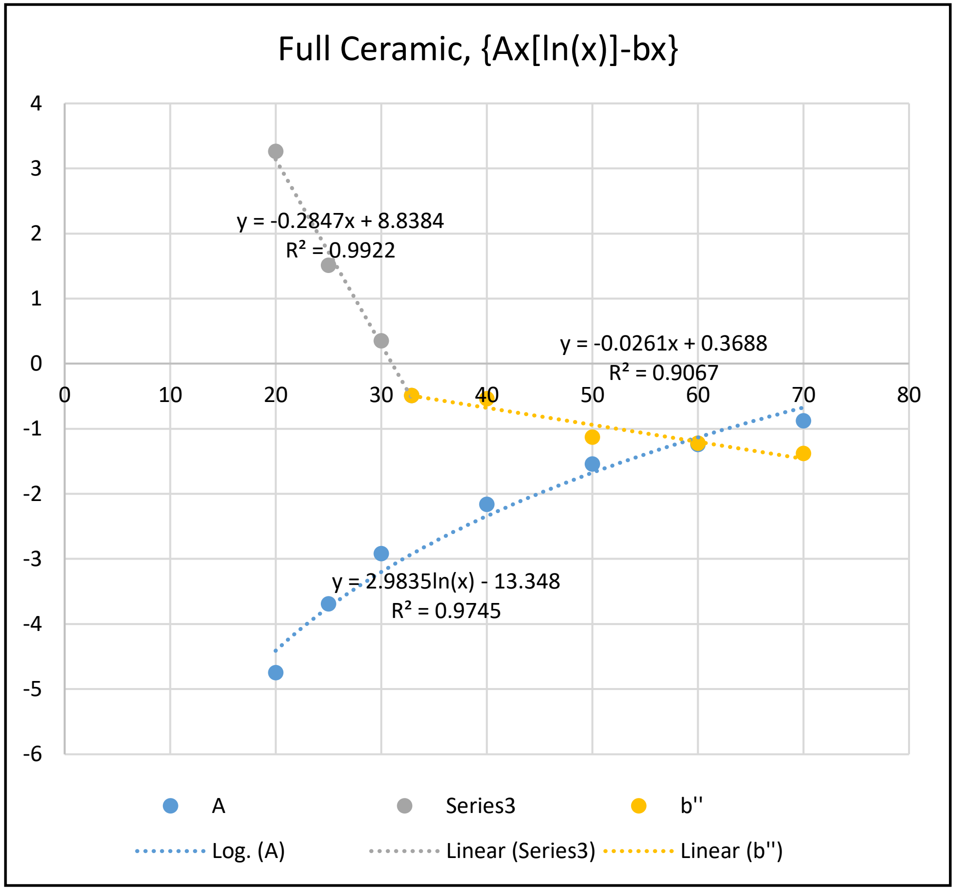
The constants

- **A & b have been calculated for the three lagging type data sets and plotted vs pressure**







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Recap

- **Lagging friction coefficient is based on creep history and is given by:**

$$\mu = Axln(x) - bx$$

- **A & b are calculated from equations that are pressure based**
- **So how do you calculate pressure?**

$$Pressure = \frac{2{*}PIW}{pulley\ diameter}$$

(Equation 6 in “Variant Friction Coefficients”)

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Recap

- We now have the math to predict the friction as both creep distance and pressure are changing
- But where does creep and pressure changes occur?
- Pressure will be changing as tension comes out of the belt
- Friction arises from creep, but creep results from tension change, which depends on local friction
- To predict total friction, local creep and friction need to calculated simultaneously

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Creep

Creep arises from three sources

- Compression of the lagging due to wrap pressure
- Shrinkage of the belt due to tension removal. This shrinkage zone is termed the “active arc”
- Global creep that generates extra friction to satisfy tension ratio requirements

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Compression of the lagging

- As the belt enters the pulley, the lagging compresses from the belt tension being wrapped on it
- This causes a small change in the diameter and the belt overruns the lagging slightly.
- This is a small creep amount (<1mm), but it works to kickstart the friction on the pulley

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Creep

Shrinkage of the belt

- Belts shrink as tension is removed, but how much?
- Belt manufacturers publish a Belt Modulus, which is a theoretical force to stretch a belt to double its original length
- Using an assumed active arc length and Belt Modulus, the spring rate of the shrinking belt can be calculated
- k=(belt modulus)/(active arc length)
- x=k/F, where F = ΔT

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Creep

Global Creep

- High Modulus belts, like steel cord do not shrink enough to create typical friction values
- A small amount of global creep occurs to generate the friction values typically used in drive design

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Calculator

An Excel calculator was created to calculate lagging friction

- Choose lagging type
- Enter data: pulley diameter, lagging thickness, T1, T2, wrap angle, belt modulus
- Balance: total slip, ΔT, assumed active arc length, and calculated final tension

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Calculator

Note lagging shear angle and total creep

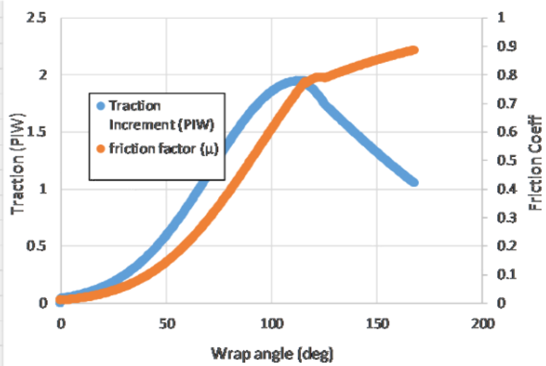
- 2.86° shear
- .463” creep

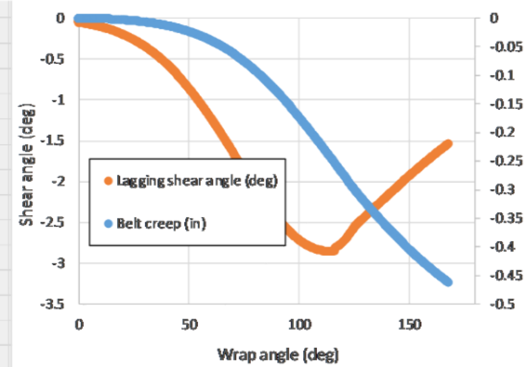
Diamond Rubber

$$x = t \times \tan\left(\frac{\tau}{G}\right)$$

48	Pulley Daimeter (in)
12	lagging thickness (mm)
290	PIW2
1062	PIW1
168	wrap angle (deg)
71.76	wrapped arc length
1170	Rubber Elastic modulus
390	Rubber Shear Modulus
74000	belt modulus (lb/in)
0.1	length increment (in)

0	Global creep (in)
0.017523	radius change (in)
2.135623	length of 5° original diameter
2.134094	length after compression
0.001529	pre-heat creep (in)
0.4633	Total creep (in)
45.49	Active arc length - assumed (in)
1626.754	belt spring rate (lb/in)
106.5	Active arc (degrees)





2.86205 <--Max Shear angle | 1.948 | 25.78932 <--Pressu

772 <--Delta PIW | 19.48136 <--Max Tr

772.3434518 <--Traction sum for entire wrap angle

Wrap angle	Wrap arc length (in)	Distance before the end of the active arc	Wrap Pressure (psi)	A	b	A'	b'	PIW	Belt creep (in)	friction factor (µ)	Traction Increment (PIW)	Lagging shear angle (deg)	Wrap angle	Belt creep (in)	Lagging shear angle (deg)	Traction Increment (PIW)	Applied Traction (psi)
		45.4						1062.34			772.3434518						
168.0	0	0	11.85006	-2.98918	-0.04672	-4.62504	3.080554	290	0.4633000	0.88623938	1.050199371	1.542872	168	-0.4633	-1.54287	1.050199371	10.50199
168.0	0	0	11.85006	-2.98918	-0.04672	-4.62504	3.080554	290	0.46336876	0.88623938	1.050199371	1.542872	168	-0.46337	-1.54287	1.050199371	10.50199
167.8	0.1	0.1	11.89298	-2.98469	-0.04731	-4.61664	3.069834	291.0502	0.46272318	0.88582741	1.053512584	1.547739	167.7659	-0.46272	-1.54774	1.053512584	10.53513
167.5	0.2	0.2	11.93603	-2.98021	-0.04791	-4.60822	3.05908	292.1037	0.4620354	0.88541414	1.056832697	1.552617	167.5318	-0.46204	-1.55262	1.056832697	10.56833
167.3	0.3	0.3	11.97921	-2.97573	-0.04851	-4.59977	3.048293	293.1605	0.46134549	0.88499957	1.060159698	1.557505	167.2976	-0.46135	-1.5575	1.060159698	10.6016

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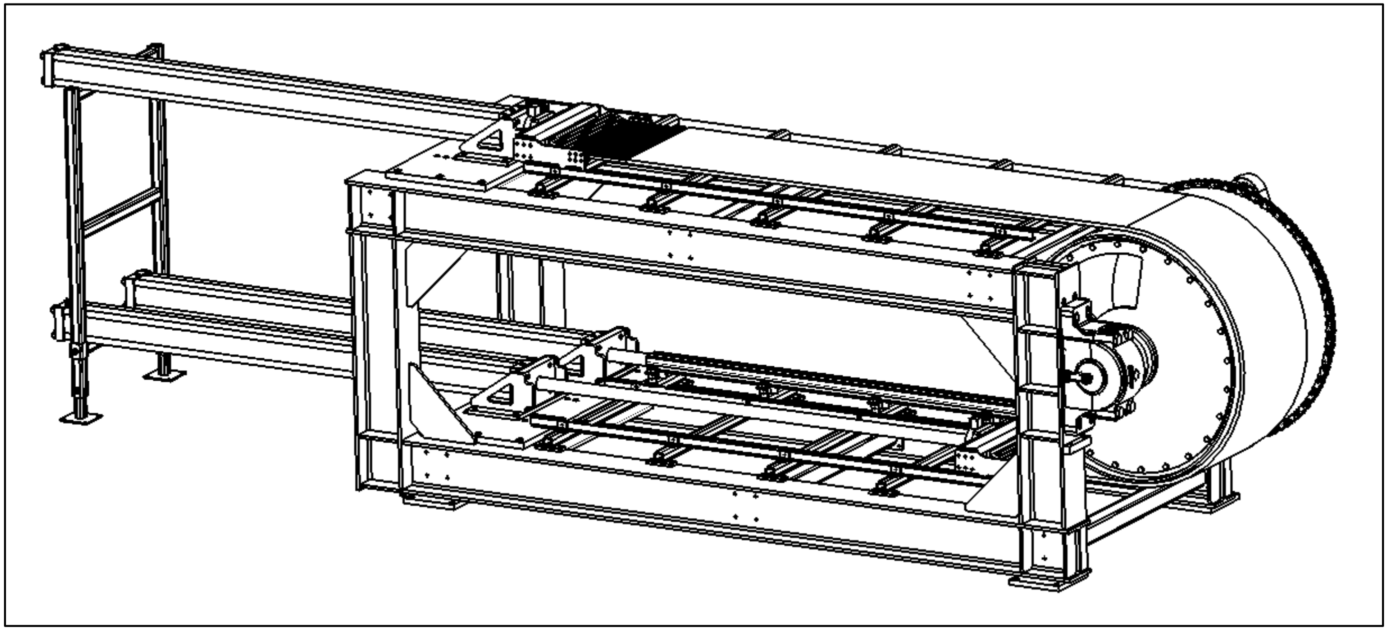
Calculator

How to we verify these calculations?

Test rig with pulley data ("Surface Dynamics of Pulleys" – Beltcon 19**)**



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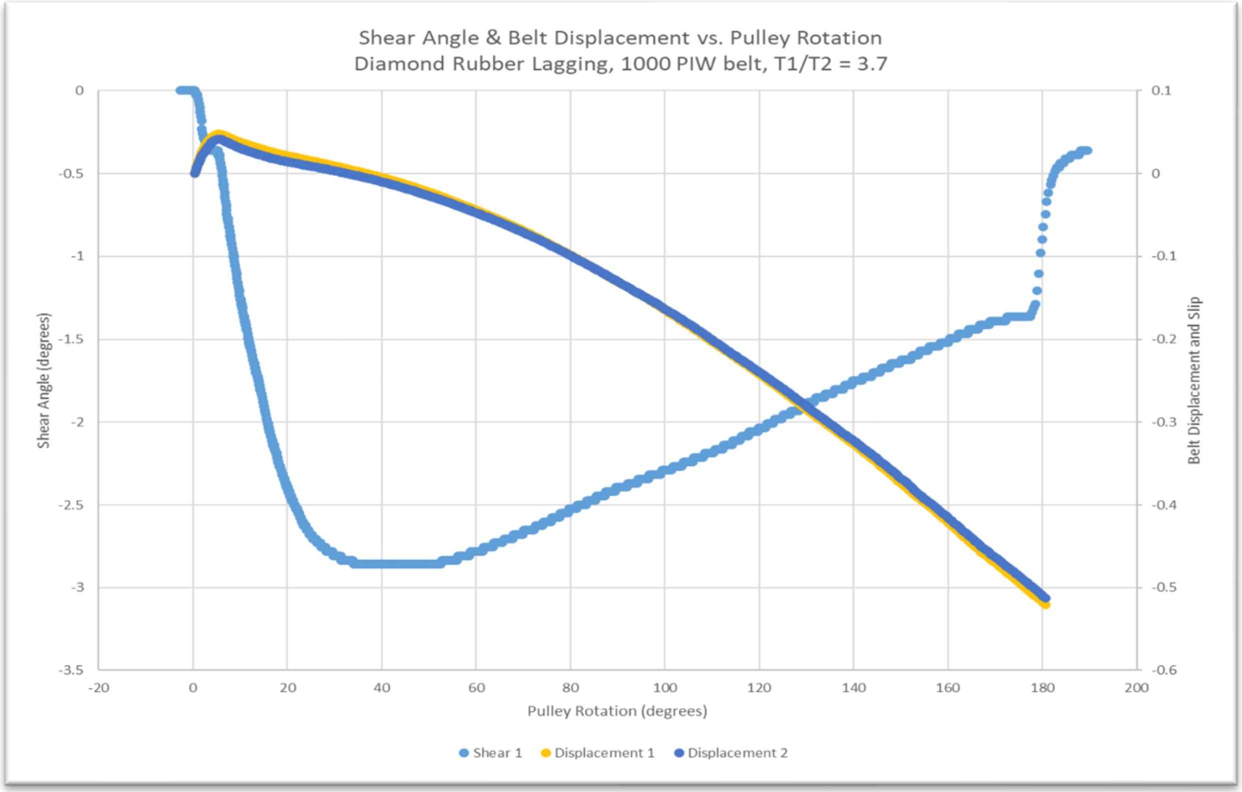
Calculator

Data from “Pulley Surface Dynamics” research

- 2.86° shear measured
- .513” creep measured



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Conclusion

There is no singular friction factor for pulley lagging

- **CEMA, DIN have conventional values**
- **Depending on conveyor parameters, these values can be upped if additional creep can be tolerated**

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Conclusion

Lagging Selection:

- **Best lagging choice comes down to minimizing creep at an acceptable cost**
  - Pulley diameter and belt modulus are in play
  - Conventional factors like T1/T2, lagging type, and lagging thickness
- **However, a rule of thumb would be**
  - Rubber lagging: 30 psi or less
  - Medium ceramic: 30 psi to 60 psi
  - Full ceramic: 60 psi to 90 psi
  - Avoid pressures greater than 90 psi

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Conclusion

Lagging will not eliminate creep, not even ceramic

- All lagging types require creep to generate friction due to the nature of rubber
- Thicker lagging will not eliminate creep

Note: Creep under pressure generates heat, which can be considered as a root cause for some lagging failures

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Conclusion

So what do I do if I don't have the calculator?

Calculator results have been converted to COF for a few samples

- Note the effect tension has on the results
- Note the effect belt modulus has on the results
- Note the effect pulley diameter has on the results

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Conclusion

Diamond Rubber Lagging, 12mm, Clean & Dry conditions, Ply belt, 180° wrap												
Calculated μ required using Euler formula to match results												
	T1 Tension (PIW)											
	100	200	300	400	500	600	700	800	900	1000	1200	1800
Belt Modulus	23000	23000	34500	44000	60000	66000	56250	88000	62532	74000	132000	125064
Max slip	.250"	.250"	.250"	.250"	.275"	.300"	.325"	.325"	.325"	.394"	.394"	.394"
10	0.70	0.50	x	x	x	x	x	x	x	x	x	x
12	0.73	0.54	x	x	x	x	x	x	x	x	x	x
14	0.73	0.56	0.46	x	x	x	x	x	x	x	x	x
16	0.77	0.59	0.48	0.40	x	x	x	x	x	x	x	x
18	0.77	0.59	0.49	0.41	0.40	0.38	x	x	x	x	x	x
20	0.77	0.59	0.49	0.41	0.41	0.40	x	x	x	x	x	x
22	x	x	0.48	0.41	0.42	0.40	x	x	x	x	x	x
24	x	x	x	0.40	0.43	0.41	x	x	x	x	x	x
26	x	x	x	x	0.42	0.41	0.34	0.38	0.28	x	x	x
28	x	x	x	x	0.41	0.40	0.34	0.38	0.28	x	x	x
30	x	x	x	x	x	x	0.35	0.38	0.30	0.33	0.37	x
32	x	x	x	x	x	x	0.37	0.38	0.31	0.33	0.37	x
34	x	x	x	x	x	x	0.38	0.37	0.32	0.34	0.38	x
36	x	x	x	x	x	x	x	x	x	0.35	0.38	0.24
38	x	x	x	x	x	x	x	x	x	0.37	0.38	0.23
40	x	x	x	x	x	x	x	x	x	0.38	0.37	0.24
42	x	x	x	x	x	x	x	x	x	0.40	0.36	0.25
44	x	x	x	x	x	x	x	x	x	0.41	0.36	0.26
46	x	x	x	x	x	x	x	x	x	0.42	0.37	0.27
48	x	x	x	x	x	x	x	x	x	0.43	0.38	0.28
50	x	x	x	x	x	x	x	x	x	0.44	0.39	0.29
		<-- Yellow highlight indicates min pulley sized specified by belt manufacturer										

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Conclusion

Medium Ceramic Lagging, 15mm, Clean & Dry conditions, Ply belt, 180° wrap

Calculated μ required using Euler formula to match results

	T1 Tension (PIW)											
	100	200	300	400	500	600	700	800	900	1000	1200	1800
Belt Modulus	23000	23000	34500	44000	60000	66000	56250	88000	62532	74000	132000	125064
Max creep	.250"	.250"	.250"	.250"	.275"	.300"	.325"	.325"	.325"	.394"	.394"	.394"
Pulley Diameter (inches)												
10	0.73	0.60	x	x	x	x	x	x	x	x	x	x
12	0.77	0.64	x	x	x	x	x	x	x	x	x	x
14	0.77	0.65	0.56	x	x	x	x	x	x	x	x	x
16	0.77	0.65	0.57	0.49	x	x	x	x	x	x	x	x
18	0.77	0.65	0.57	0.50	0.49	0.46	x	x	x	x	x	x
20	0.80	0.63	0.56	0.50	0.51	0.47	x	x	x	x	x	x
22	x	x	0.53	0.48	0.51	0.48	x	x	x	x	x	x
24	x	x	x	0.49	0.51	0.48	x	x	x	x	x	x
26	x	x	x	x	0.49	0.47	0.40	0.45	0.34	x	x	x
28	x	x	x	x	0.49	0.46	0.43	0.44	0.35	x	x	x
30	x	x	x	x	x	x	0.45	0.44	0.37	0.39	0.44	x
32	x	x	x	x	x	x	0.47	0.43	0.39	0.41	0.44	x
34	x	x	x	x	x	x	0.49	0.45	0.40	0.42	0.44	x
36	x	x	x	x	x	x	x	x	x	0.44	0.43	0.30
38	x	x	x	x	x	x	x	x	x	0.45	0.42	0.31
40	x	x	x	x	x	x	x	x	x	0.47	0.41	0.33
42	x	x	x	x	x	x	x	x	x	0.49	0.42	0.33
44	x	x	x	x	x	x	x	x	x	0.51	0.44	0.34
46	x	x	x	x	x	x	x	x	x	0.52	0.46	0.35
48	x	x	x	x	x	x	x	x	x	0.54	0.47	0.36
50	x	x	x	x	x	x	x	x	x	0.55	0.49	0.37

<-- Yellow highlight indicates min pulley sized specified by belt manufacturer

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Conclusion

Medium Ceramic Lagging, 15mm, Clean & Dry conditions, Ply belt, 180° wrap

Calculated μ required using Euler formula to match results

	Belt Tension Rating														
	ST800	ST1000	ST1250	ST1400	ST1600	T1800	ST2000	ST2250	ST2500	ST3150	ST3500	ST4000	ST4500	ST5000	ST5400
T1 PIW	685	860	1070	1195	1370	1535	1720	1920	2140	2690	2985	3440	3840	4280	4605
Belt Modulus	329000	411000	514000	576000	658000	740000	822000	925000	1030000	1295000	1439000	1640000	1850000	2055000	2220000
Max creep	.250"	.250"	.250"	.250"	.250"	.275"	.300"	.325"	.325"	.350"	.350"	.350"	.350"	.350"	.350"
Pulley Diameter (inches)															
20	0.52	0.44	x	x	x	x	x	x	x	x	x	x	x	x	x
22	0.52	0.47	x	x	x	x	x	x	x	x	x	x	x	x	x
24	0.54	0.50	0.42	0.38	x	x	x	x	x	x	x	x	x	x	x
26	0.54	0.51	0.44	0.40	x	x	x	x	x	x	x	x	x	x	x
28	x	0.53	0.47	0.43	0.38	0.37	x	x	x	x	x	x	x	x	x
30	x	x	0.49	0.45	0.40	0.39	x	x	x	x	x	x	x	x	x
32	x	x	0.51	0.47	0.42	0.41	0.40	0.39	x	x	x	x	x	x	x
34	x	x	x	x	0.44	0.43	0.42	0.41	x	x	x	x	x	x	x
36	x	x	x	x	0.45	0.45	0.44	0.43	0.39	x	x	x	x	x	x
38	x	x	x	x	0.47	0.46	0.45	0.44	0.41	x	x	x	x	x	x
40	x	x	x	x	x	x	0.45	0.45	0.42	0.37	0.33	x	x	x	x
42	x	x	x	x	x	x	x	x	0.44	0.39	0.35	x	x	x	x
44	x	x	x	x	x	x	x	x	0.44	0.40	0.36	x	x	x	x
46	x	x	x	x	x	x	x	x	x	0.41	0.38	x	x	x	x
48	x	x	x	x	x	x	x	x	x	0.42	0.39	0.34	0.30	x	x
50	x	x	x	x	x	x	x	x	x	0.43	0.40	0.35	0.31	x	x
52	x	x	x	x	x	x	x	x	x	0.43	0.41	0.37	0.33	x	x
54	x	x	x	x	x	x	x	x	x	x	x	0.38	0.34	0.30	0.27
56	x	x	x	x	x	x	x	x	x	x	x	0.39	0.35	0.31	0.28
58	x	x	x	x	x	x	x	x	x	x	x	0.40	0.36	0.32	0.29
60	x	x	x	x	x	x	x	x	x	x	x	0.40	0.37	0.34	0.31

<-- Yellow highlight indicates min pulley sized specified by belt manufacturer

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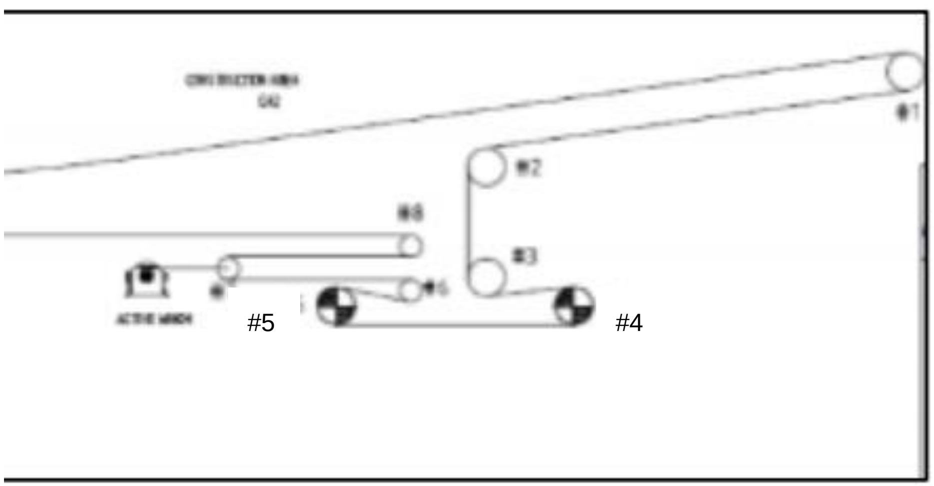
A long ST1250 belt in South America has the drive configuration shown below

- #4 is the first drive
- #5 is the second drive
- Since the belt runs directly between them, you would expect #5 to have less wear since it is the lower tension pulley



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Example

7.4 POLEA 04

Polea DRIVE (Polea 4) FAJ019-P04					
Distancia de medición (mm)	Posición	Espesor Nominal (mm)	Espesor Actual (mm)	Desgaste Actual (mm)	% Desgaste
200	A	20	**14.62**	5.38	26.9%
400	B	20	**13.8**	6.2	31.0%
600	C	20	**13.45**	6.55	32.75%
800	D	20	**13**	7	35.0%
1000	E	20	**13.1**	6.9	34.5%
			DESGASTE MÁX.	**6.9**	**35.0%**

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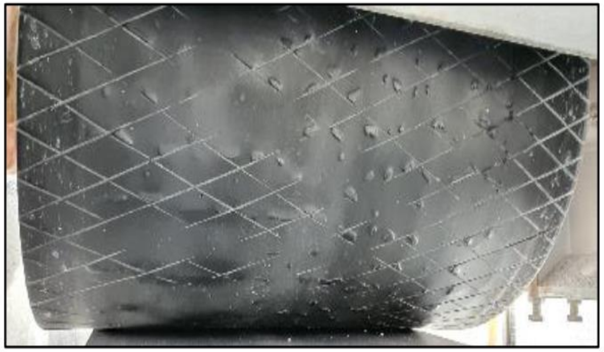
Example

- **Pulley #5 has more wear! Why?**

7.5 POLEA 05



Polea DRIVE (Polea 5) FAJ019-P05					
Longitud total de la polea: 1160 mm					
Distancia de medición (mm)	Posición	Espesor Nominal (mm)	Espesor Actual (mm)	Desgaste Actual (mm)	% Desgaste
200	A	20	**15.2**	4.8	24.0%
400	B	20	**13.98**	6.02	30.1%
600	C	20	**11.8**	8.2	41.0%
800	D	20	**13.2**	6.8	34.0%
1000	E	20	**12.65**	7.35	36.75%
			DESGASTE MÁX.	**7.35**	**41.0%**

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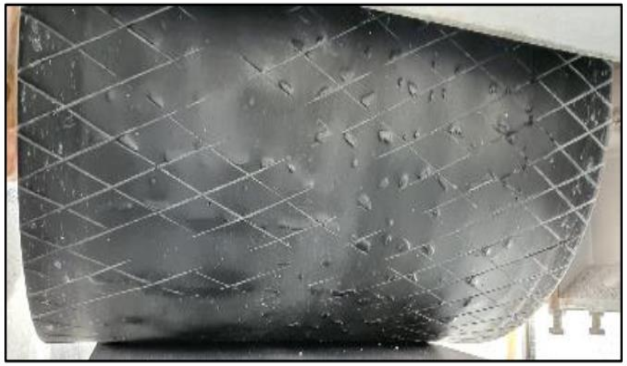
Example

- **Pulley #5 has more wear (41% vs. 35%)**
- **Does creep driven friction explain this?**

7.5 POLEA 05



Polea DRIVE (Polea 5) FAJ019-P05					
Longitud total de la polea: 1160 mm					
Distancia de medición (mm)	Posición	Espesor Nominal (mm)	Espesor Actual (mm)	Desgaste Actual (mm)	% Desgaste
200	A	20	**15.2**	4.8	24.0%
400	B	20	**13.98**	6.02	30.1%
600	C	20	**11.8**	8.2	41.0%
800	D	20	**13.2**	6.8	34.0%
1000	E	20	**12.65**	7.35	36.75%
			DESGASTE MÁX.	**7.35**	**41.0%**

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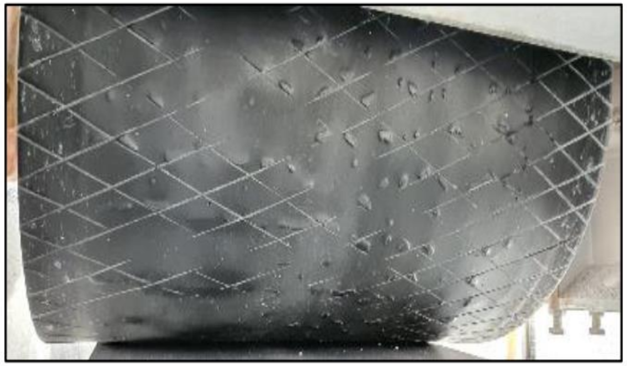
Example

- **The calculator says pulley #5 has more creep at the same torque as #4**
- **If the RPMs are identical, #5 will experience repeated small breakaway events increasing wear.**

7.5 POLEA 05



Polea DRIVE (Polea 5) FAJ019-P05					
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600	C	20	**11.8**	8.2	41.0%
800	D	20	**13.2**	6.8	34.0%
1000	E	20	**12.65**	7.35	36.75%
			DESGASTE MÁX.	**7.35**	**41.0%**

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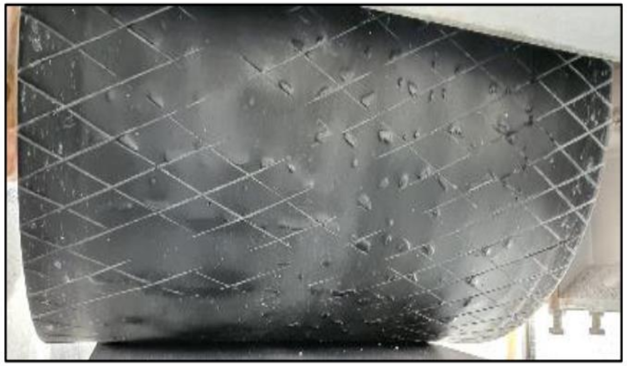
Example

- **To eliminate breakaway, #4 should run at 103.52 RPM, but #5 should be at 103.53 RPM**

- **Small difference but explains why the lower pressure pulley has more wear**

7.5 POLEA 05



Polea DRIVE (Polea 5) FAJ019-P05					
Longitud total de la polea: 1160 mm					
Distancia de medición (mm)	Posición	Espesor Nominal (mm)	Espesor Actual (mm)	Desgaste Actual (mm)	% Desgaste
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800	D	20	**13.2**	6.8	34.0%
1000	E	20	**12.65**	7.35	36.75%
			DESGASTE MÁX.	**7.35**	**41.0%**

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Conclusion

Questions?

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