



Investigation and comparison of hardness meters

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Outline

- Background
 - Hardness definition
 - Evolution of the hardness tester
 - Measuring hardness
- Comparison of hardness testers
 - Filtrona DHT and Cerulean QTM 7
 - Comparison to Eastman model
- Discrepancies between testers

Outline

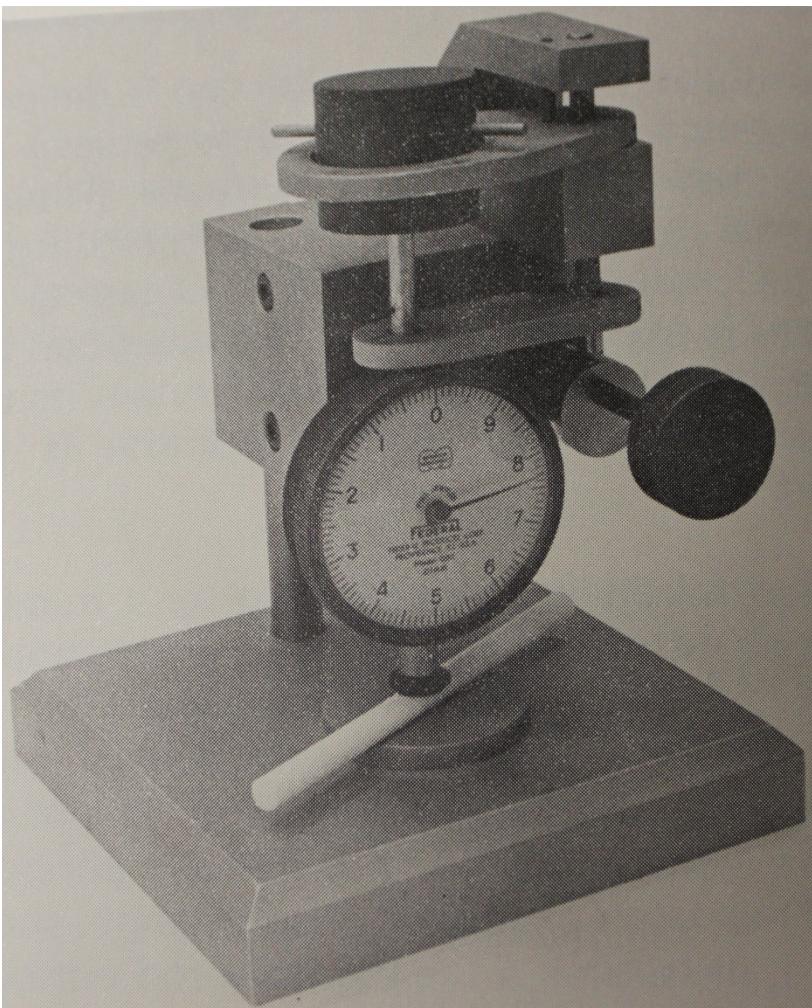
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Hardness

The firmness or rigidity of a filter rod, expressed in units that relate to the degree of deflection or deformation of the rod when subjected to a standard force exerted over a standard area.

Importance of hardness → perception of quality

Eastman HT-1



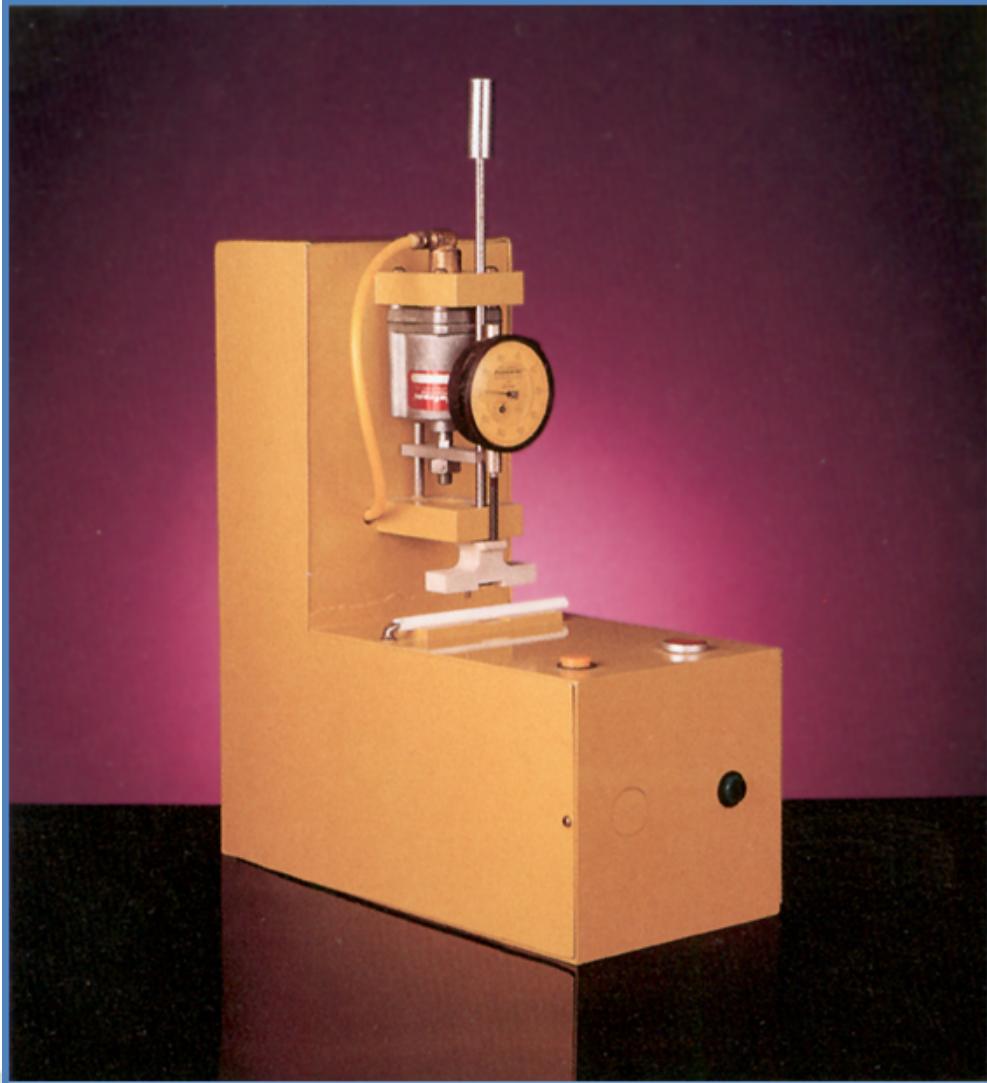
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Filtrona Hardness and Resilience Tester Mark 4E



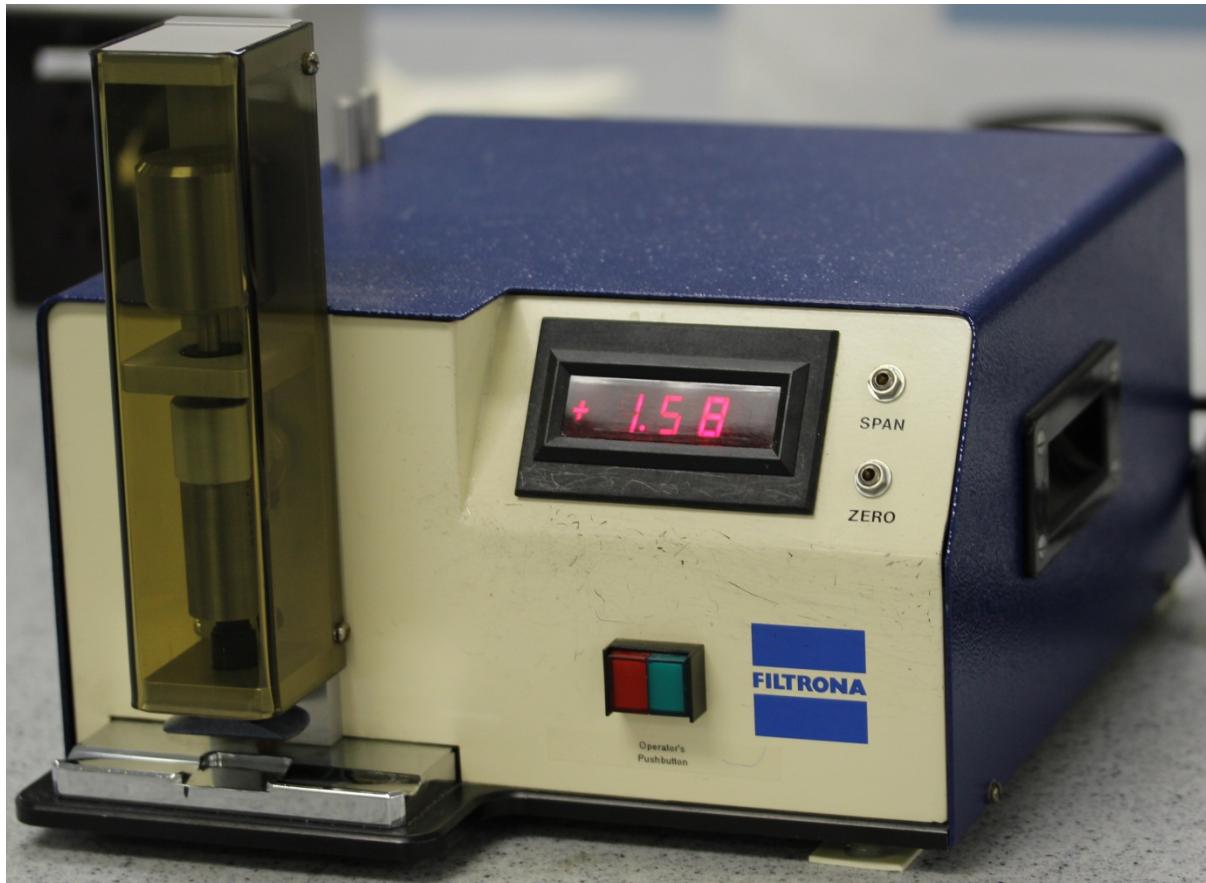
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Eastman HT-2



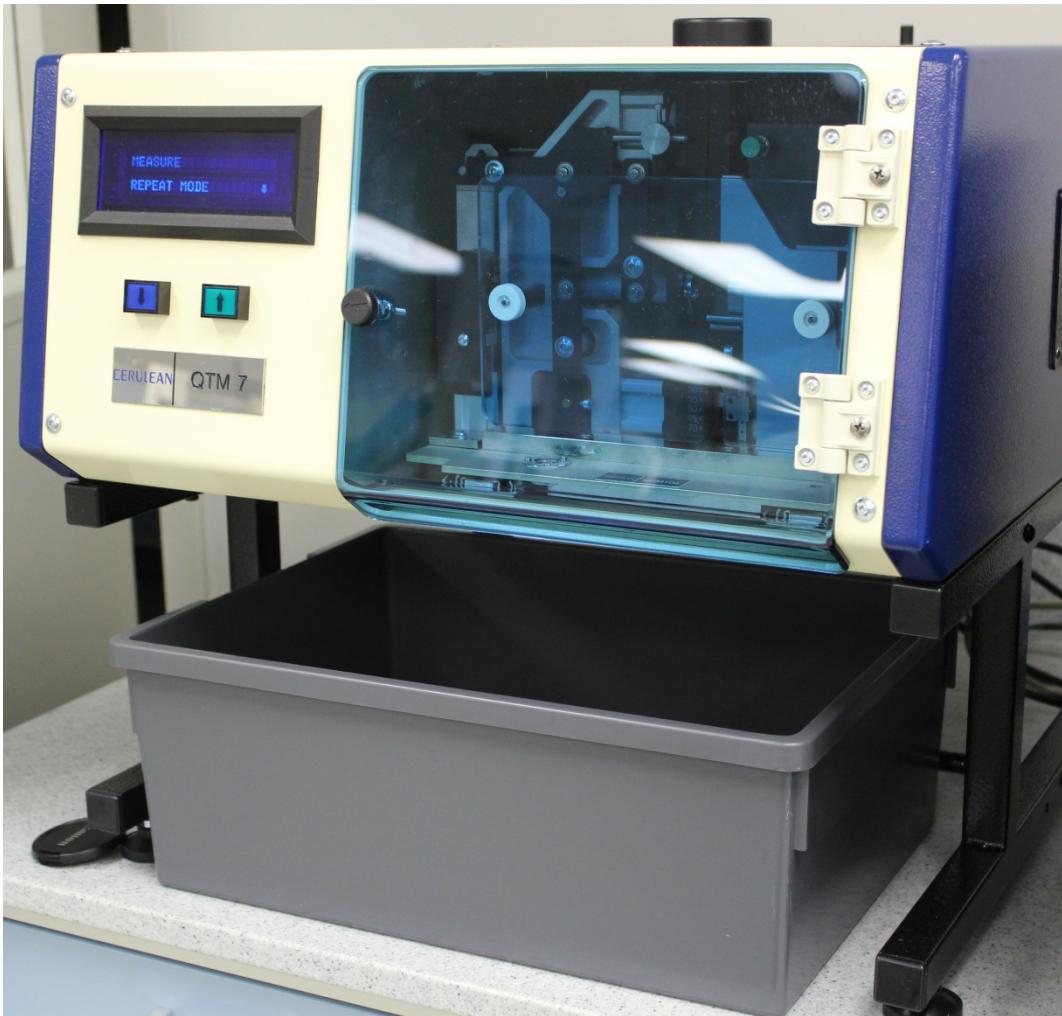
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Filtrona Digital Hardness Tester



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Cerulean QTM 7



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Measuring hardness

- Suppliers
 1. Borgwaldt
 2. Cerulean (formerly Filtrona Instruments)
 3. Sodim
 4. Burghart
 5. Toshi
- Calculate hardness in similar ways

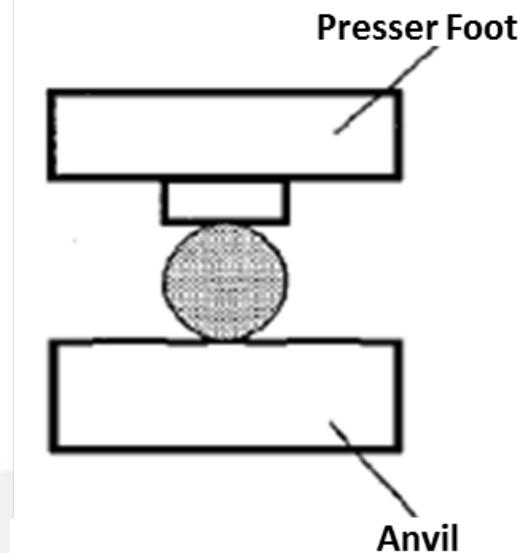
$$\%H = \frac{\text{compressed diameter}}{\text{original diameter}} \times 100$$

Filtrona Digital Hardness Tester

$$\%H = \frac{\frac{C}{\Pi} - P}{\frac{C}{\Pi}} \times 100$$

C = circumference of rod

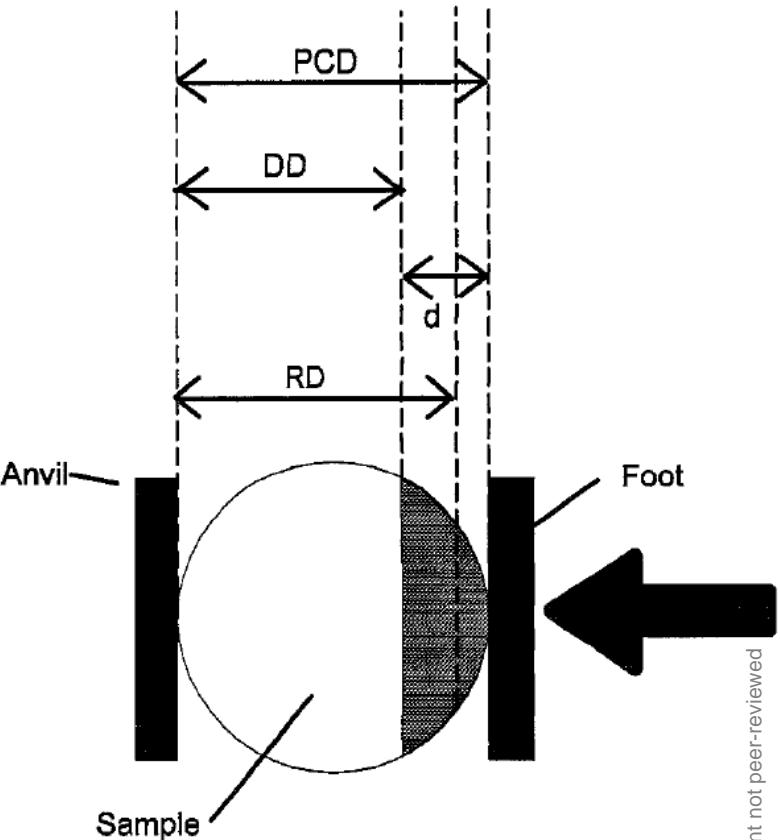
P = penetration of weighted shoe



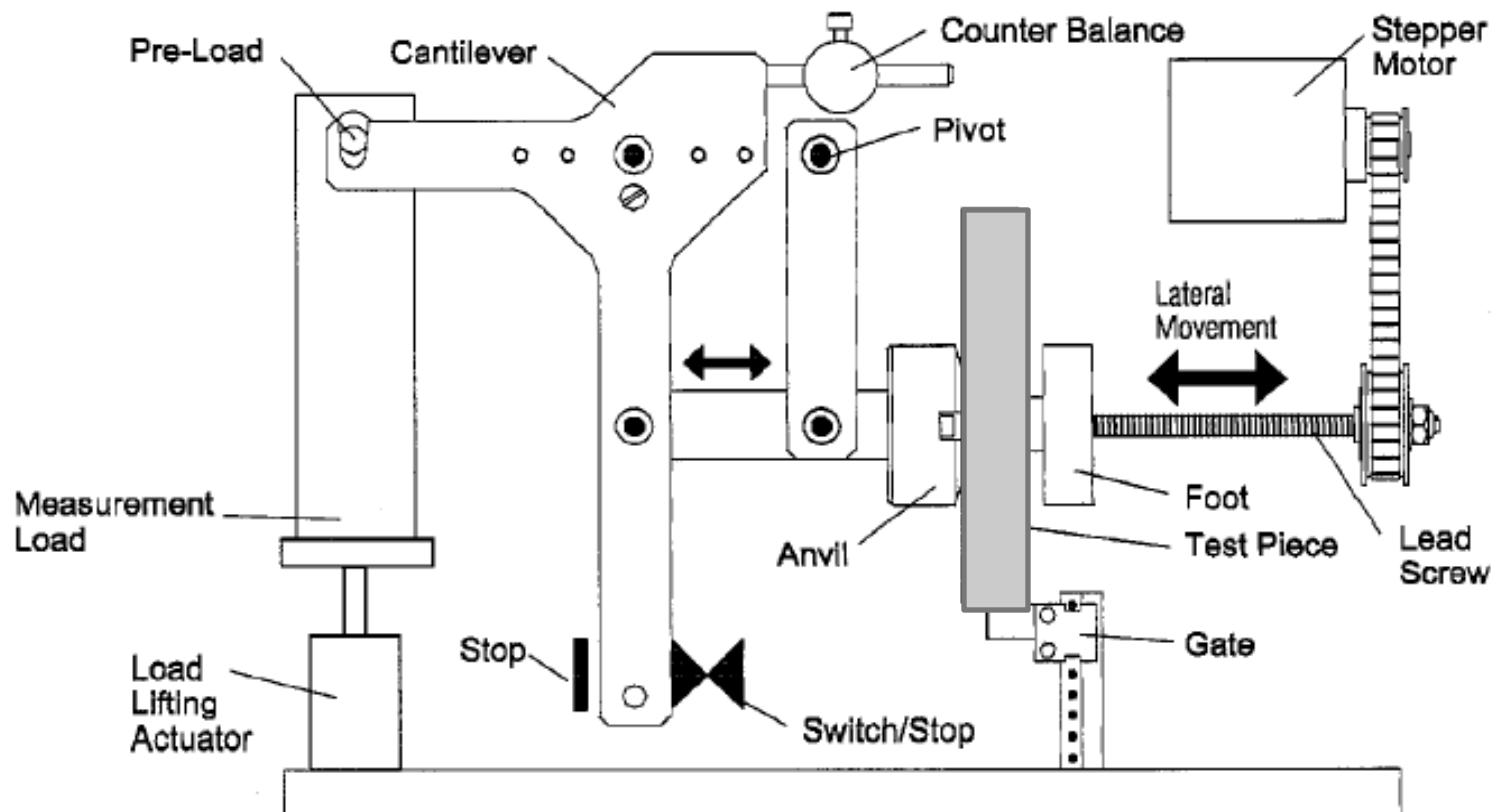
Cerulean QTM 7

4 Measurements

1. Point Contact Diameter (PCD)
2. Depressed Diameter (DD)
3. Relaxed Diameter (RD)
4. Depression (d)



Measurements



Calculated values

- % Hardness (%H)

$$\%H = \frac{DD}{PCD} \times 100$$

- % Resilience (%R)

$$\%R = \frac{RD}{PCD} \times 100$$

- % Resilience Return

$$\%RR = \frac{RD - DD}{DD}$$

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Comparison of hardness testers

Parameter	DHT	QTM
Pre-load	N/A	10 g
Load	300 g	300 g
Load duration	15 sec	10 sec
Compression speed	~0.5 mm/sec*	2.0 mm/sec
Presser foot shape	Flat, 12 mm diameter	Flat, 12 mm diameter
Anvil shape	Flat	Flat
Diameter measurement	Independent	Integrated
Filter rod orientation	Horizontal	vertical

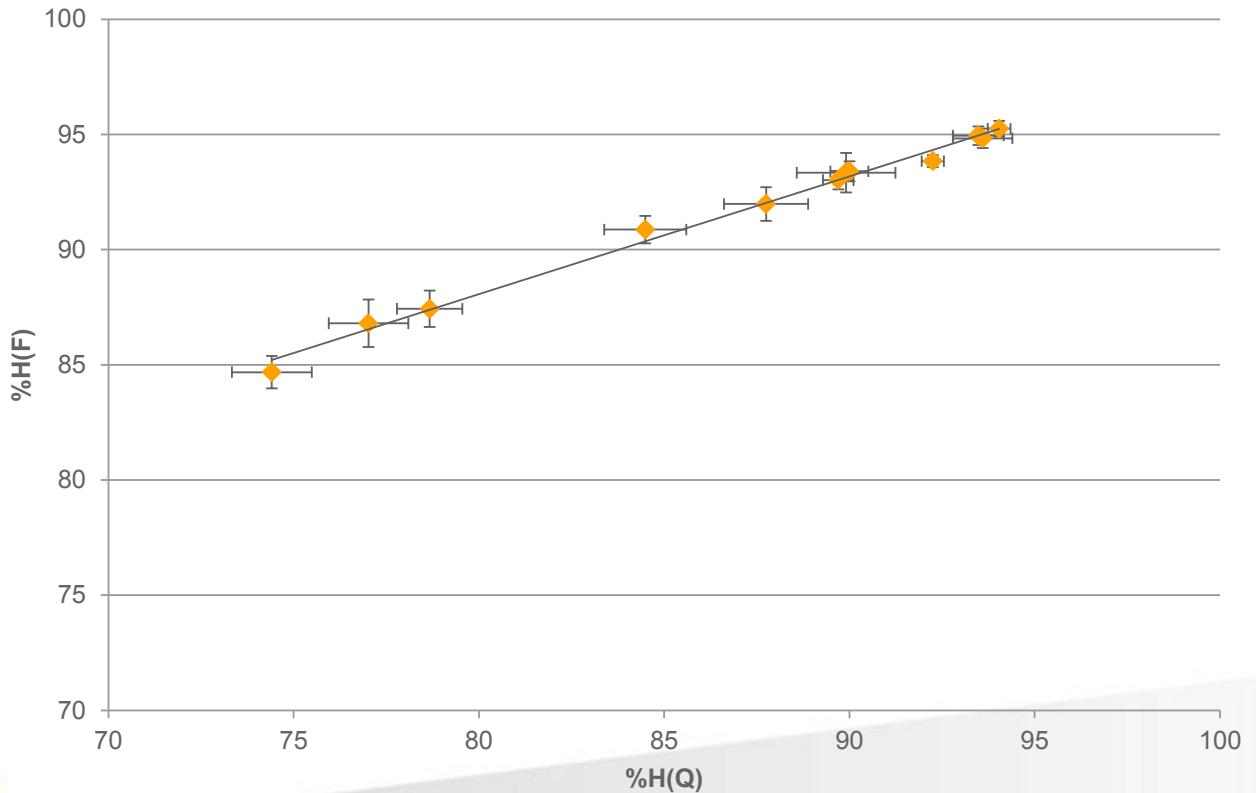
*manual estimate

Experimental

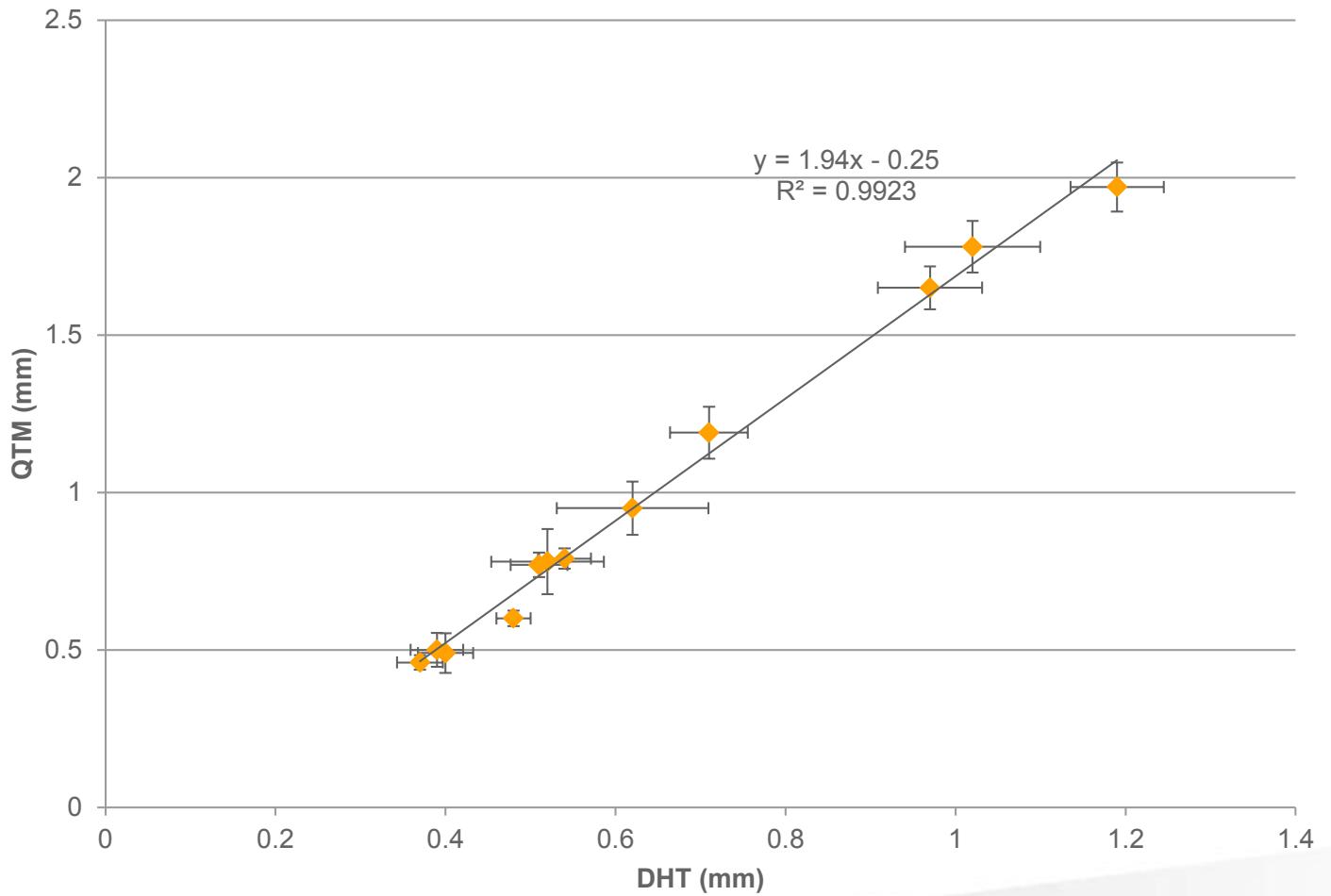
- Rods from 4 different tow items tested on each instrument
 1. 2.0/Y/33
 2. 2.9/Y/31
 3. 2.8/Y/34
 4. 5.3/Y/34
- 10 rods each at three different rod weights
- Mean values plotted for
 1. depression
 2. %H
 3. %R
 - n = 10
 - Error bars = $\pm \frac{2\sigma}{\sqrt{n}}$

%H(Q) v %H(F)

Regression	R ²	Equation
Linear	0.9928	$F = 0.51(Q) + 47.20$
2 nd Order Poly (int = 0)	0.9957	$F = -0.0066(Q)^2 + 1.63(Q)$

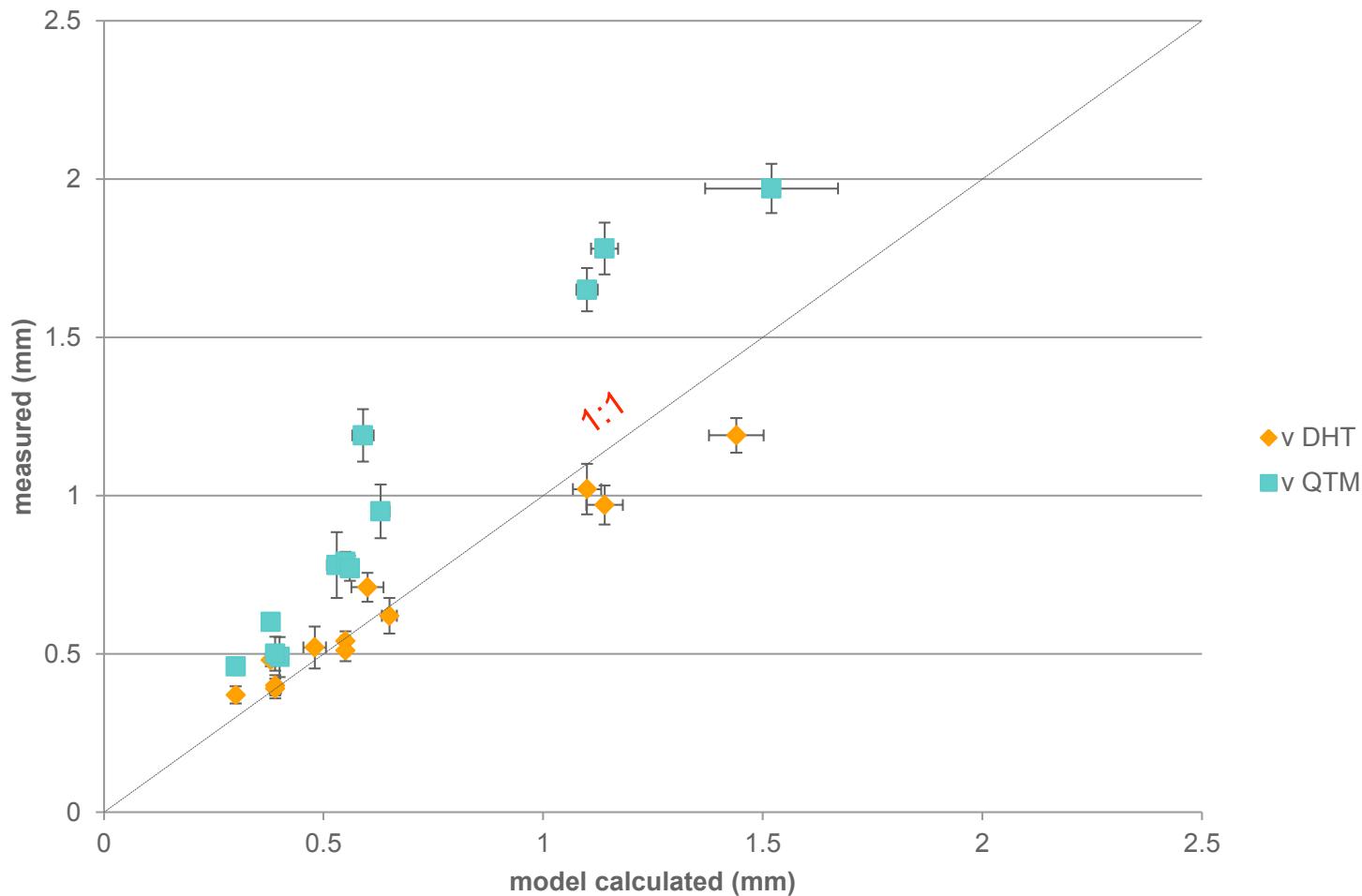


Depression



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Comparison to model calculations



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Discrepancies between testers

Penetration values for QTM 7 are ~2x those at the DHT

Why?

1. Parameters

- Load amount
- Settling time
- Pre-load
- Speed of compression

2. Mechanical functioning of DHT

- Dirt and grime buildup
- Frictional discrepancies
- Rod compression discrepancies

3. Circumference measurements

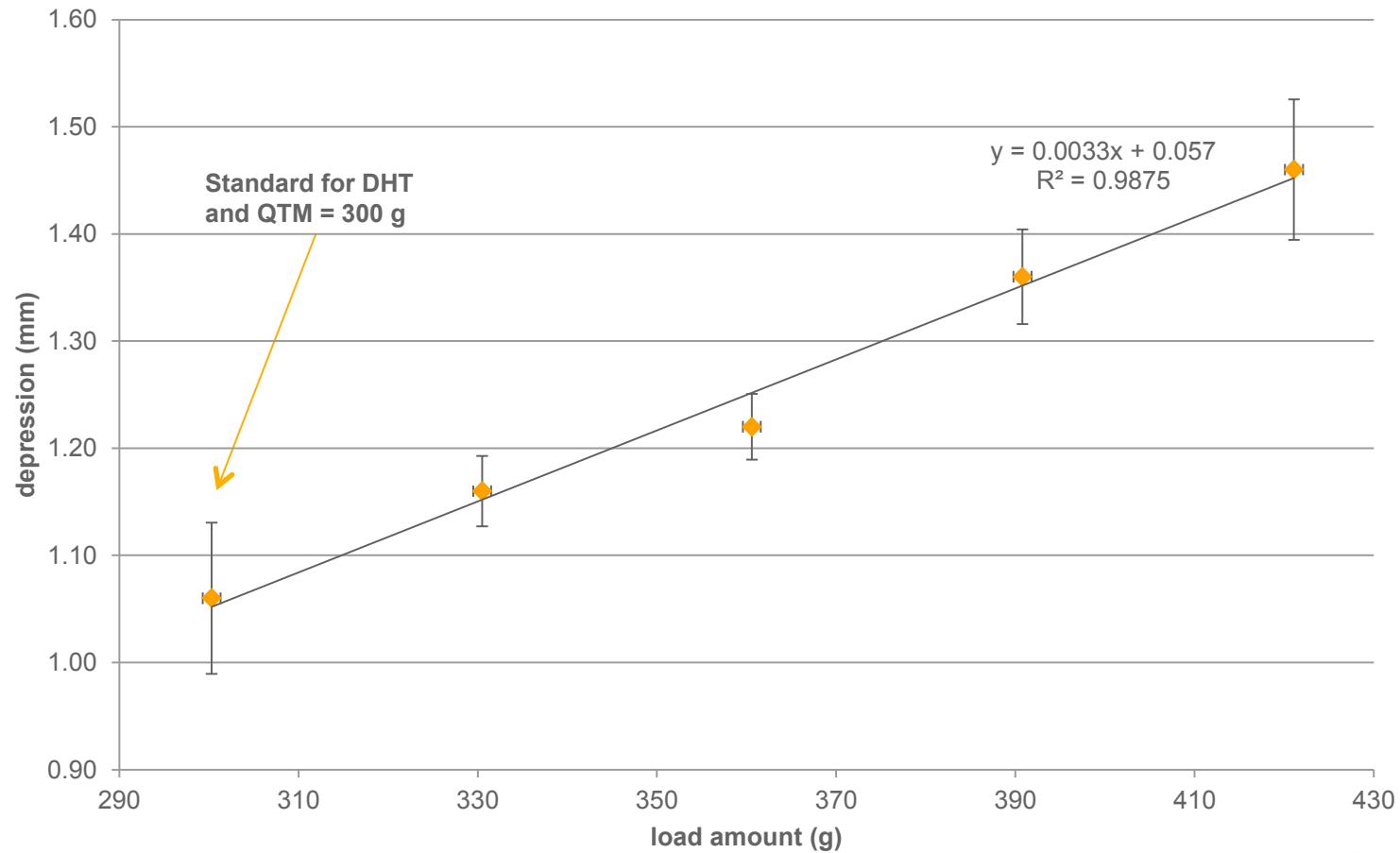
Load amount

Components of load on each instrument weighed

QTM 7 Total Load Mass	300.3 g
DHT Total Load Mass	294.6 g

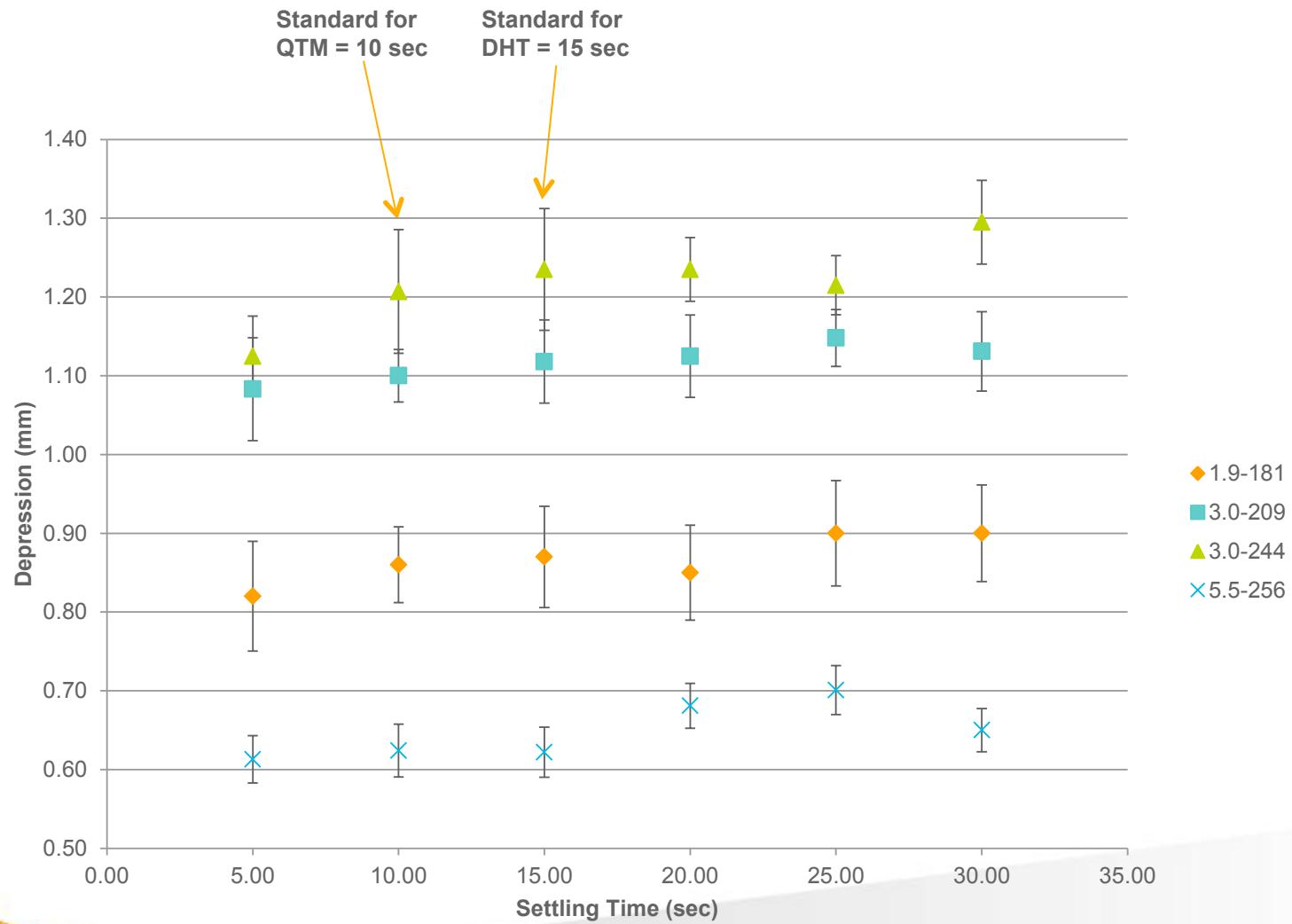
5.7 g difference

Load amount

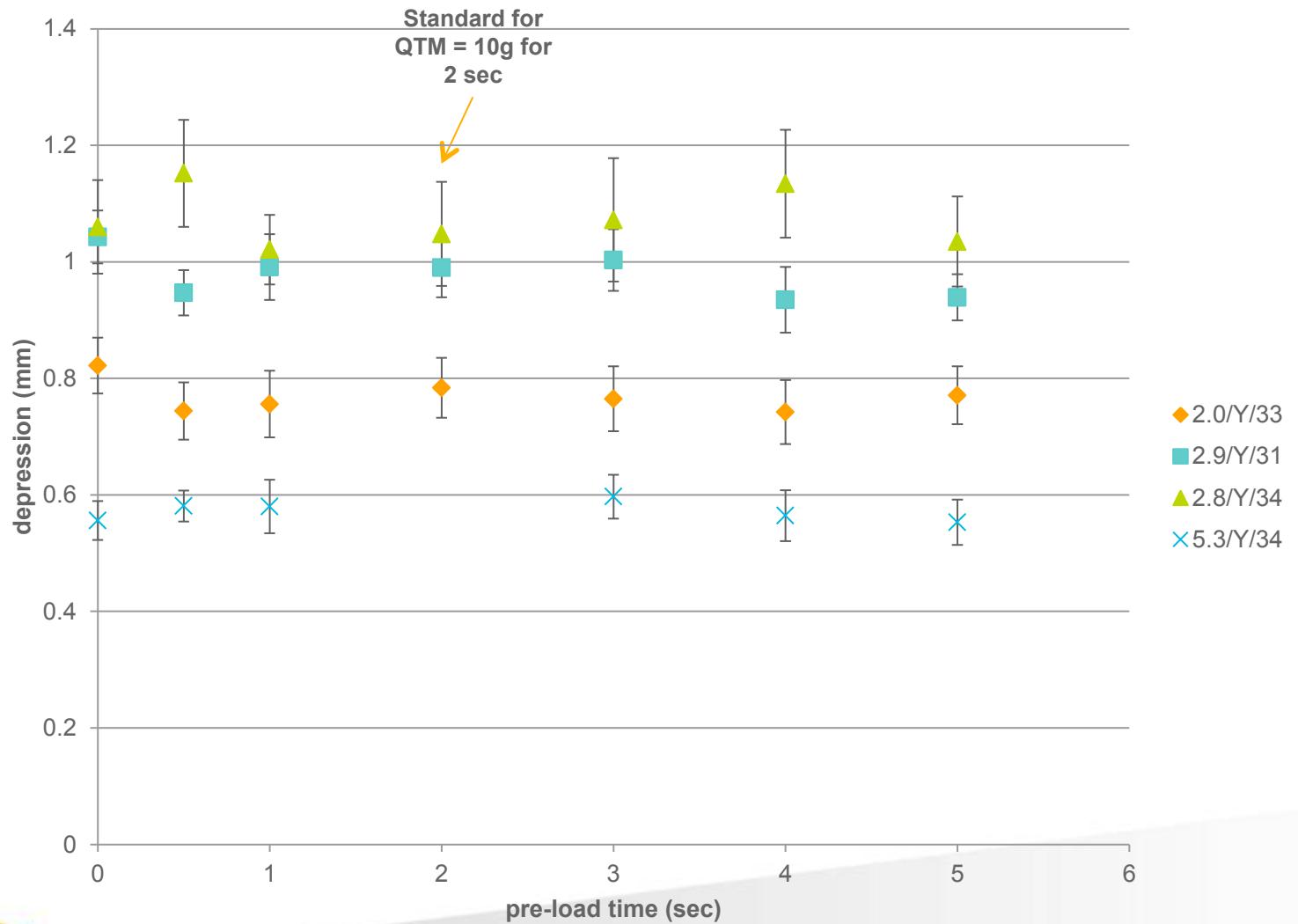


Load mass change of 5.7g = ~2% change in depression

Settling time



Pre-load



Negligible effect on depression

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Compression speed

An MTS 50W force compression device was used to apply a 300 g load to filter rods at two different compression speeds

	2.0/Y/33	5.3/Y/34
0.075 mm/sec	1.10 ± 0.050 mm	0.91 ± 0.040 mm
2.0 mm/sec	1.05 ± 0.066 mm	0.92 ± 0.046 mm

- <5% change in depression reading at softer tow item
- Negligible change in depression reading at harder tow item

Dirt and grime buildup

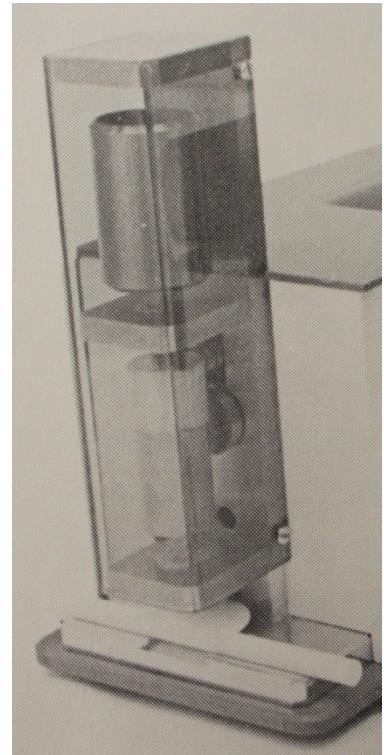
Hardness measurements taken prior to cleaning, after cleaning, and on a separate DHT

	Before	After	Other DHT
Mean Dep (mm)	0.71 ± 0.06	0.75 ± 0.09	0.74 ± 0.06
Mean %H(F)	90.76 ± 0.79	90.23 ± 1.16	90.32 ± 0.75

Issues with the DHT

Two issues:

1. Friction b/w compression foot and measurement probe
2. Filter rod distortion during compression

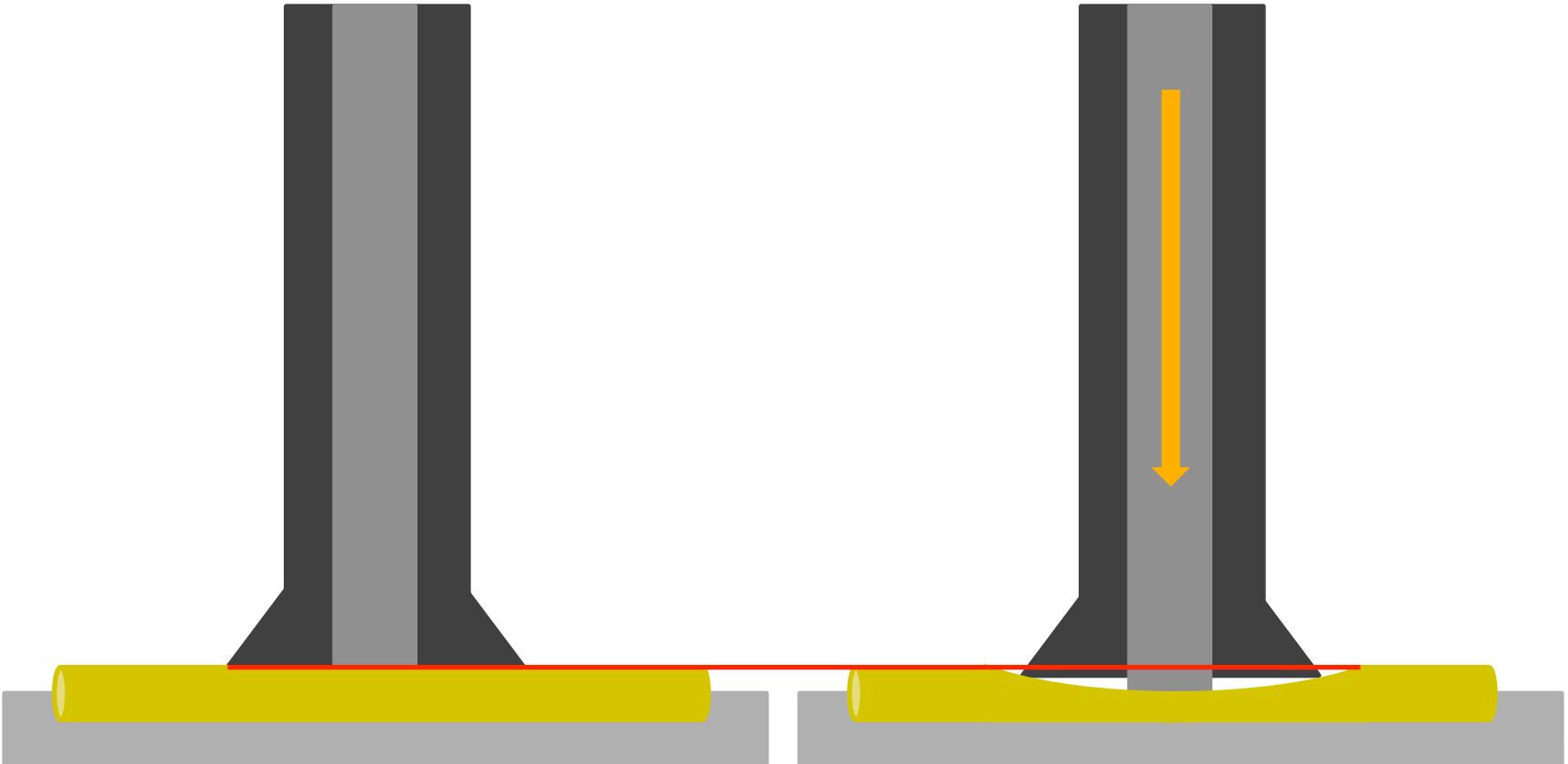


Frictional discrepancies



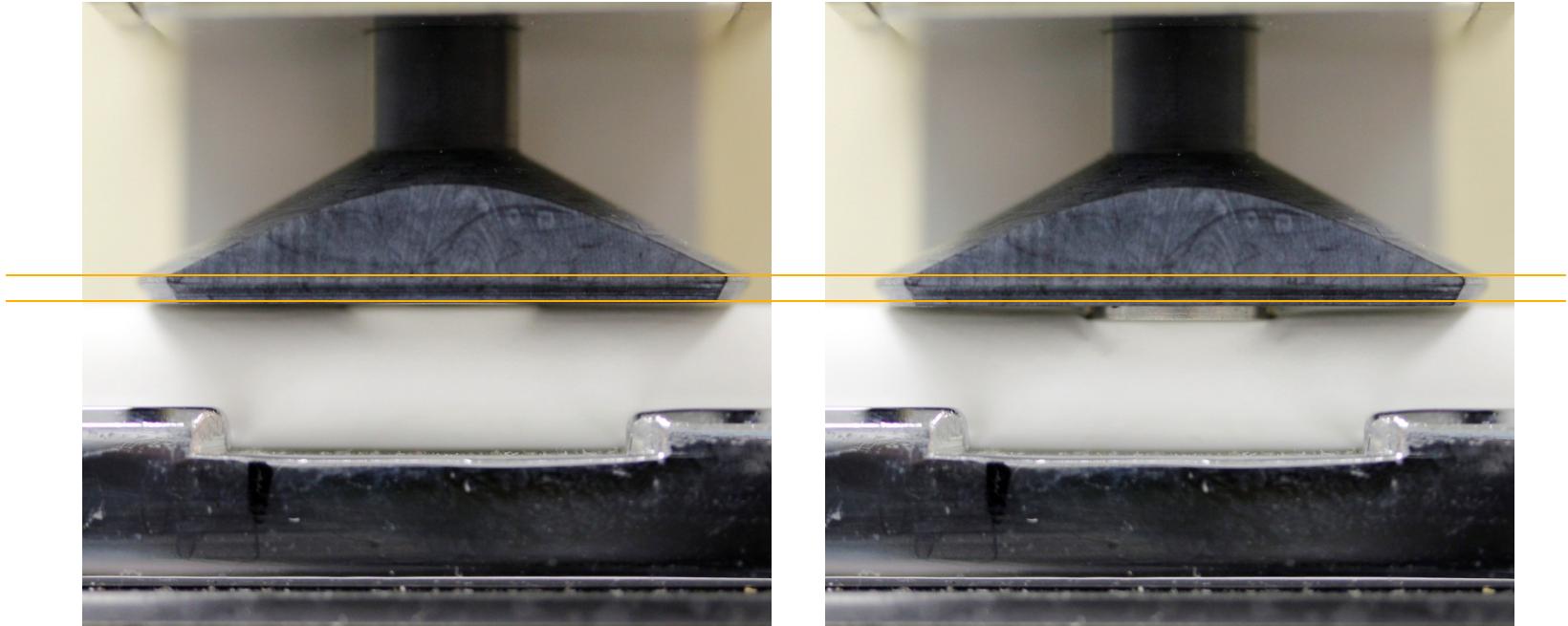
Applied load of DHT tested = ~298 g

Rod distortion upon compression



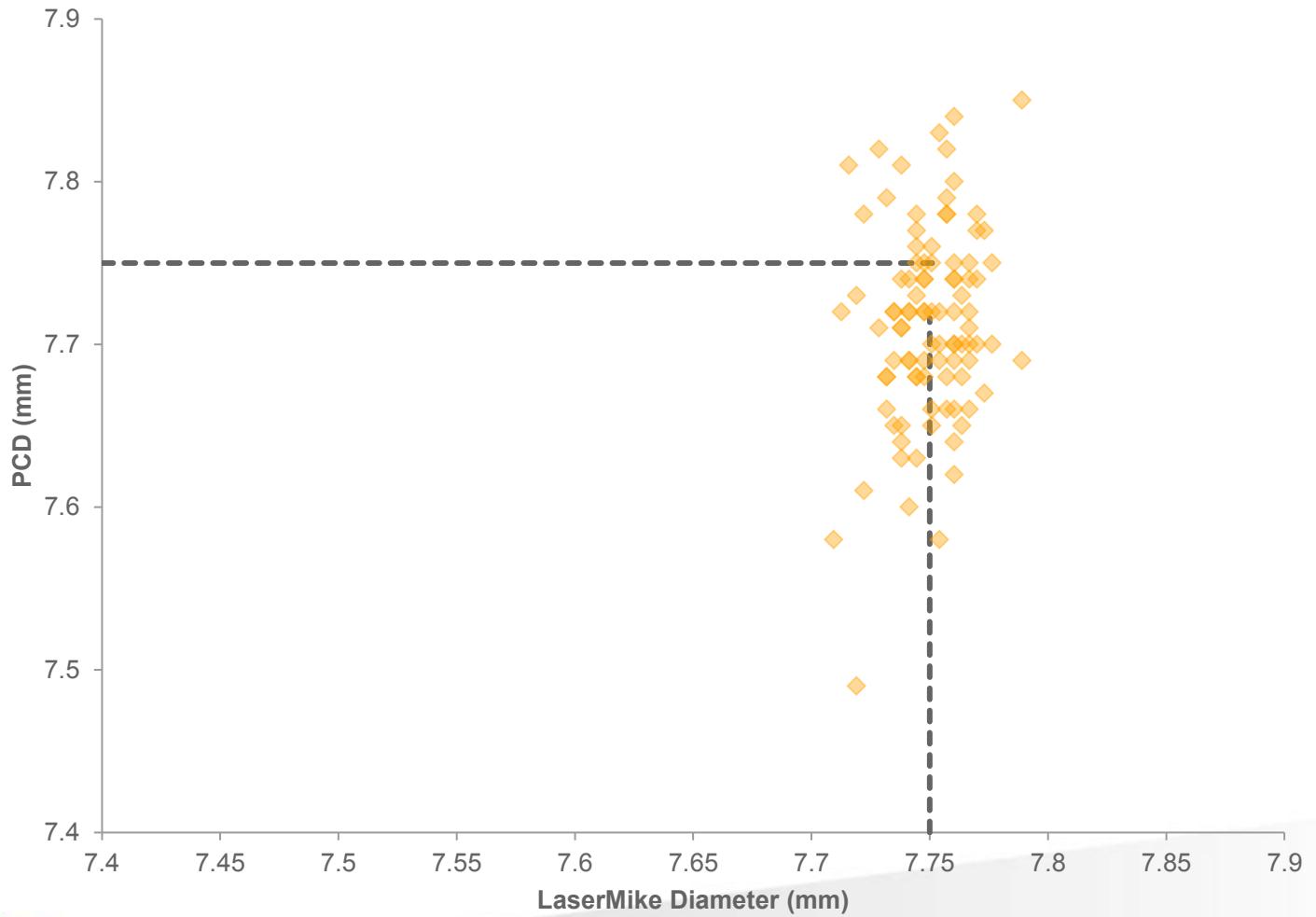
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Rod distortion upon compression



- Discrepancy of ~0.8mm upon compression
- ~7% difference in depression

PCD v Laser Mike diameter



Summary

- As hardness testers evolve, it is important to develop correlations and understand differences between them
- Strong correlations observed for depression and %H measurements between instruments
- DHT values correspond better than QTM values to Eastman's hardness model
- The QTM 7 exhibits many similarities to the DHT, and offers the advantage of having many adjustable parameters

Discrepancies between testers

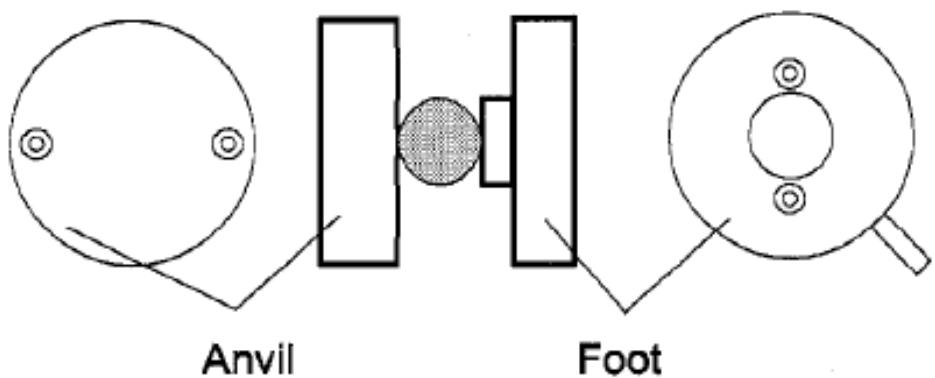
Factor	Contribution to depression discrepancy
Load amount	~2%
Settling time	Negligible
Pre-load	Negligible
Compression speed	<5% for softer tow items Negligible for harder tow items
Dirt/grime build-up	Negligible
Friction	Negligible
Rod compression discrepancies	~7%
Circumference measurement	Negligible

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EXTRA SLIDES

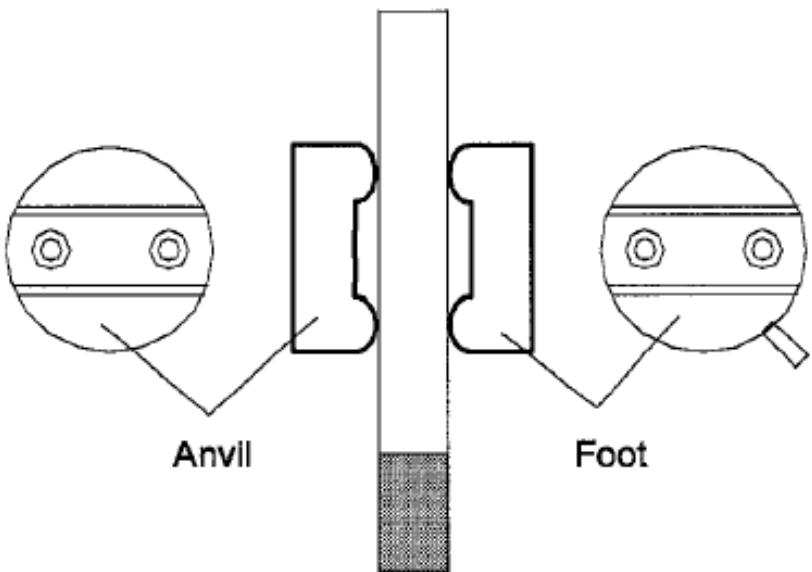
Presser Foot A

- CORESTA recommended
- Similar to Filtrona
- Circular foot
 - 12 mm diameter
 - Opposed by lower anvil
 - Parallel flat surface
 - Load = 290 g + 10 g pre-load = 300 g total



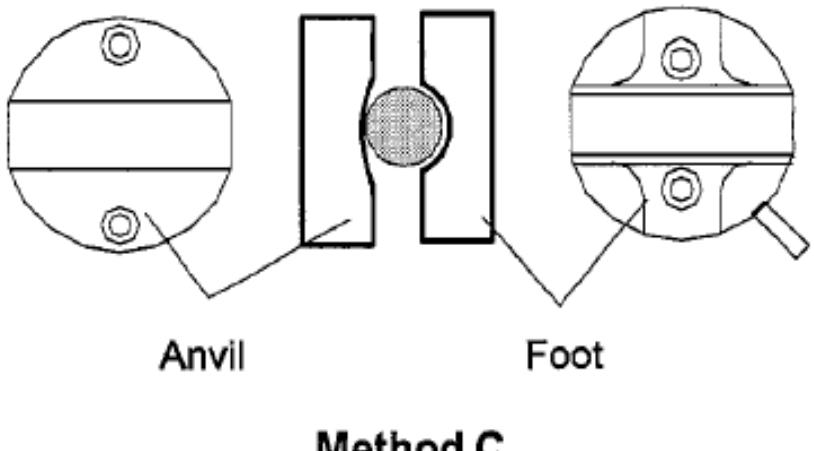
Presser Foot B

- Upper foot and lower anvil
 - 5 mm radii profiles on 23 mm pitch
 - Diametrically opposed
 - 90° to longitudinal axis of test piece
- Designed to match Borgwaldt



Presser Foot C

- Semicircular foot
 - 5 mm radius
- Anvil
 - shallow curved surface
 - 45 mm radius
- Anvil and foot 35 mm long
- Designed to match Sodim



Filtrona v Borgwaldt Correlation

■ 1. Salyer

- For 2 kg Borgwaldt

$$H_B = 0.44(H_F)^{1.17}$$

$$R^2 = 0.98$$

- For 3 kg Borgwaldt

$$H_B = 0.05(H_F)^{1.64}$$

$$R^2 = 0.98$$

2. Fritsch

- For 2 kg Borgwaldt

$$\log(100-B) = 0.9165[\log(100-F)] + 0.2408$$

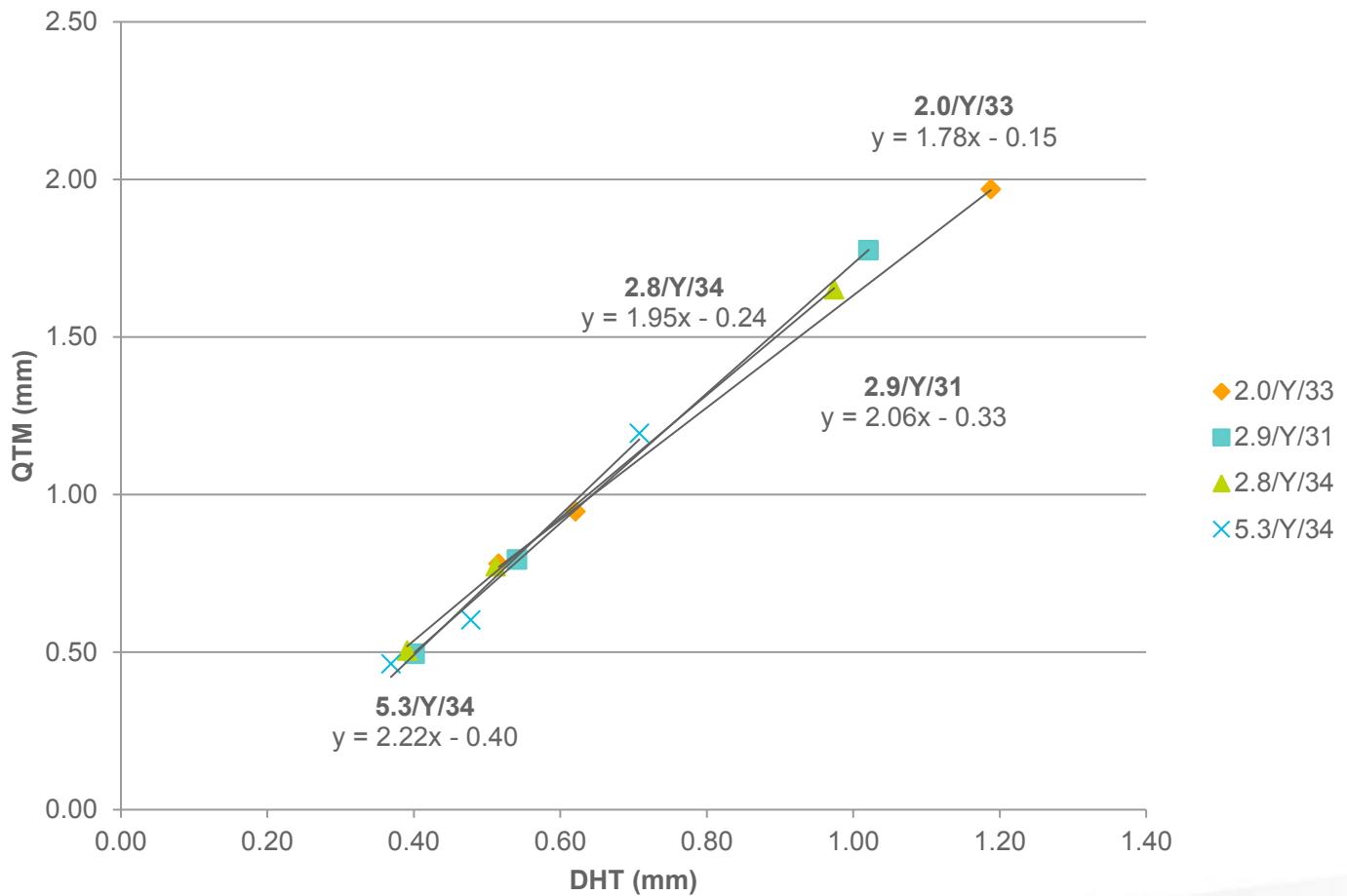
QTM 7 v Filtrona Conversion Celanese

- Uses depression, not diameter
- 30 rods each tested 4 times (2X Filtrona, 2X QTM)
 - 2.7/35 tow
 - 24.5 circumference
 - 3, 7.5, 12 g above min point
 - 0, 4, 7% PZ

$$\text{QTM mm depression} = 1.436 (\text{FTS mm depression}) + 0.068$$
$$R^2 = 0.985$$

- correlates with my hardness data

DHT v QTM 7 depression



%H(Q) v %H(F)

Regular Circumference Rods

Regression	R^2	Equation
Linear	0.9928	$F = 0.51(Q) + 47.20$
2 nd Order Poly (int = 0)	0.9957	$F = -0.0066(Q)^2 + 1.63(Q)$
3 rd Order Poly (int = 0)	0.9958	$F = 1.0E^{-5}(Q)^3 - 0.0089(Q)^2 + 1.73(Q)$
4 th Order Poly (int = 0)	0.9969	$F = 8.0E^{-6} - 0.002(Q)^3 + 0.16(Q)^2 - 3.08(Q)$
Log	0.9943	$\log(F) = 0.48 \log(Q) + 1.04$
Log(100-X)	0.7619	$\log(100 - F) = 0.44[\log(100 - Q)] + 0.40$
Ln	0.9943	$\ln(F) = 0.48 \ln(Q) + 2.38$

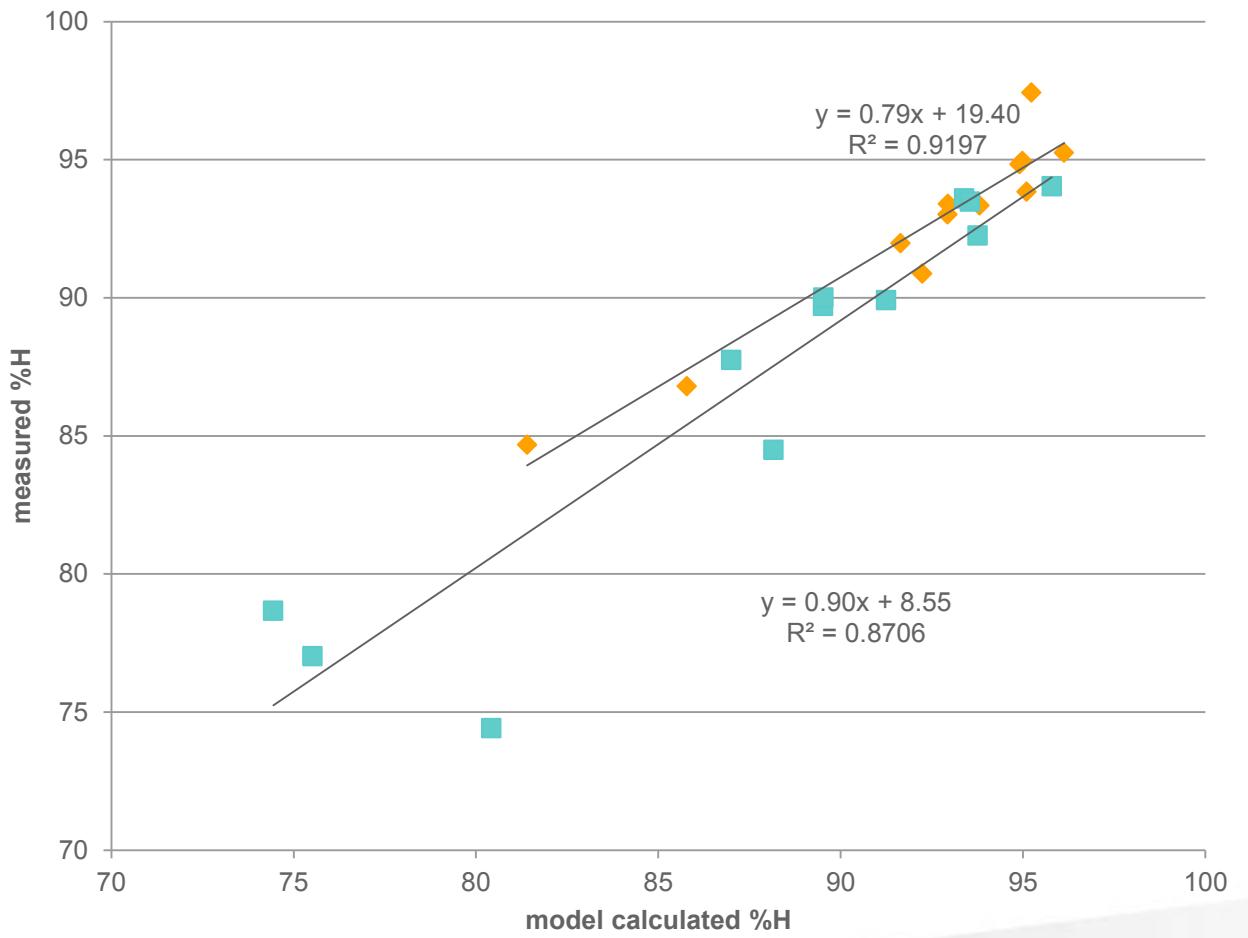
%R(Q) v %H(F)

Regression	R ²	Equation
Linear	0.9915	$F = 2.01R - 104.85$
2 nd Order Poly (int=0)	0.9916	$F = 0.011R^2 - 0.15R$
Log	0.9917	$\log(F) = 2.16 \log(R) - 2.35$
Log(100-X)	0.9880	$\log(100 - F) = 0.52[\log(100 - R)] + 0.77$
Ln	0.9917	$\ln(F) = 2.16 \ln(R) - 5.40$

%R(Q) v %H(Q)

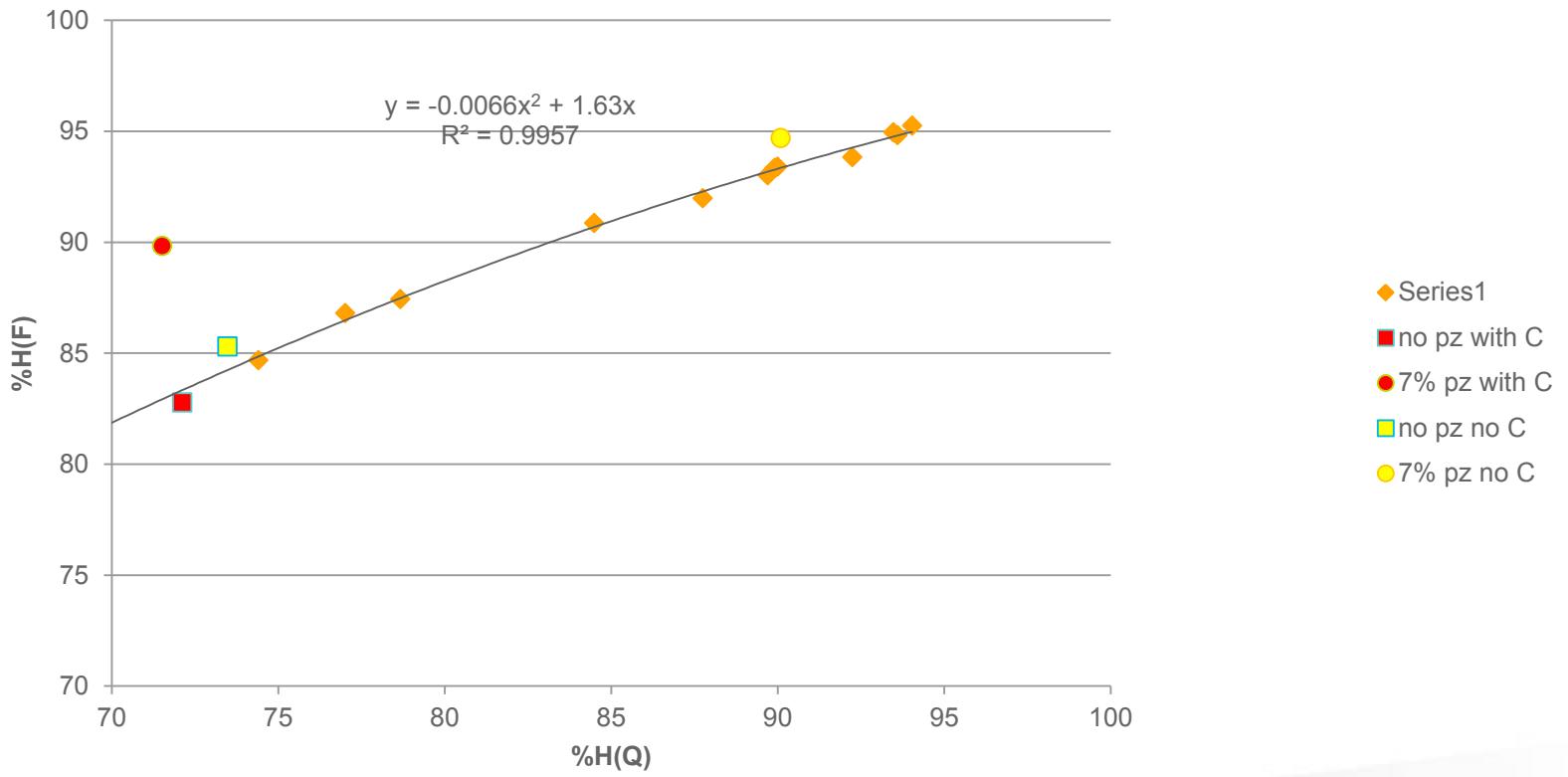
Regression	R^2	Equation
Linear	0.9935	$Q = 3.93R - 296.62$
2 nd Order Poly (int=0)	0.9945	$Q = 0.032R^2 - 2.20R$
Log	0.9960	$\log(Q) = 4.52 \log(R) - 7.06$
Log(100-X)	0.9966	$\log(100 - Q) = 0.68[\log(100 - R)] + 0.90$
Ln	0.9960	$\ln(Q) = 4.52 \ln(R) - 16.26$

Comparison to Eastman model



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Carbon and PZ Addition



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Load amount

- One tow item (2.9/Y/31) tested at various load amounts
 1. 300.3 g
 2. 330.5 g
 3. 360.6 g
 4. 390.8 g
 5. 421.1 g

Load amount

(1) V %H(Q)

Regression	R ²	Equation
Linear	0.9858	$y = -0.044x + 99.34$
2 nd Order Poly	0.9913	$y = -9.0 \times 10^{-5}x^2 + 0.022x + 87.61$

(2) V %R

Regression	R ²	Equation
Linear	0.8221	$y = -0.0085x + 100.67$
2 nd Order Poly	0.9086	$y = -8.0 \times 10^{-5}x^2 + 0.047x + 90.75$

(3) V depression

Regression	R ²	Equation
Linear	0.9872	$y = 0.0033x + 0.054$
2 nd Order Poly	0.9918	$y = 6.0 \times 10^{-6}x^2 - 0.0013x + 0.87$

Settling time

- 4 different tow items tested
 1. 2.0/Y/33
 2. 2.9/Y/31
 3. 2.8/Y/34
 4. 5.5-256
- Each tow item tested at various settling times
 1. 5 s
 2. 10 s
 3. 15 s
 4. 20 s
 5. 25 s
 6. 30 s

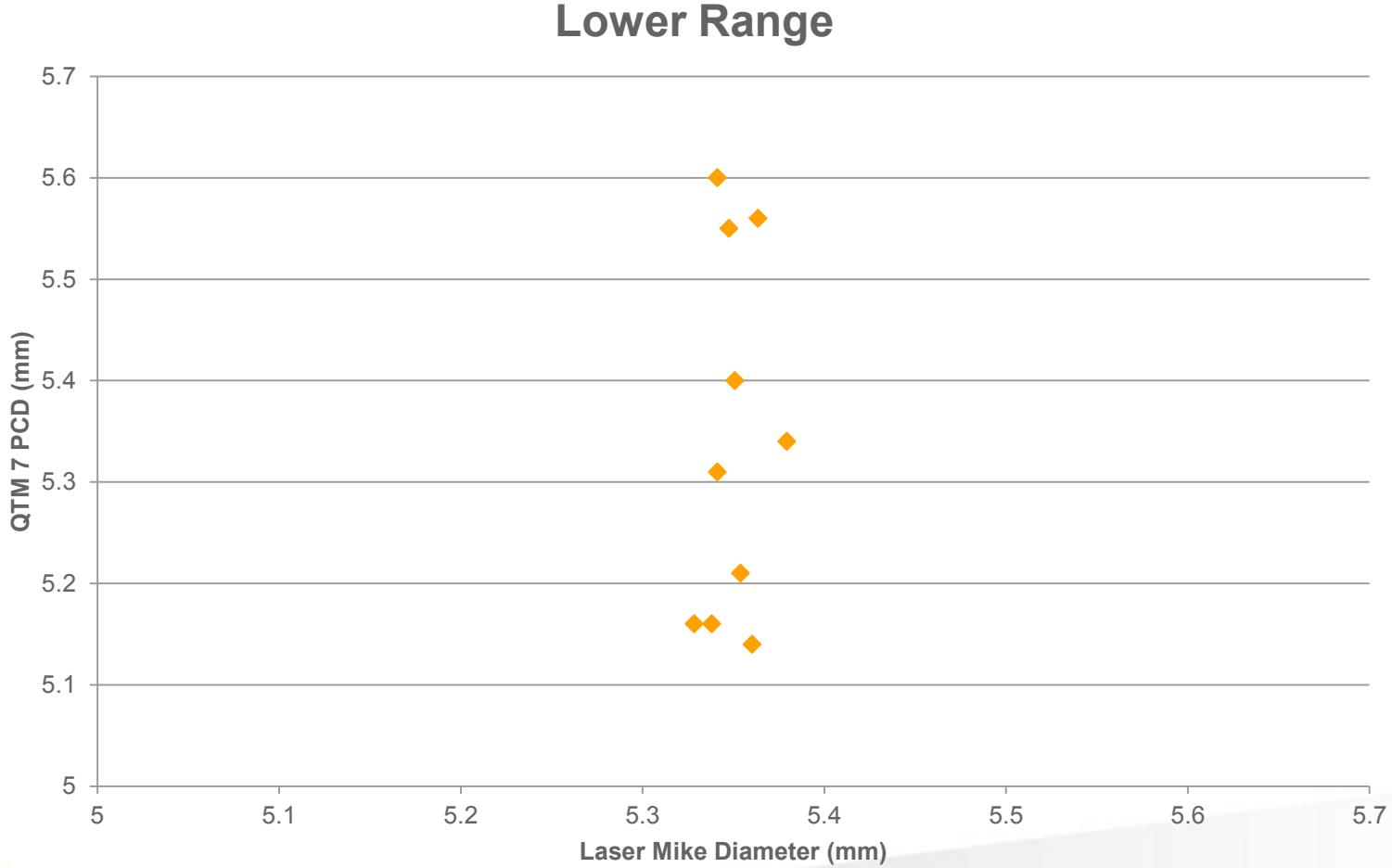
Settling Time v %H(Q)

Tow Item	D/F	TD	%H Eqn (R^2)
1.9-181	1.97	33	$y = 0.0004x^2 - 0.025x + 89.34$ ($R^2 = 0.7532$)
3.0-209	2.89	31.2	$y = 0.0016x^2 - 0.084x + 86.22$ ($R^2 = 0.8962$)
3.0-244	2.83	34	$y = 0.0019x^2 - 0.13x + 86.64$ ($R^2 = 0.7505$)
1.9-181	5.26	34.3	$y = 0.002x^2 - 0.11x + 97.70$ ($R^2 = 0.6085$)

Settling Time v %R

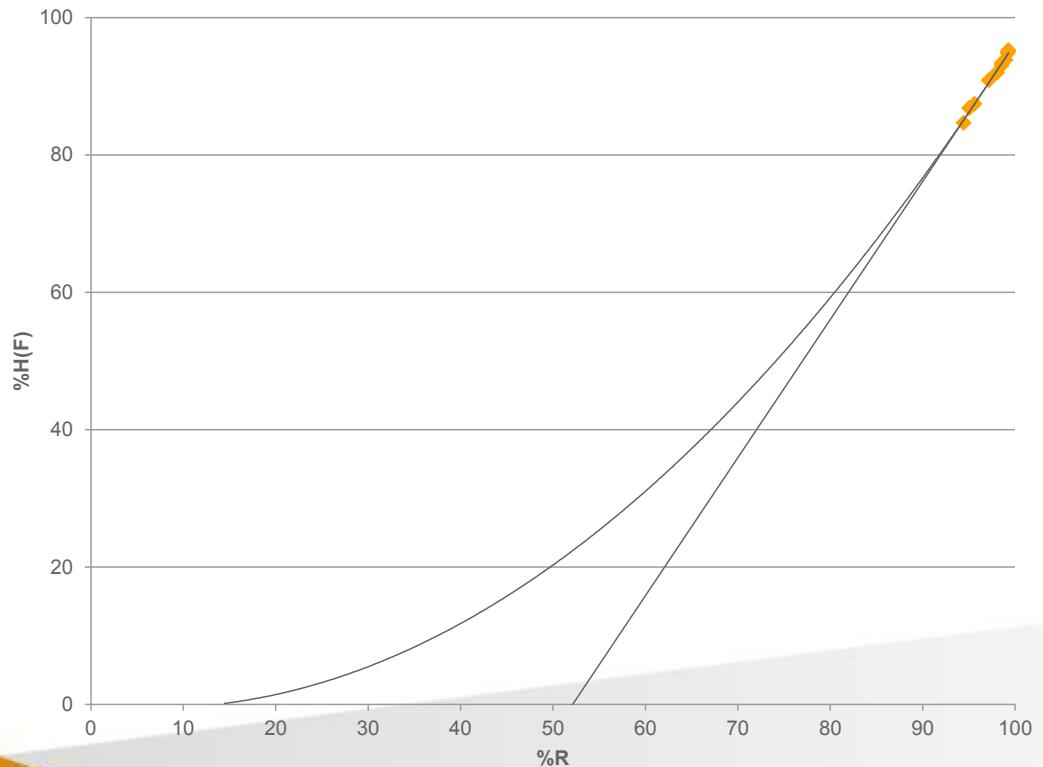
Tow Item	D/F	TD	%R Eqn (R^2)
1.9-181	1.97	33	$y = 0.00002x^2 - 0.042x + 98.80$ ($R^2 = 0.9737$)
3.0-209	2.89	31.2	$y = 0.0009x^2 - 0.079x + 98.50$ ($R^2 = 0.9999$)
3.0-244	2.83	34	$y = 0.0001x^2 - 0.070x + 98.22$ ($R^2 = 0.9841$)
1.9-181	5.26	34.3	$y = 0.0008x^2 - 0.059x + 99.35$ ($R^2 = 0.9020$)

PCD v Laser Mike Diameter



%R(Q) v %H(F)

Regression	R ²	Equation
Linear	0.9915	$F = 2.01R - 104.85$
2 nd Order Poly (int=0)	0.9916	$F = 0.011R^2 - 0.15R$



%R(Q) v %H(Q)

Regression	R^2	Equation
Linear	0.9935	$Q = 3.93R - 296.62$
2 nd Order Poly (int=0)	0.9945	$Q = 0.032R^2 - 2.20R$

