Optimizing Ceramic Filters in Ghana

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MIT Masters of Environmental and Water Quality Engineering

Final Presentation, May 2010

Outline

- **Project Overview**
- Filter Performance
  - Goal
  - Study Design
  - Results
- Filter Durability
  - Questions
  - Results
  - Recommendations
- Combined Recommendations
- Paraboloid Filter Flow
  - Goal
  - Study Design
  - Results

Project Overview

- Team Objective
  - Recommend type of ceramic pot filter to manufacture
  - Simultaneously optimized for flow rate, removal efficiencies, and durability
- Travis Reed Miller
  - Investigate impact of design variables on coliform and turbidity removal, and flowrate
  - Model flow of innovative paraboloid shape
- Travis Russell Watters
  - Investigate impact of design variables on durability

Design Variables and Parameters

Variable \ Parameter		*E. Coli* Removal	Total Coliform Removal	Flowrate	Turbidity Removal	Strength
Combustible Type	Rice Husk					
	Sawdust					
Addition of Grog	Grog					
	No Grog					
Combustible Volume	Low : 43-47%					
	Med: 51-54%					
	High: 50-56%					
Additional Variables	Sifting					
	Shape					

Filter Recipes

Filter Recipe	Combustible Type	Hammermill Product	Combustible Amount	Grog Added	Shape
1	Rice Husk	Fine & Waste	Low	No	Flower Pot
2	Rice Husk	Fine & Waste	Low	Yes	Flower Pot
3	Rice Husk	Fine & Waste	Medium	No	Flower Pot
4	Rice Husk	Fine & Waste	Medium	Yes	Flower Pot
5	Rice Husk	Fine & Waste	High	No	Flower Pot
6	Rice Husk	Fine & Waste	High	Yes	Flower Pot
7	Sawdust	Fine & Waste	Low	No	Flower Pot
8	Sawdust	Fine & Waste	Low	Yes	Flower Pot
9	Sawdust	Fine & Waste	Medium	No	Flower Pot
10	Sawdust	Fine & Waste	Medium	Yes	Flower Pot
11	Sawdust	Fine & Waste	High	No	Flower Pot
12	Sawdust	Fine & Waste	High	Yes	Flower Pot
13	Sawdust	*Fine, Sifted*	Low	No	Flower Pot
14	Rice Husk	*Fine, Sifted*	Low	No	Flower Pot
15	Rice Husk	Fine & Waste	Low	Yes	*Paraboloid*

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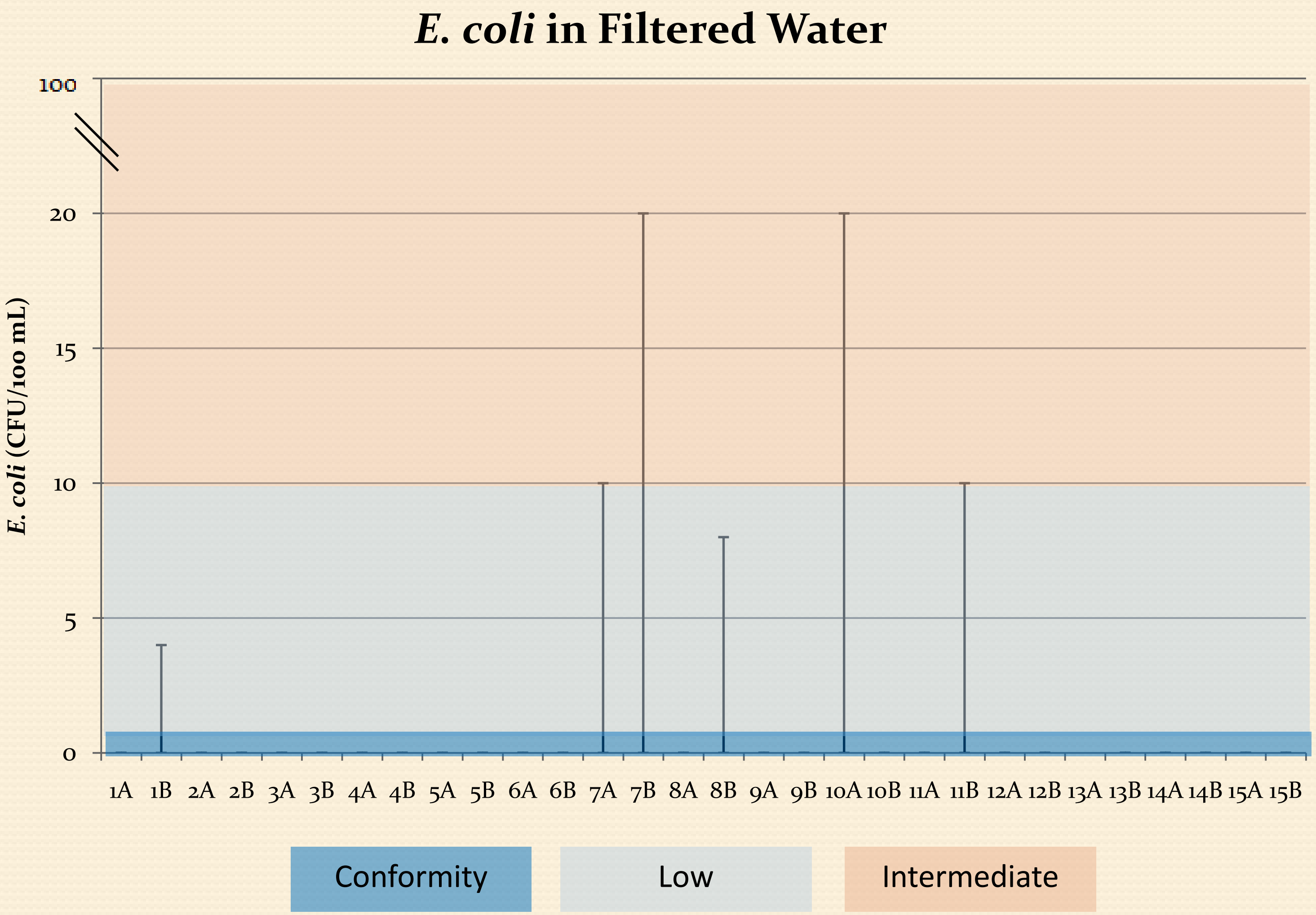
Filter Performance Study Design

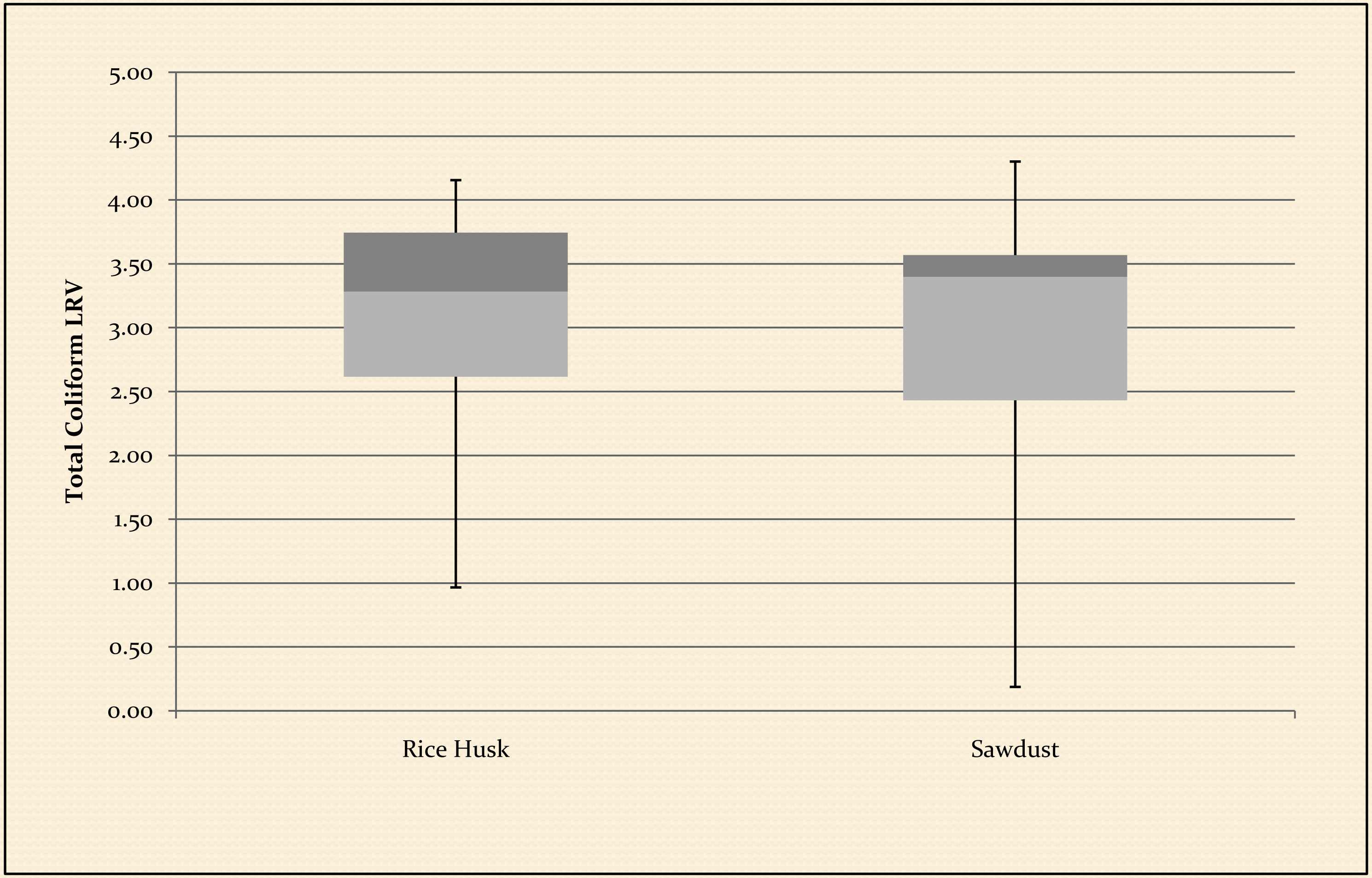
Analysis

- Statistical analysis of data
  - T-tests to *estimate* difference between population means
    - Influence of design variables on performance
    - Relatedness of duplicate filters
  - T-tests to *test* difference between population means
    - Ranking of filters for recommendation

Impact of Combustible Type: *E. coli* Count

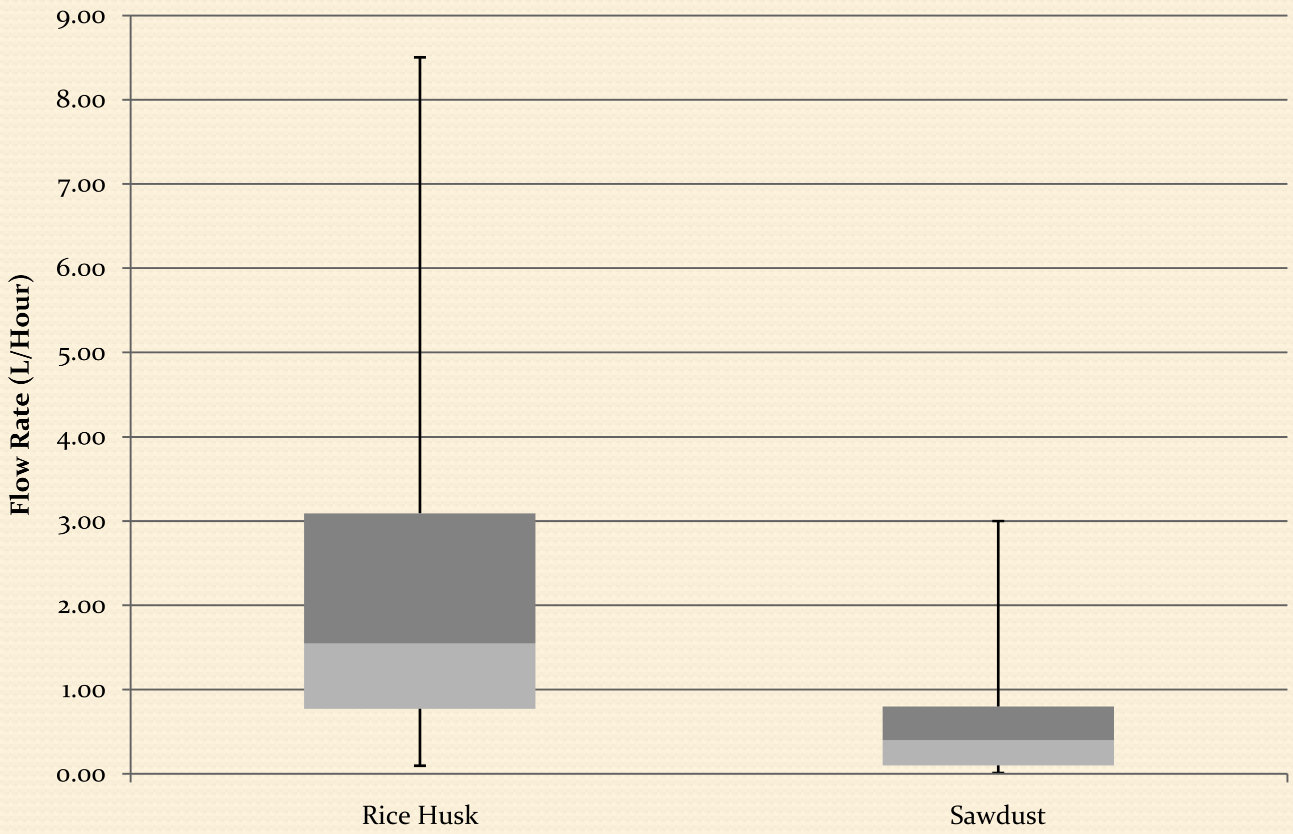


Impact of Combustible Type: Total Coliform Log Removal



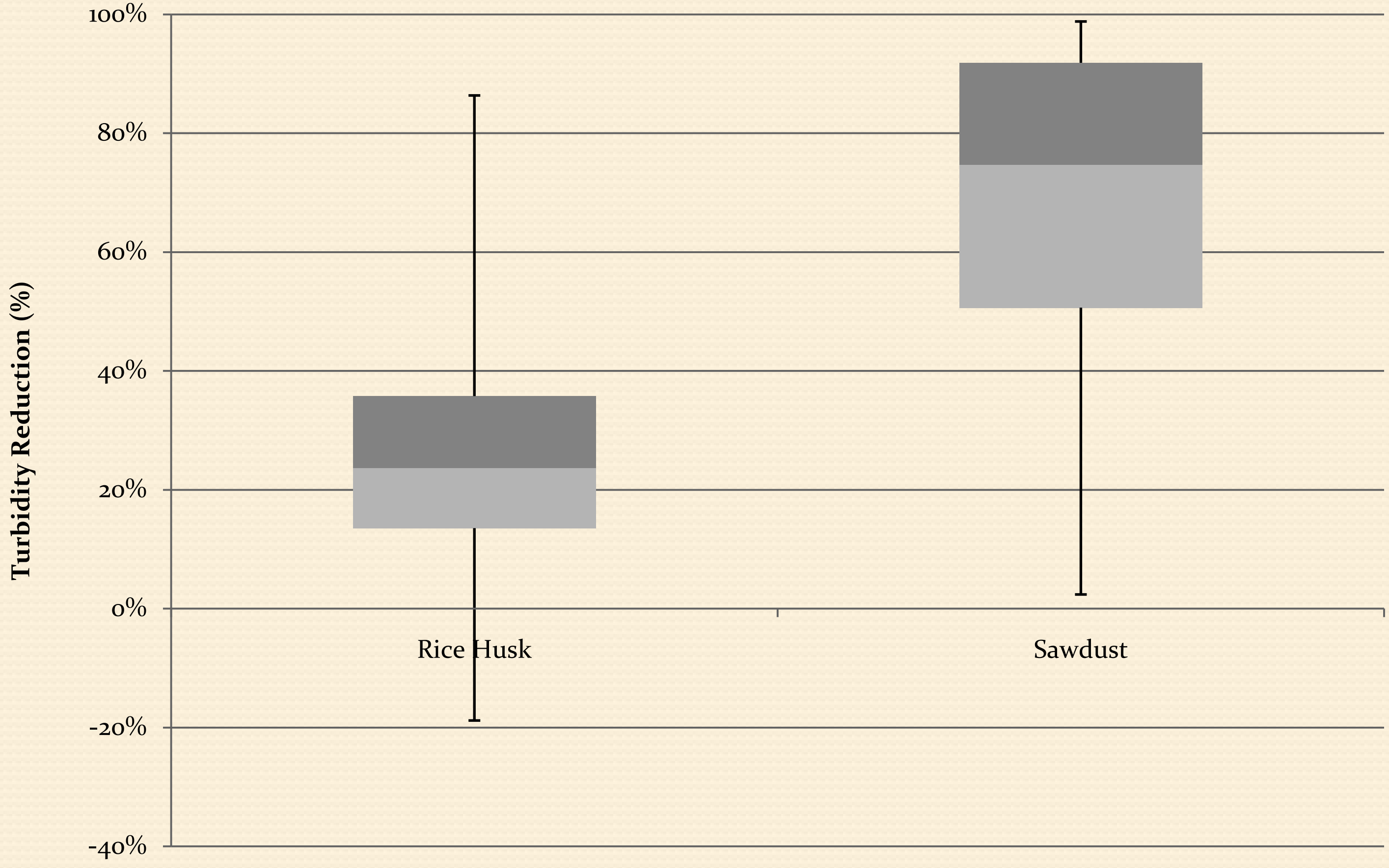
Statistically significant difference

Impact of Combustible Type: Flowrate



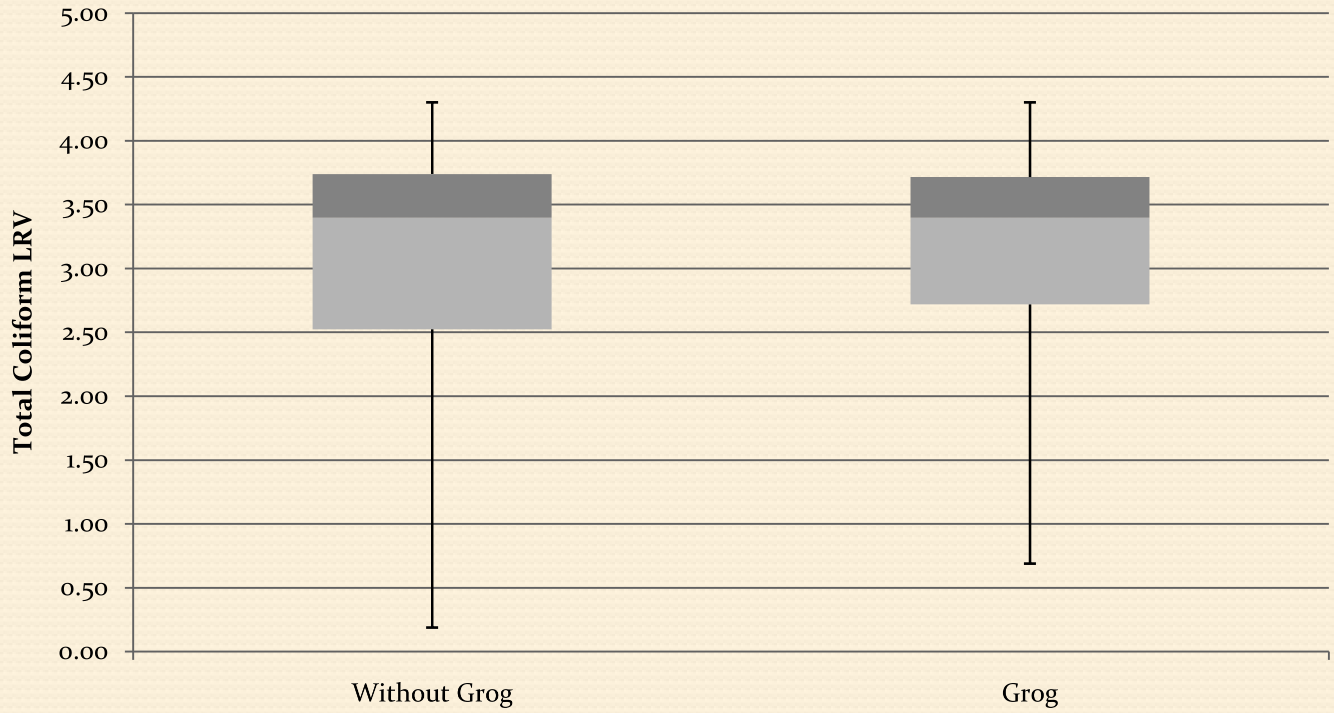
Statistically significant difference

Impact of Combustible Type: Turbidity Removal



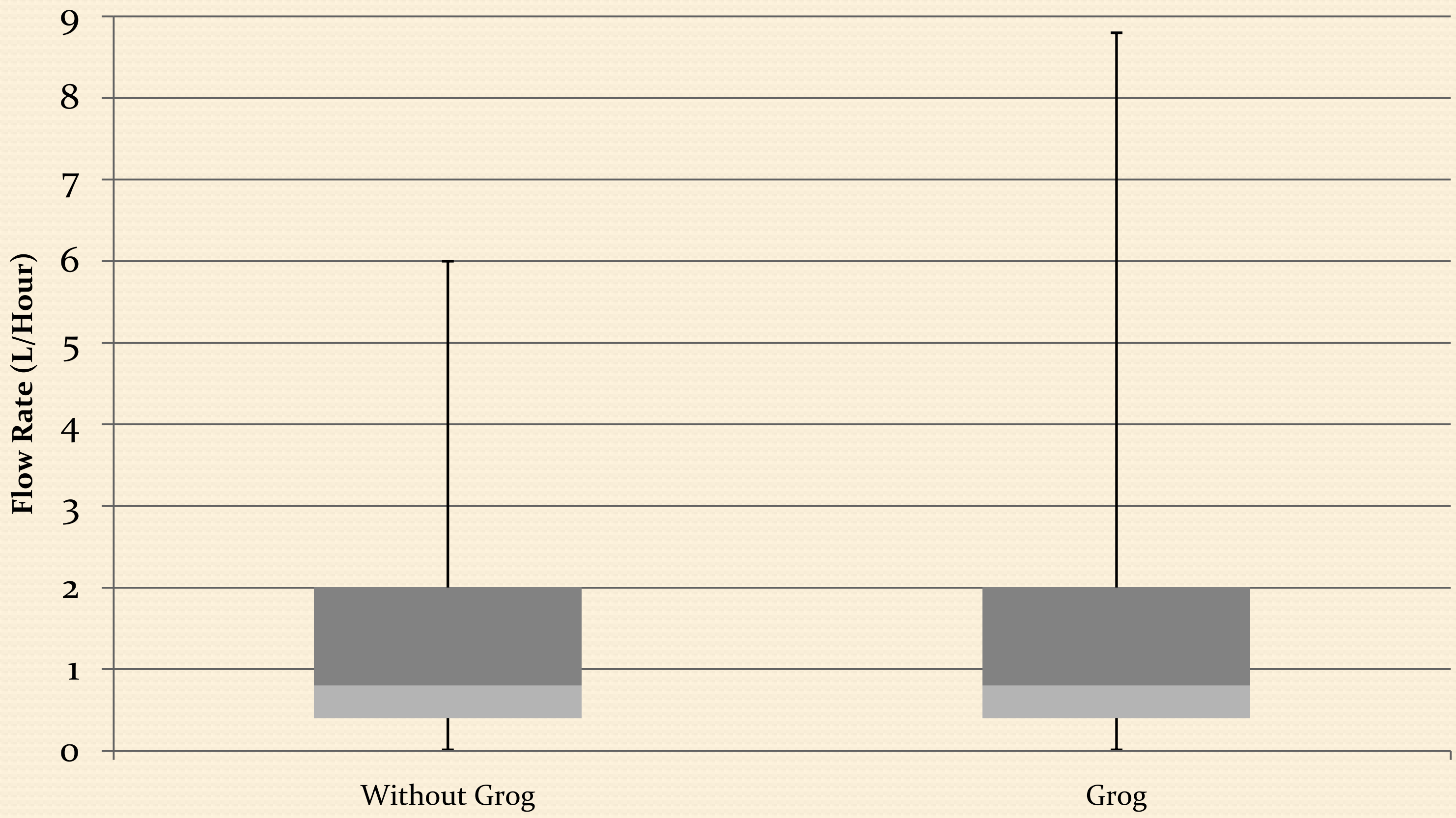
Statistically significant difference

Impact of Addition of Grog: Total Coliform Removal



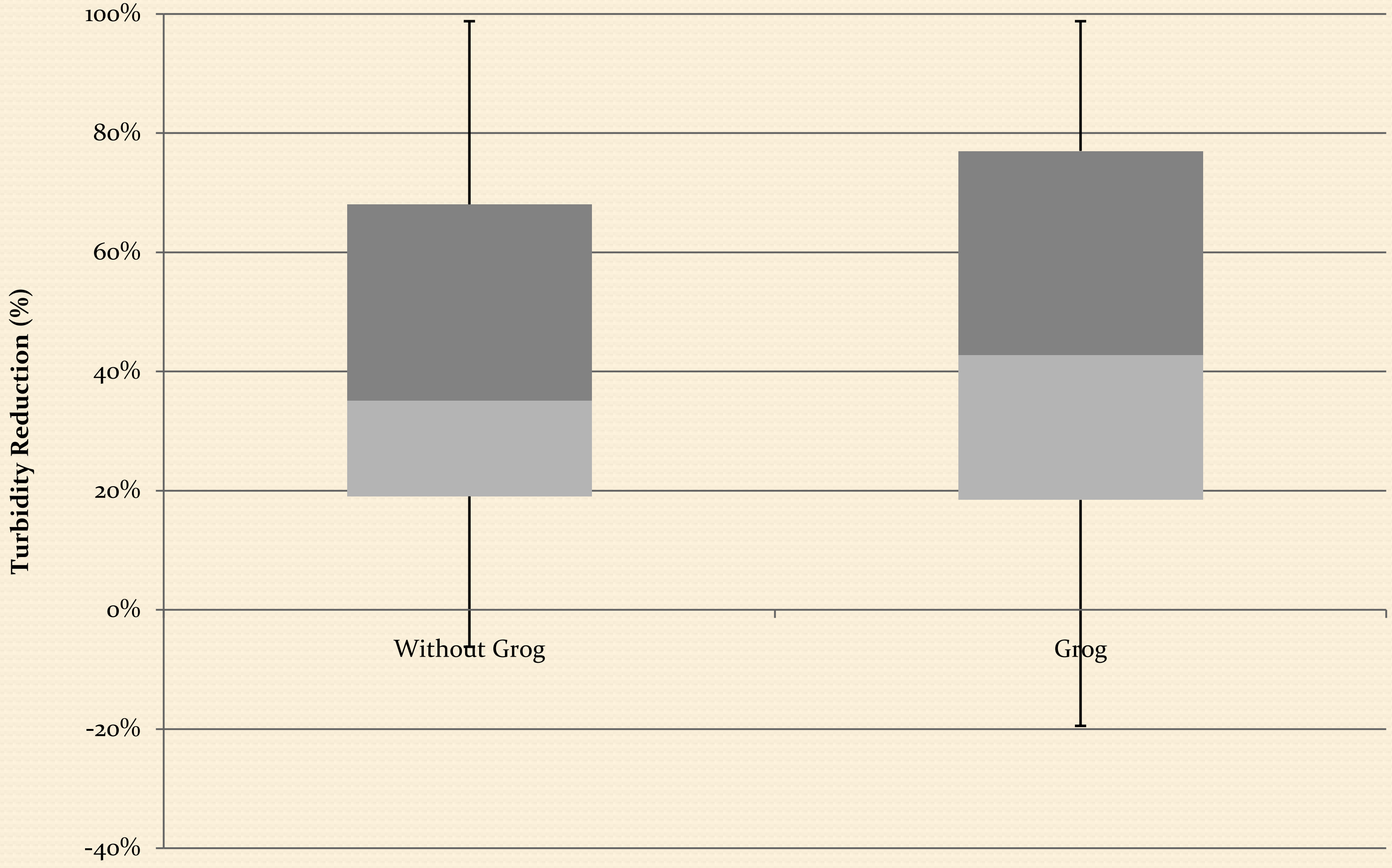
Statistically <u>not</u> significant difference

Impact of Addition of Grog: Flowrate



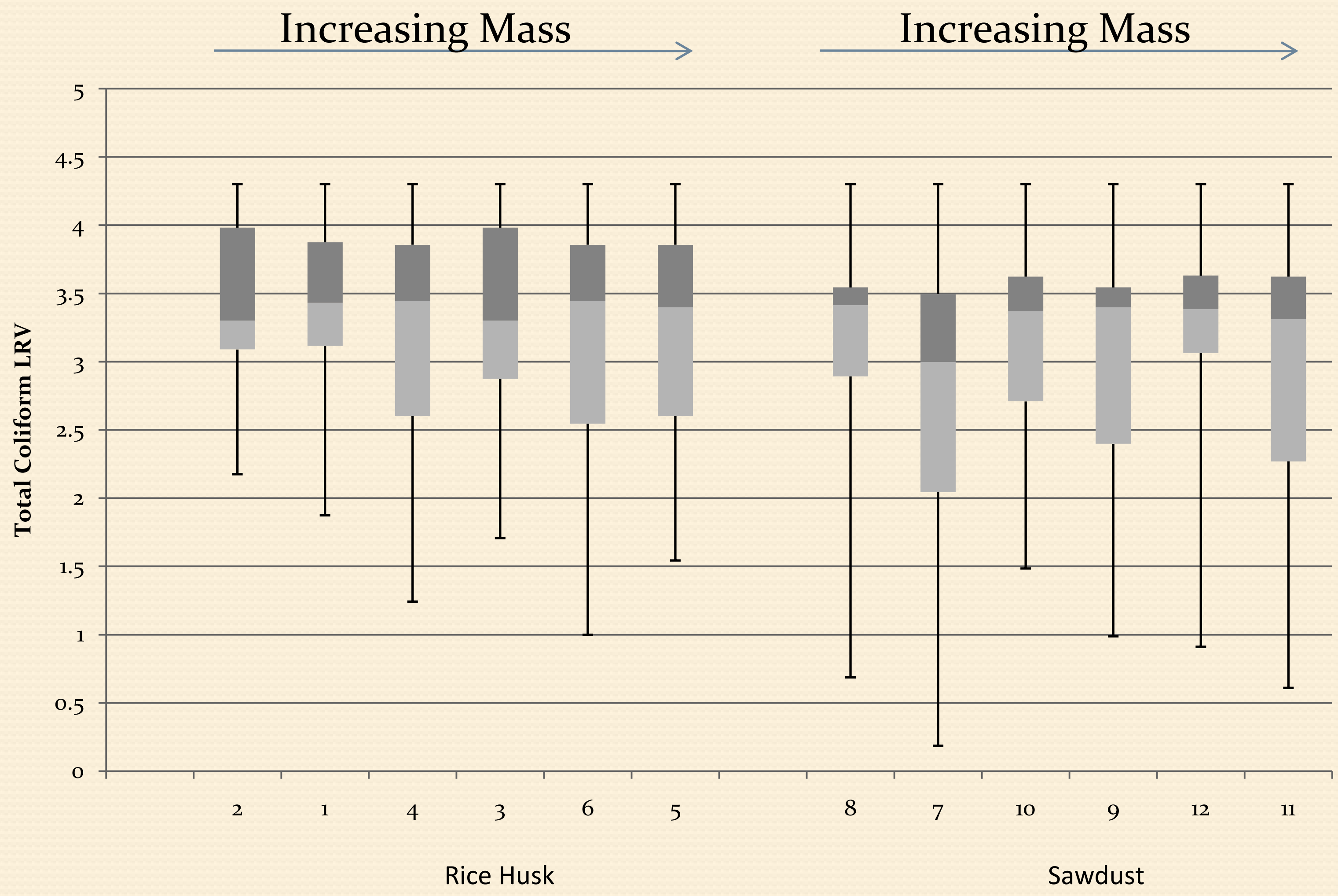
Statistically <u>not</u> significant difference

Impact of Addition of Grog: Turbidity Removal

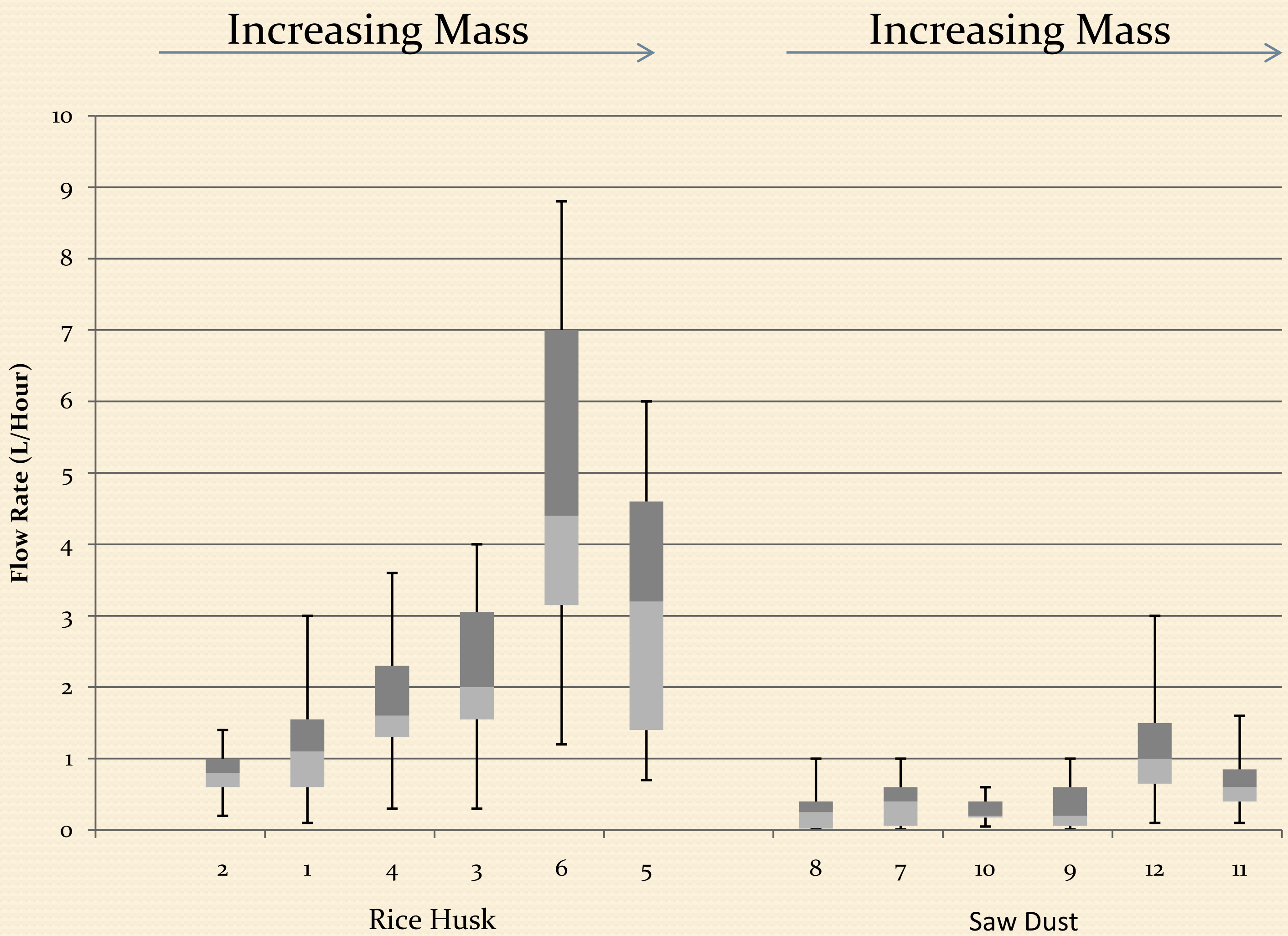


Statistically not significant difference

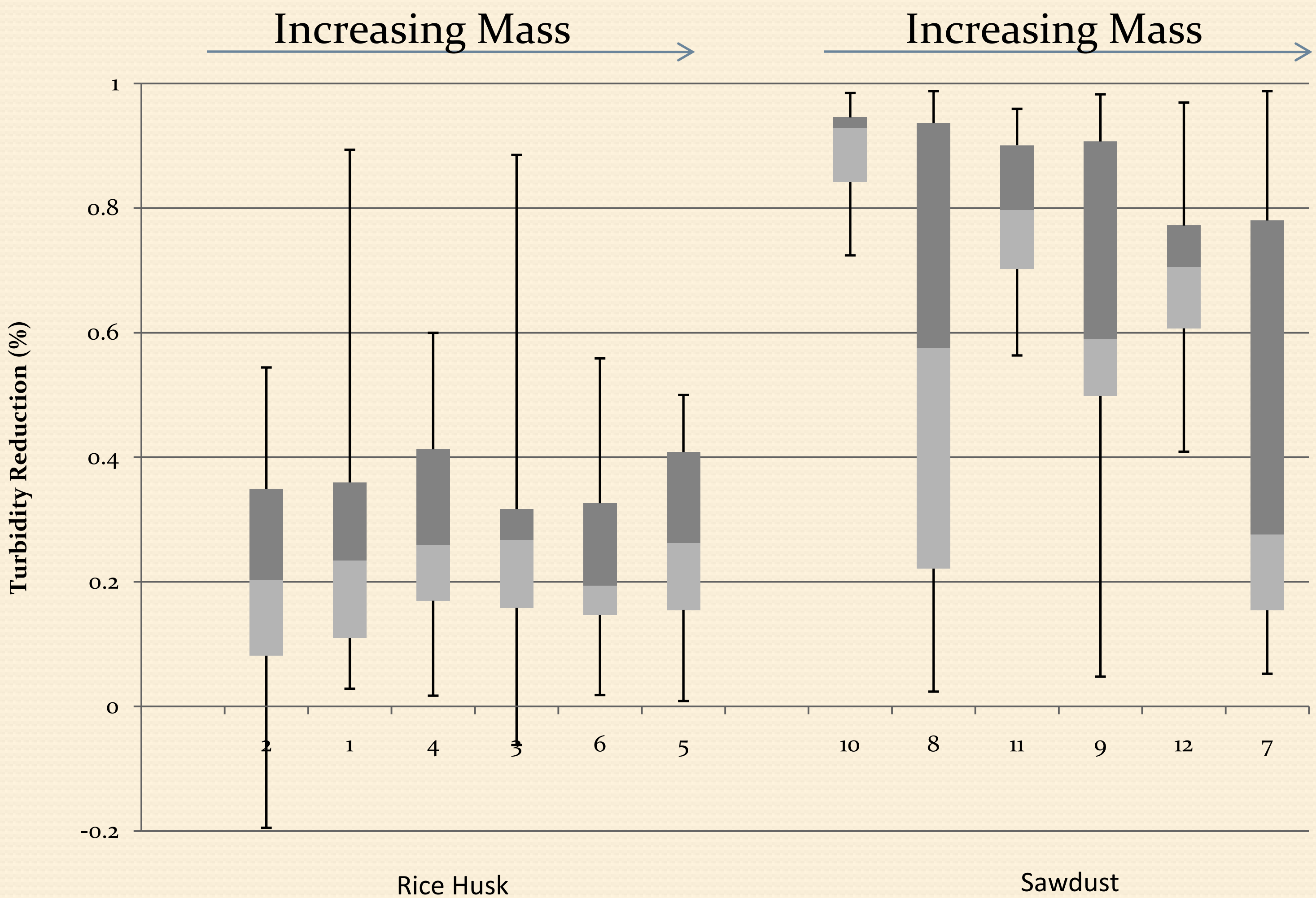
Impact of Mass of Combustible: Total Coliform Removal



Impact of Mass of Combustible: Flowrate



Impact of Mass of Combustible: Turbidity Removal



Impact of Additional Variables

- Hammermilled and sifted combustible material reduces flowrate
- Paraboloid shape reduces flowrate by 0.2 to 0.6 L/hr

Design Variables and Parameters

Key:
+ Variable increases parameter
-- Variable decreases parameter
o No effect

Variable \ Parameter		*E. Coli* Removal	Total Coliform Removal	Flowrate	Turbidity Removal	Strength
Combustible Type	Rice Husk	--	+	+	--	
	Sawdust	+	--	--	+	
Addition of Grog	Grog	o	o	o	o	
	No Grog	o	o	o	o	
Combustible Volume	Low : 43-47%	o	o	--	o	
	Med: 51-54%	o	o	o	o	
	High: 50-56%	o	o	+	o	
Additional Variables	Sifting	o	o	--	o	
	Shape	o	o	-	o	

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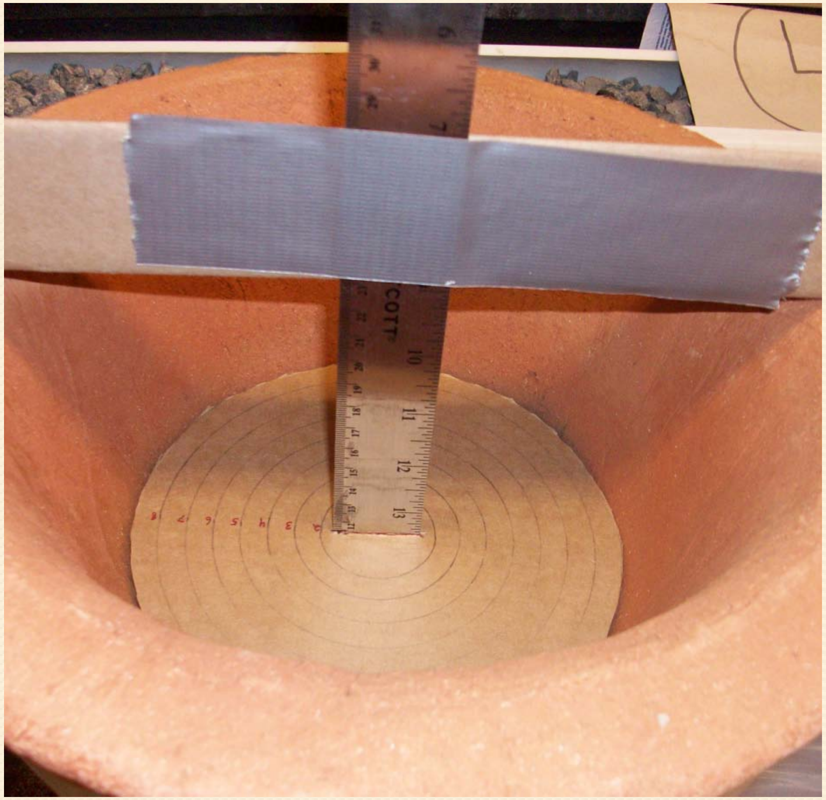
Paraboloid Filter Flow

- Goal
  - Derive equation to represent flow through paraboloid filter based on Darcy’s law
  - Test to see if hydraulic conductivity is homogenous throughout filter

Drawdown Test

Determining Radii



Results: Flowrate Model

- Flowrate model in terms of z, height with Darcy's Law

$$Q = \frac{4\pi cK}{3t}\left[-H_w(c^2/4)^{\frac{3}{2}} + \frac{2}{5}\left((c^2/4 + H_w)^{\frac{5}{2}} - (c^2/4)^{\frac{5}{2}}\right)\right]$$

  - Q is the flowrate
  - c is the coefficient relating the change in radius with height, $r=cz^{1/2}$
  - K is the hydraulic conductivity
  - t is the thickness
  - H_w is the height of the water

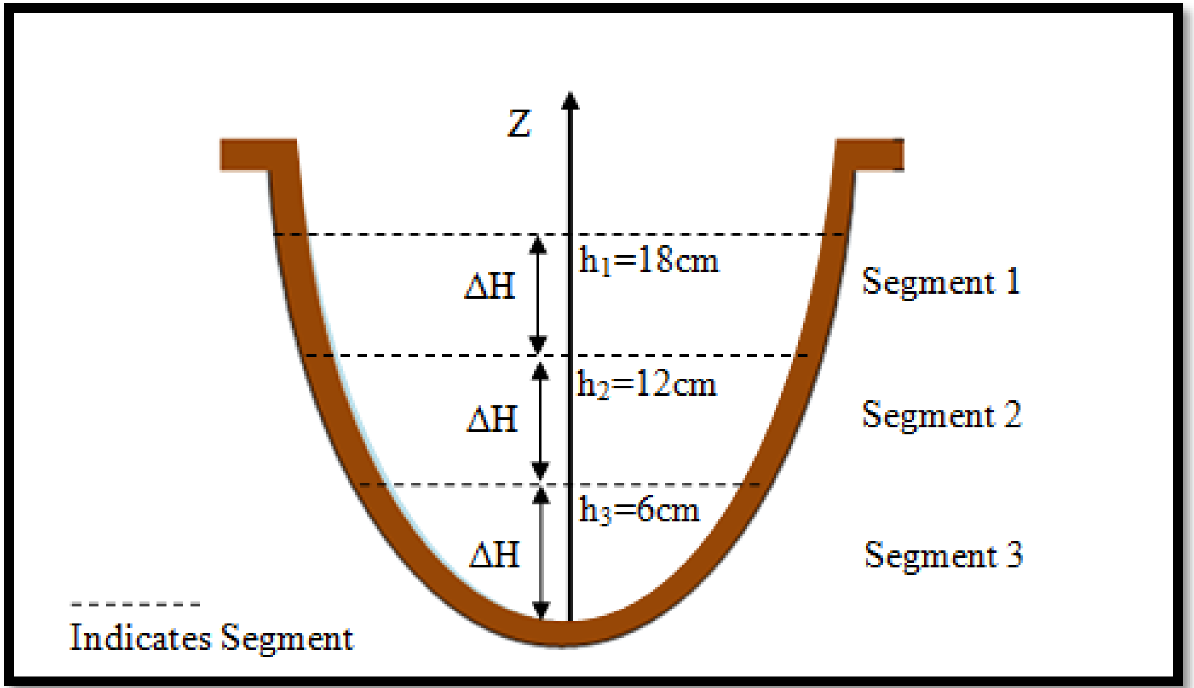
1.Determining Weighted Ave. K

- Three methods were used to determine K with height
- Using the drawdown data, the weighted average K was found for each interval measured by fitting the model to the measured flowrate

2.Determing K: Three Segments

- The hydraulic conductivity of three large segments was calculated using drawdown data

$$K_1 = \frac{t}{A_1 \Delta H}\left(\frac{4V_1}{\Delta T_1} - \frac{16V_2}{\Delta T_2} + \frac{32V_3}{\Delta T_3}\right)$$

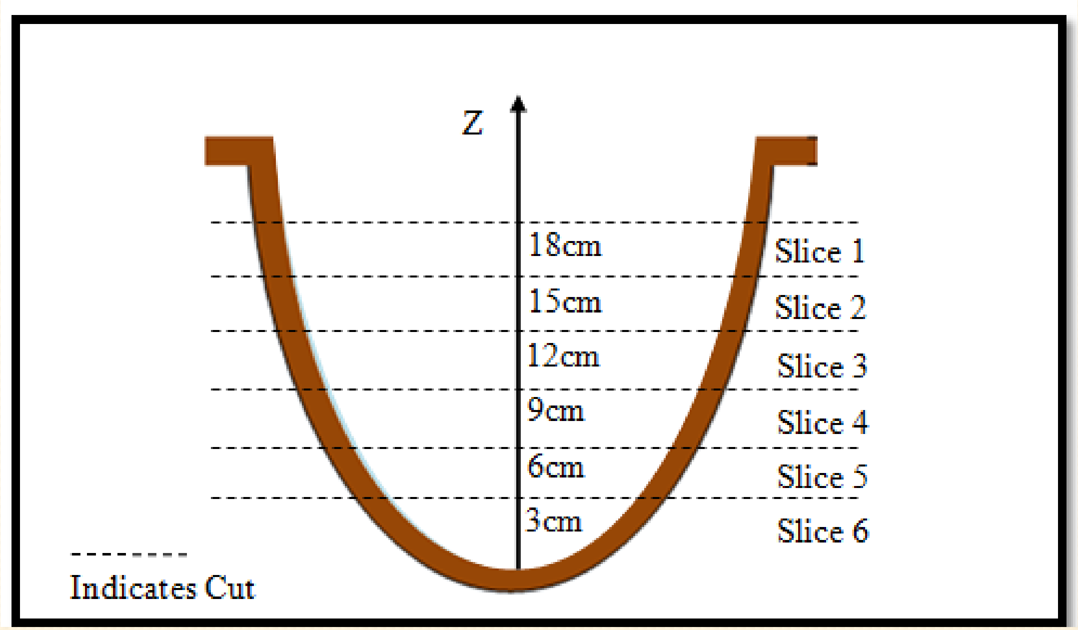


$$K_2 = \frac{t}{A_2 \Delta H}\left(\frac{4V_2}{\Delta T_2} - \frac{16V_3}{\Delta T_3}\right)$$

$$K_3 = \frac{t}{A_3 \Delta H}\left(\frac{4V_3}{\Delta T_3}\right)$$

3.Determing K of Filter Slices

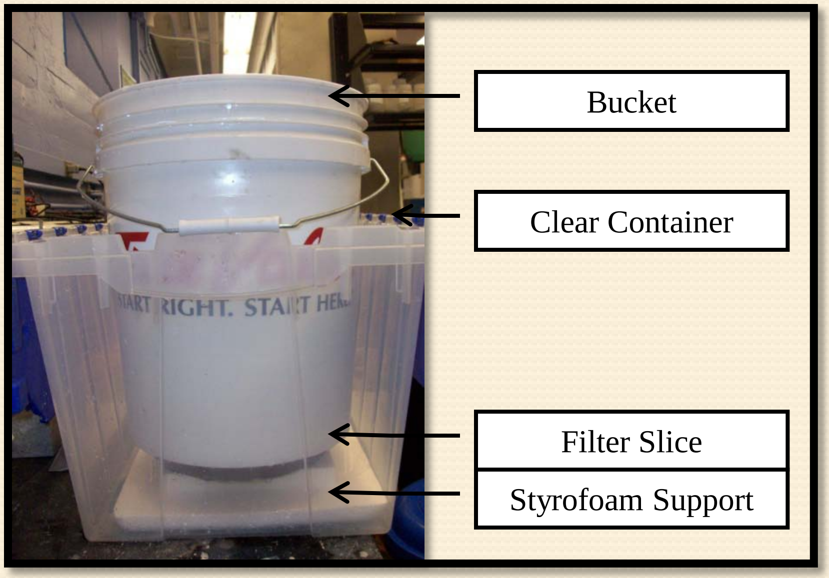
- The filter was cut into 6 slices, and the flow through each was measured and modeled



$$Q = \frac{4\pi cK}{3t}\left[\left((H_w - H_U)(c^2/4 + H_U)^{\frac{3}{2}} - (H_w - H_L)(c^2/4 + H_L)^{\frac{3}{2}}\right) + \frac{2}{5}\left((c^2/4 + H_U)^{\frac{5}{2}} - (c^2/4 + H_L)^{\frac{5}{2}}\right)\right]$$

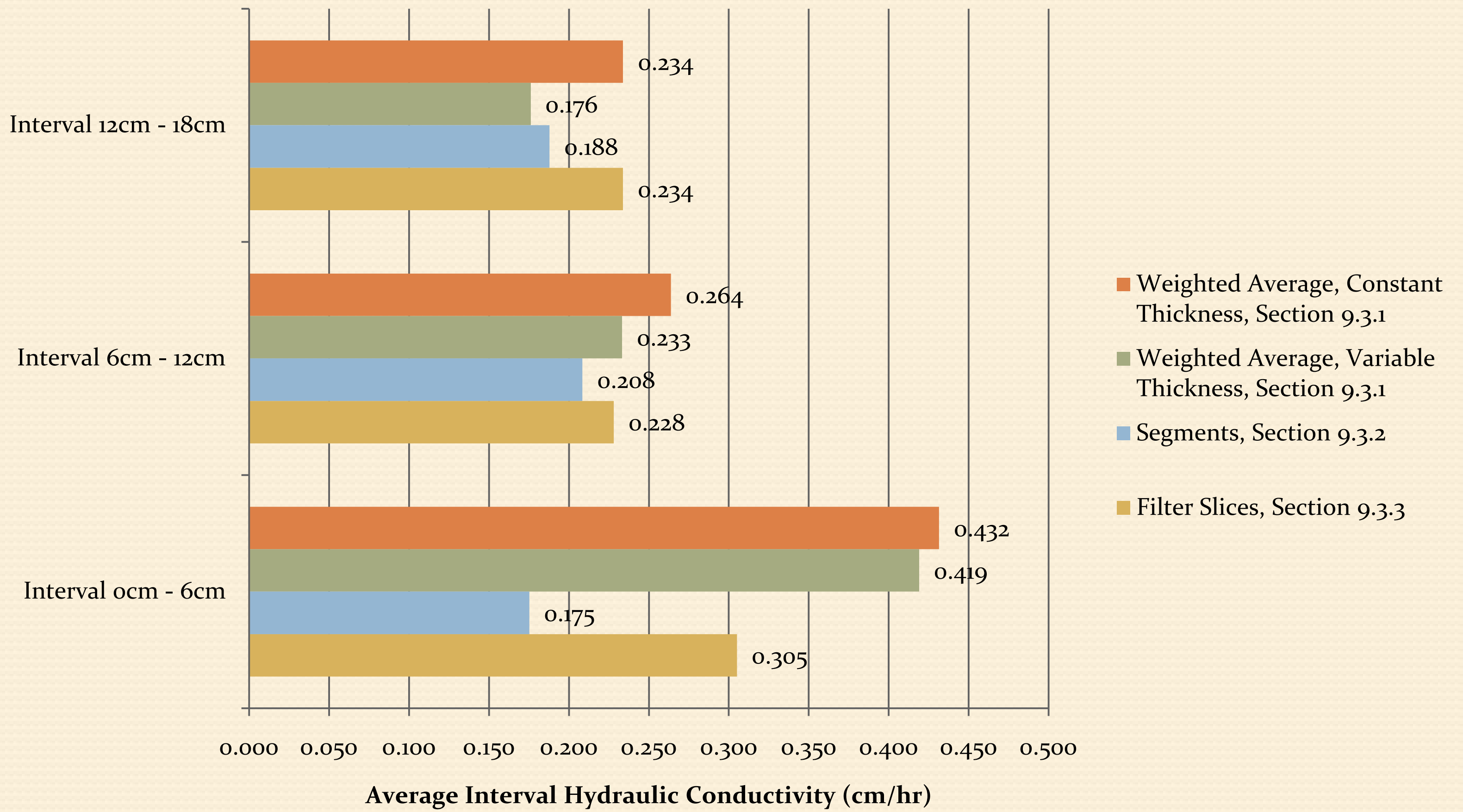
3.Determining K of Filter Slices

- The slices were attached to the bottoms of buckets with holes cut out, and placed inside containers



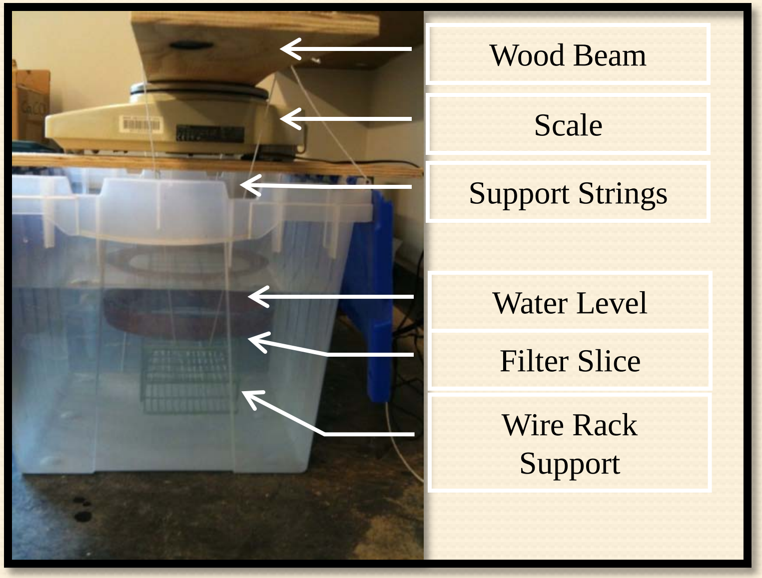
Results: Hydraulic Conductivity

- Hydraulic Conductivity constant, ~0.22 cm/hr



Determining Total Porosity

- The total porosity, V_{voids}/V_{filter} of the filter slices was also determined
  - $V_{voids} = M_{Saturated} - V_{Dry}$
  - V_{filter} was found by displacement of water



Results: Porosity of Filter Slices

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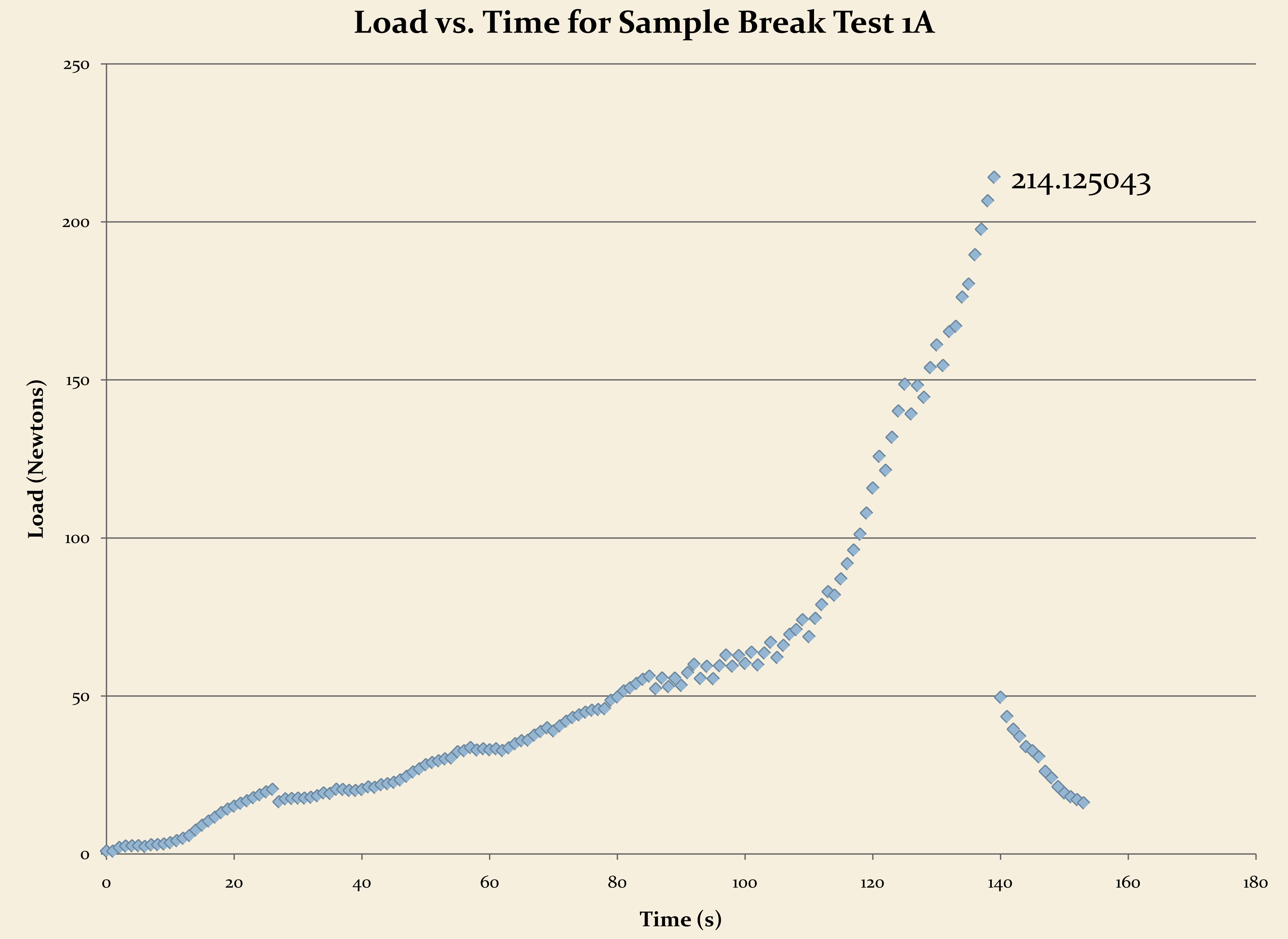
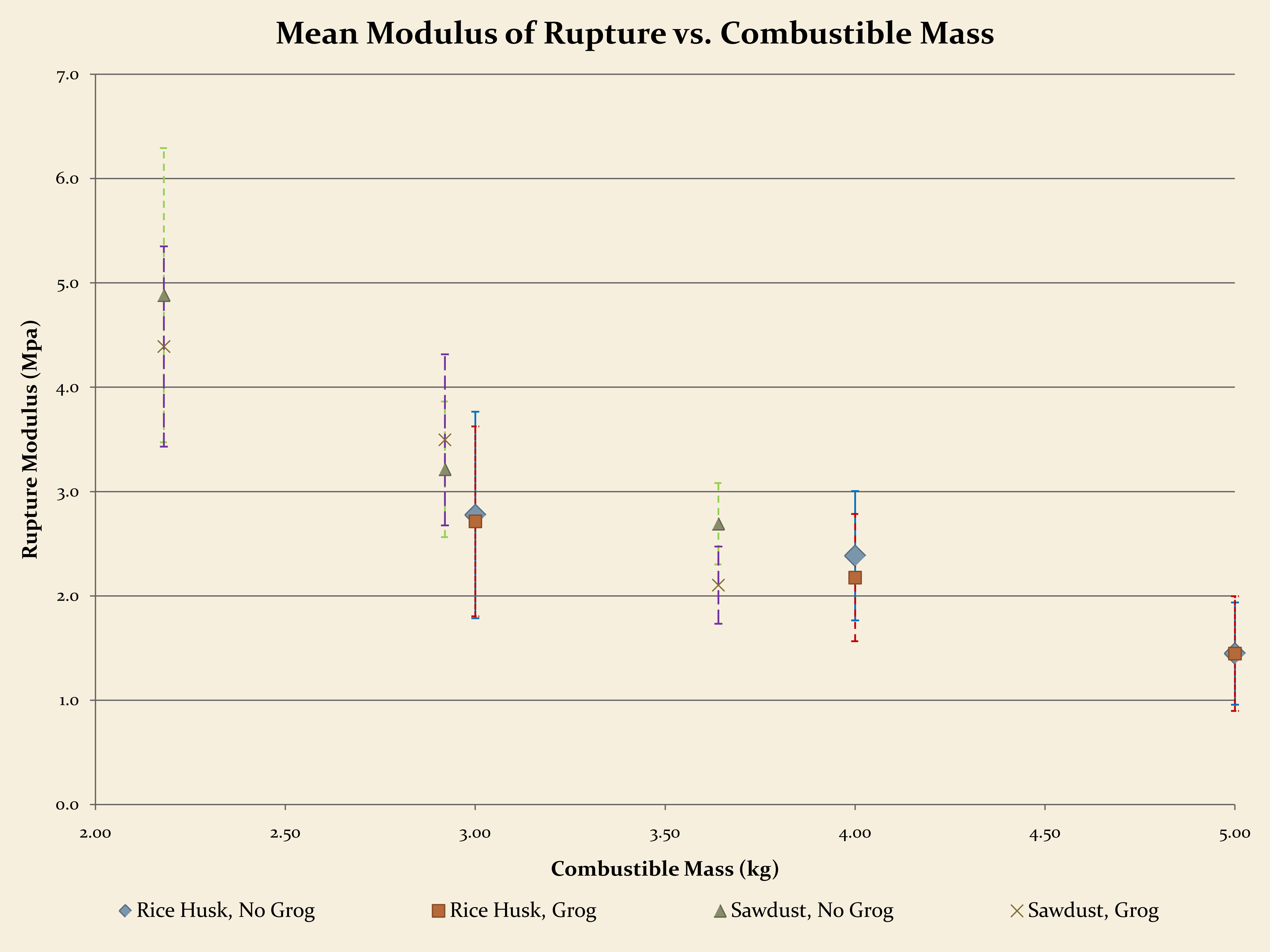
MTS
6D
INSTRON


Load vs. Time for Sample Break Test 1A
Load (Newtons)
Time (s)
214.125043
0
50
100
150
200
250
0
20
40
60
80
100
120
140
160
180

Questions

- How Does Combustible Mass Affect Bending Strength?



Mean Modulus of Rupture vs. Combustible Mass
Rupture Modulus (Mpa)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Combustible Mass (kg)
Rice Husk, No Grog
Rice Husk, Grog
Sawdust, No Grog
Sawdust, Grog

Comparison of Mean Modulus of Rupture Between Recipes with Incrementally Differing Combustible Mass, 95% Confidence

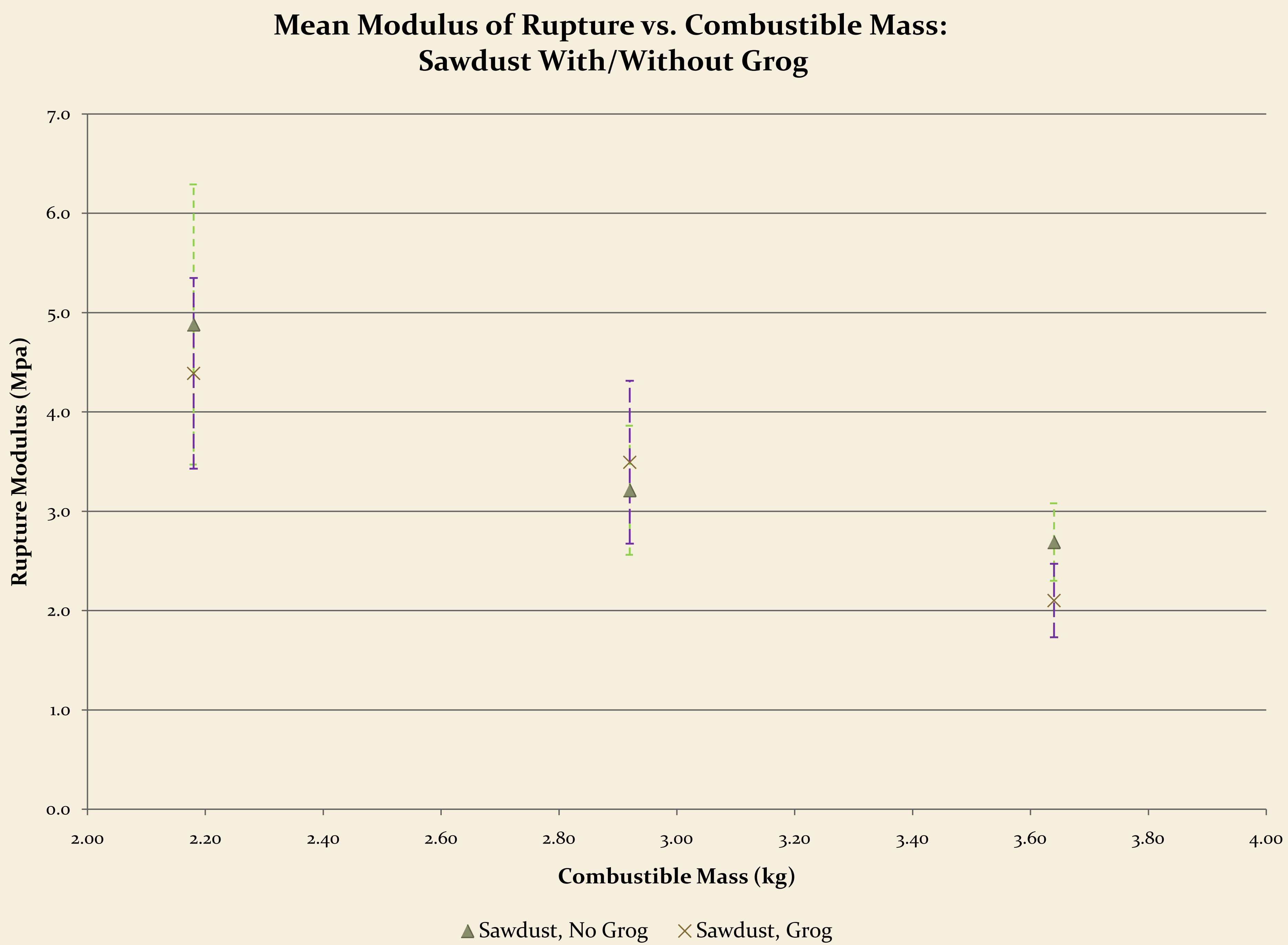
Test	t	$T_{.05}$	$t>T_{.05}$?
1>3	1.0	1.746	FALSE
2>4	1.5	1.746	FALSE
3>5	3.4	1.761	TRUE
4>6	2.7	1.746	TRUE
7>9	3.2	1.746	TRUE
8>10	2.1	1.746	TRUE
9>11	2.1	1.746	TRUE
10>12	4.7	1.746	TRUE

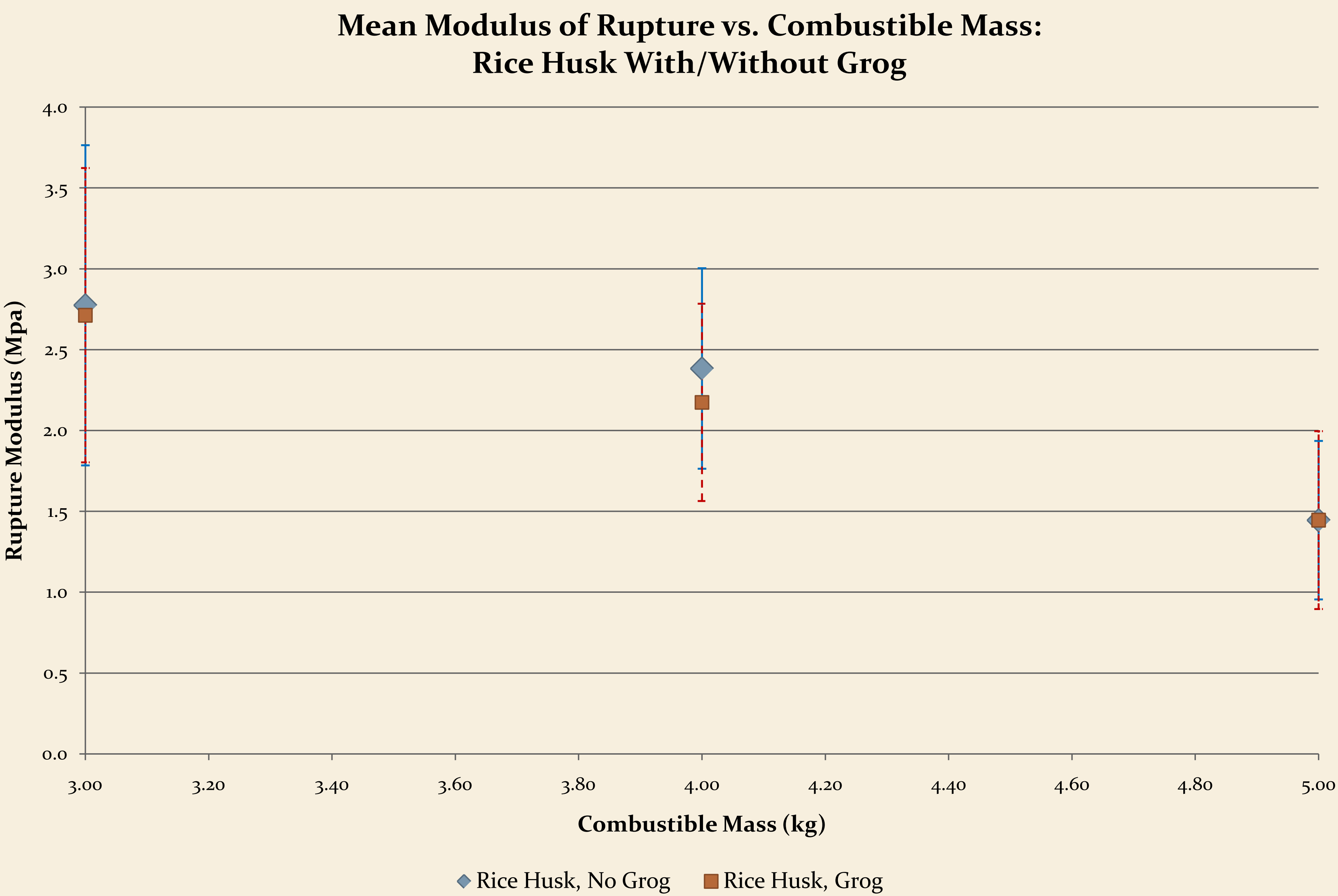
Questions

- How Does Combustible Mass Affect Bending Strength?
  - In general, increasing the mass of combustible causes a decrease in bending strength.

Questions

- How Does the Inclusion of Grog Affect Bending Strength?


Mean Modulus of Rupture vs. Combustible Mass:
Sawdust With/Without Grog
Rupture Modulus (Mpa)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
Combustible Mass (kg)
Sawdust, No Grog
Sawdust, Grog



Mean Modulus of Rupture vs. Combustible Mass:
Rice Husk With/Without Grog
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Rupture Modulus (Mpa)
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
4.60
4.80
5.00
Combustible Mass (kg)
Rice Husk, No Grog
Rice Husk, Grog

Comparison of Mean Modulus of Rupture Between Recipes With and Without Grog, 95% Confidence

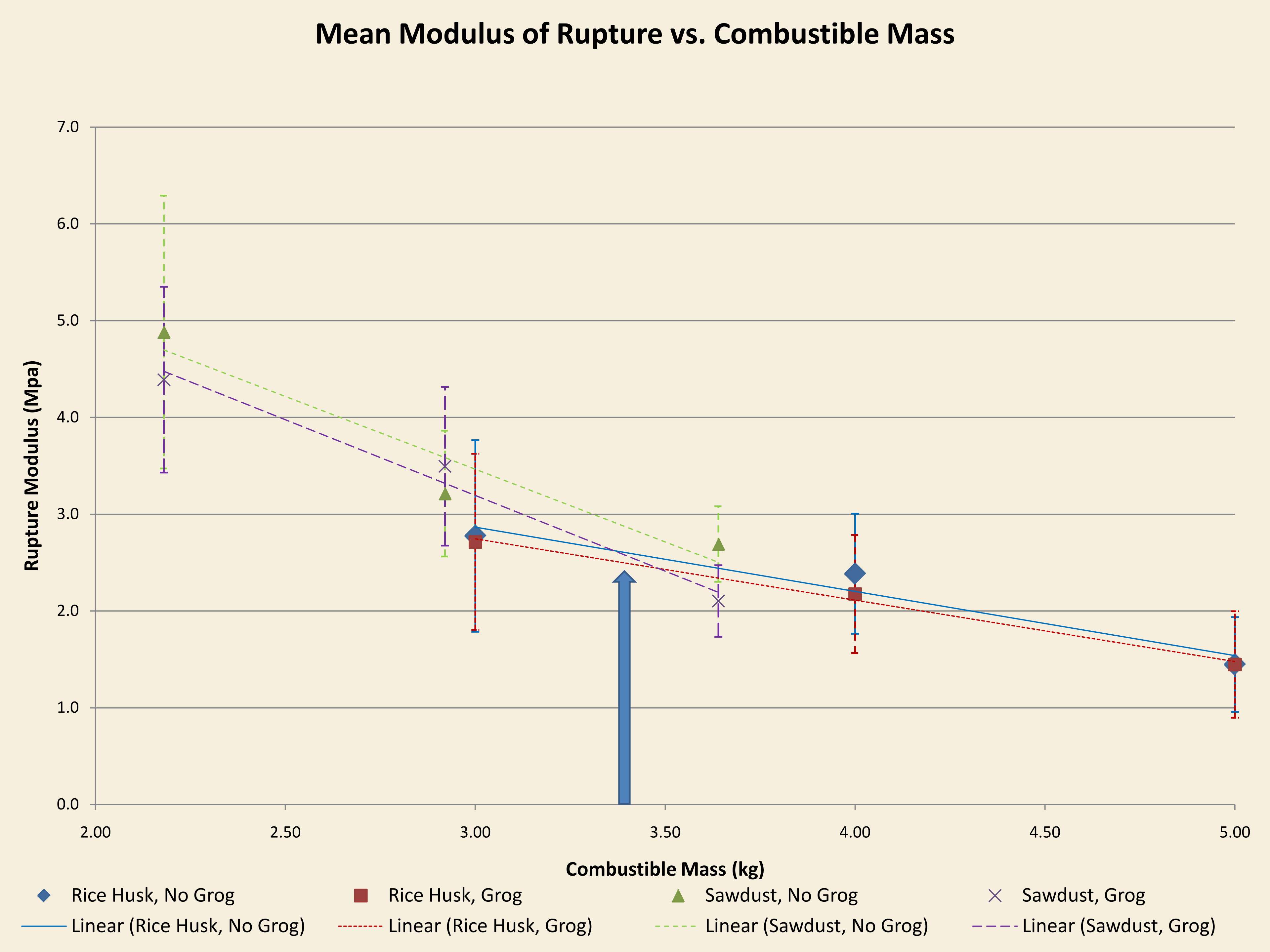
Test	t	$T_{.05}$	$t>T_{.05}$?
1>2	0.14	1.746	FALSE
3>4	0.72	1.746	FALSE
6>5	.0011	1.761	FALSE
7>8	0.86	1.746	FALSE
10>9	0.81	1.746	FALSE
11>12	3.3	1.746	TRUE

Questions

- How Does the Inclusion of Grog Affect Bending Strength?
  - In general, the inclusion of grog does not statistically significantly impact bending strength.

Questions

- Which is Stronger in Bending – Recipes with Sawdust or Recipes with Rice Husk?



Mean Modulus of Rupture vs. Combustible Mass
Rupture Modulus (Mpa)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Combustible Mass (kg)
Rice Husk, No Grog
Rice Husk, Grog
Sawdust, No Grog
Sawdust, Grog
Linear (Rice Husk, No Grog)
Linear (Rice Husk, Grog)
Linear (Sawdust, No Grog)
Linear (Sawdust, Grog)

Comparison of Mean Modulus of Rupture for Recipes Containing Similar Masses of Different Combustible Types, 95% Confidence

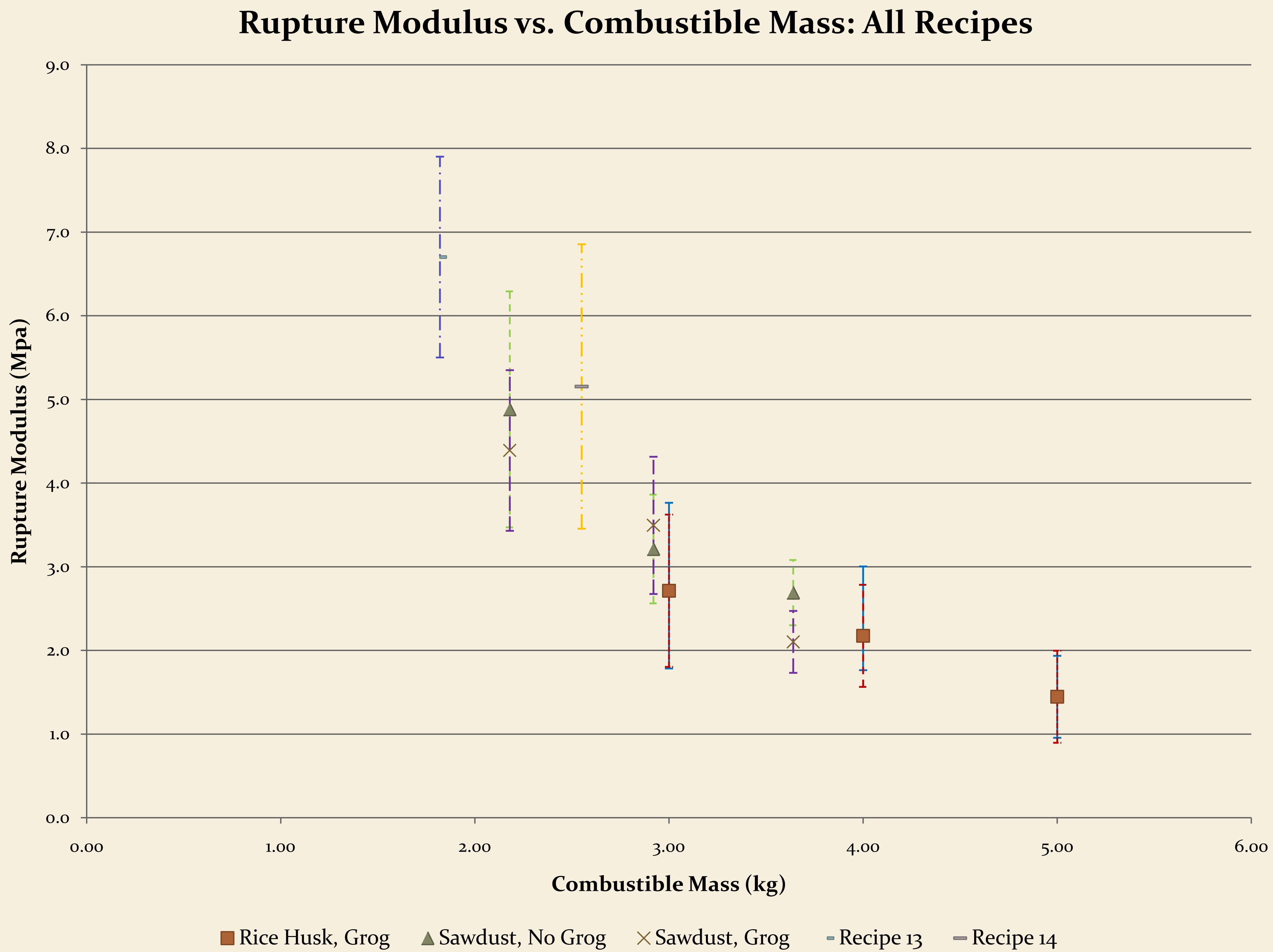
Test	t	$T_{.05}$	$t>T_{.05}$?
9>1	1.1	1.746	FALSE
10>2	1.9	1.746	TRUE

Questions

- Which is Stronger in Bending – Recipes with Sawdust or Recipes with Rice Husk?
  - Statistically significant conclusions cannot be drawn from the available data.

Questions

- How does the Bending Strength of the Recipes Compare Overall?


Rupture Modulus vs. Combustible Mass: All Recipes
Rupture Modulus (Mpa)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Combustible Mass (kg)
Rice Husk, Grog
Sawdust, No Grog
Sawdust, Grog
Recipe 13
Recipe 14

Simple Rank Ordering of Mean Modulus of Rupture

Recipe #	Rank	R_{mean} (Mpa)
13	1	6.7
14	2	5.2
7	3	4.9
8	4	4.4
10	5	3.5
9	6	3.2
1	7	2.8
2	8	2.7
11	9	2.7
3	10	2.4
4	11	2.2
12	12	2.1
6	13	1.4
5	14	1.4

95% Confidence Tiered Rank Ordering of Mean Modulus of Rupture

Recipe #s	Rank	Stronger Than:
13	1’	14
14,7,8	2’	10
10	3’	2
9	4’	11
11	5’	4
1,2	6’	12
3,4,12	7’	6
6,5	8’	None

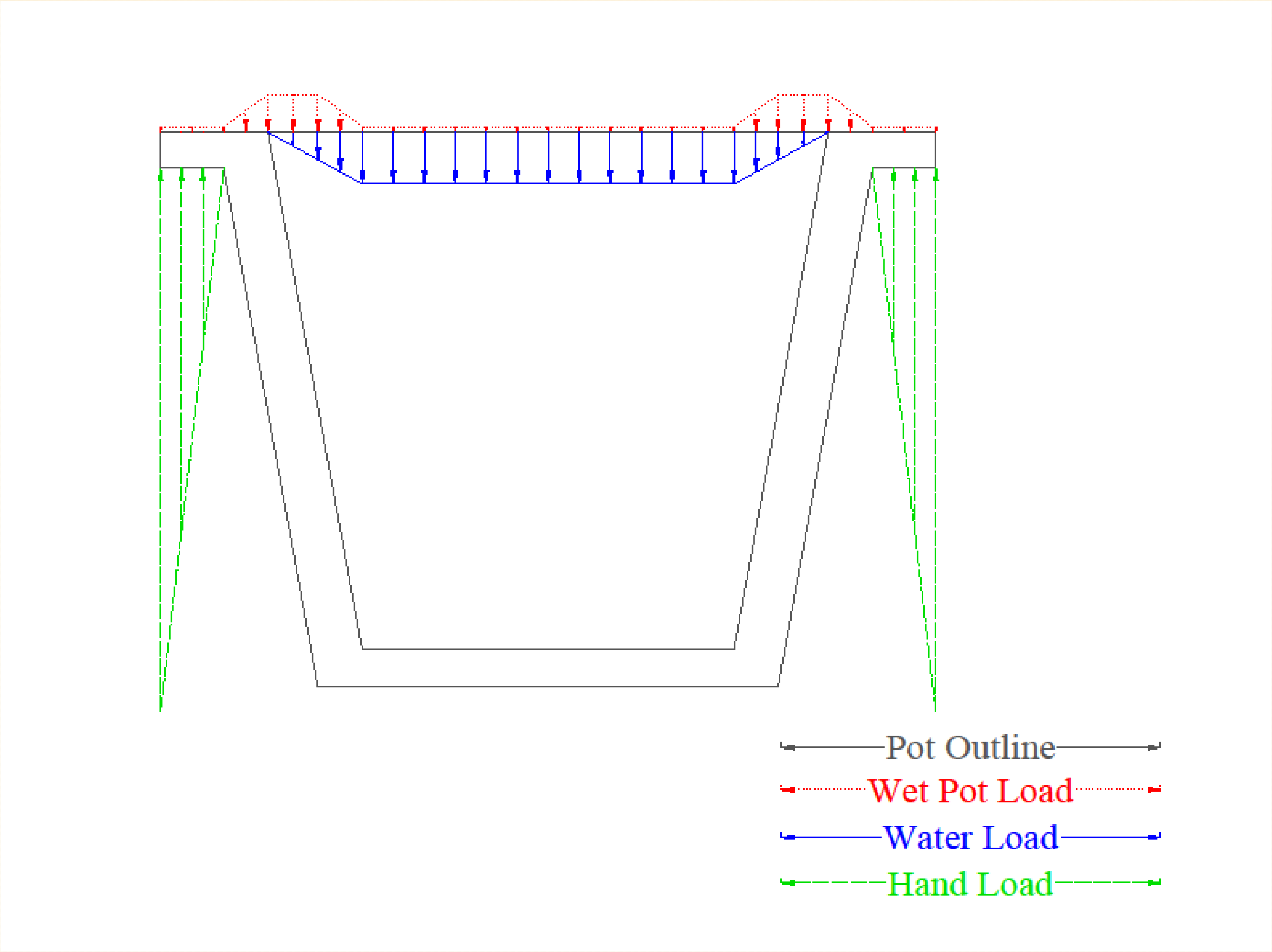
Questions

- How does the Bending Strength of the Recipes Compare Overall?
  - Recipes 13 and 14, whose manufacturing process included only fine materials, are strongest.
  - There is a generally decreasing trend in strength as combustible mass is added.
  - Recipes 6 and 5, containing the greatest combustible mass, are weakest.

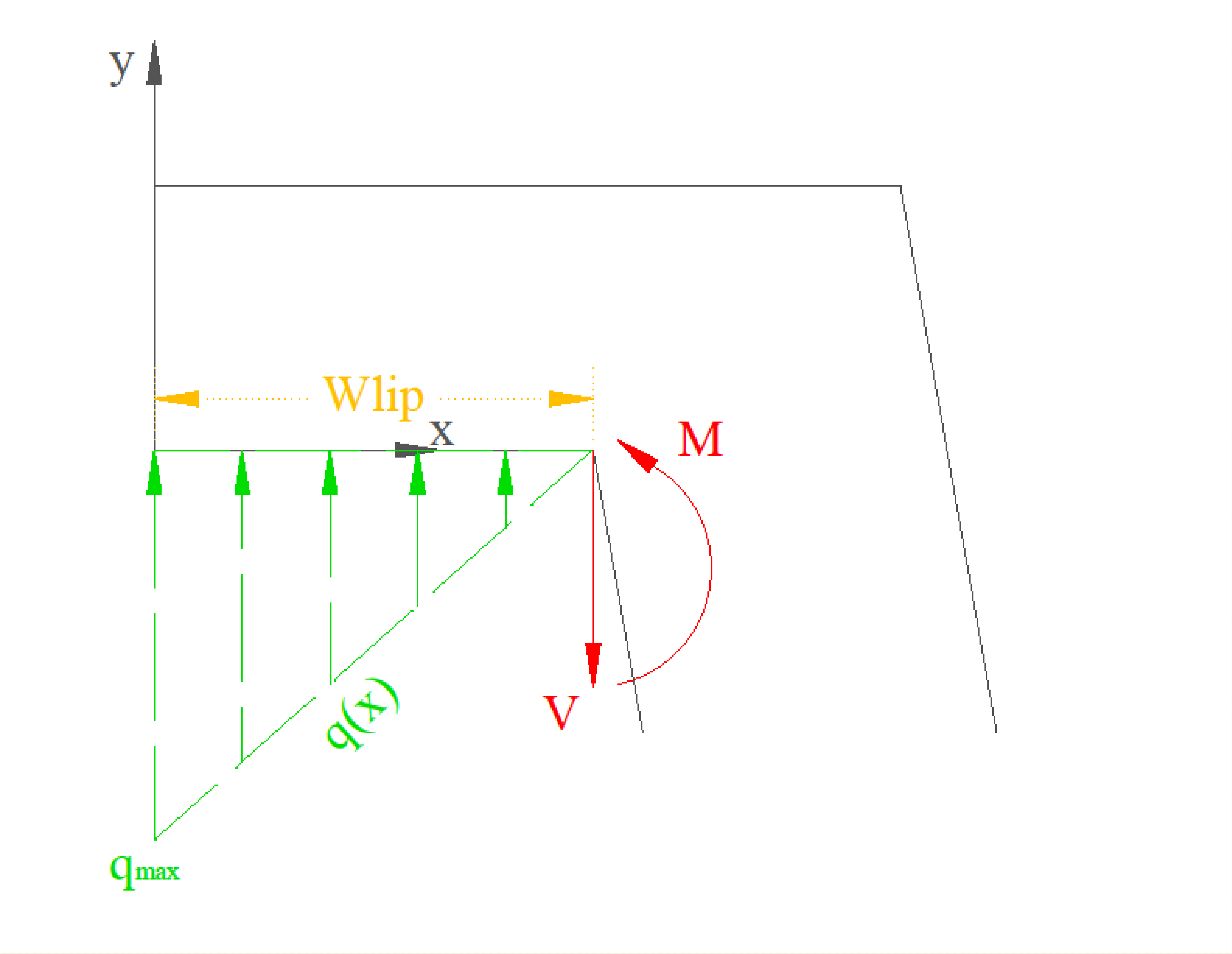
Questions

- How do the Observed Bending Strengths Compare to Common Loading Conditions?

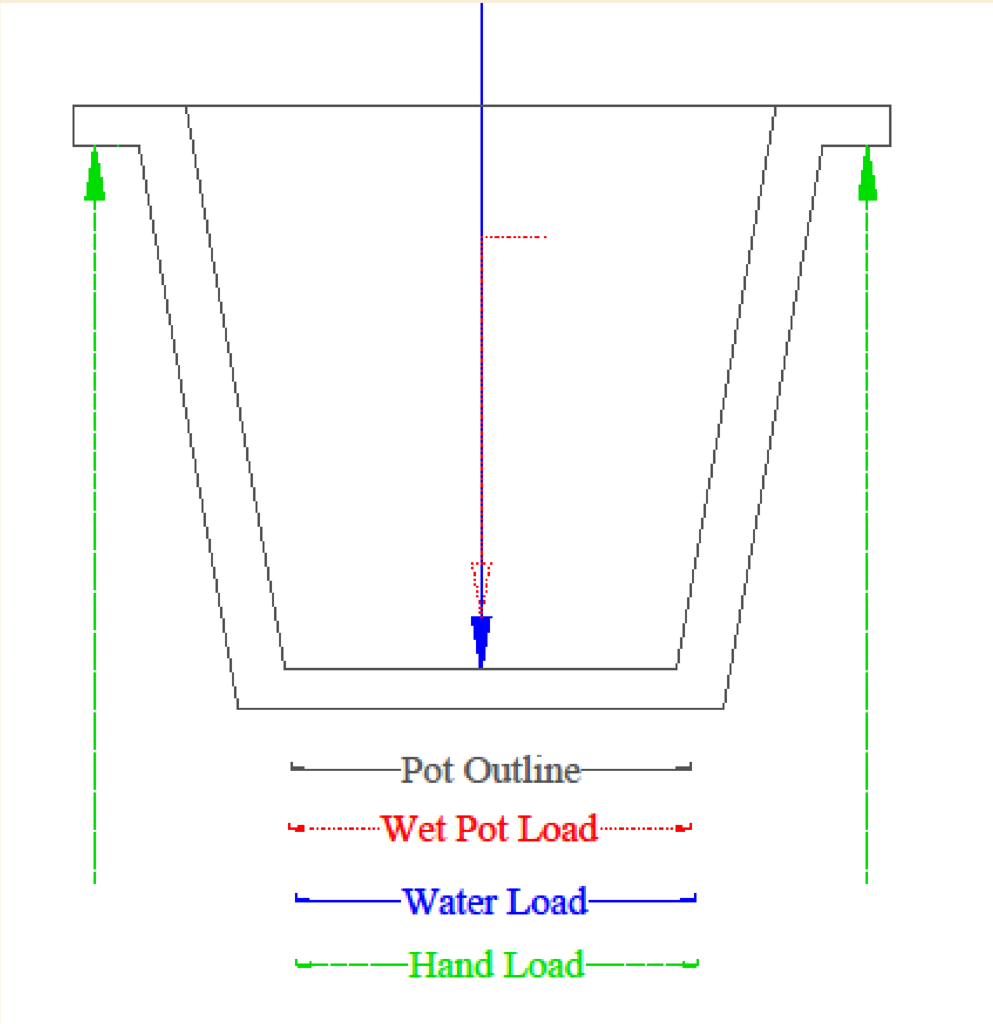
Modeling of Common Loading Condition



Model of the Loading Condition of the Filter Lip



Resultants



Comparison of Lower Bound of 95% Confidence Interval for Mean Modulus of Rupture to Expected Bending Stress

Recipe #	Lower Bound (Mpa)	>0.45Mpa (Full Pot)?	>.20Mpa (Empty Pot)?
13	5.8	YES	YES
14	3.9	YES	YES
7	3.8	YES	YES
8	3.7	YES	YES
10	2.9	YES	YES
9	2.7	YES	YES
1	2.0	YES	YES
2	2.0	YES	YES
11	2.4	YES	YES
3	1.9	YES	YES
4	1.7	YES	YES
12	1.8	YES	YES
6	1.0	YES	YES
5	1.0	YES	YES

Probability that the Modulus of Rupture of a Particular Sample from a Given Recipe will be Less than the Expected Bending Stress Arising from A Full Water Load

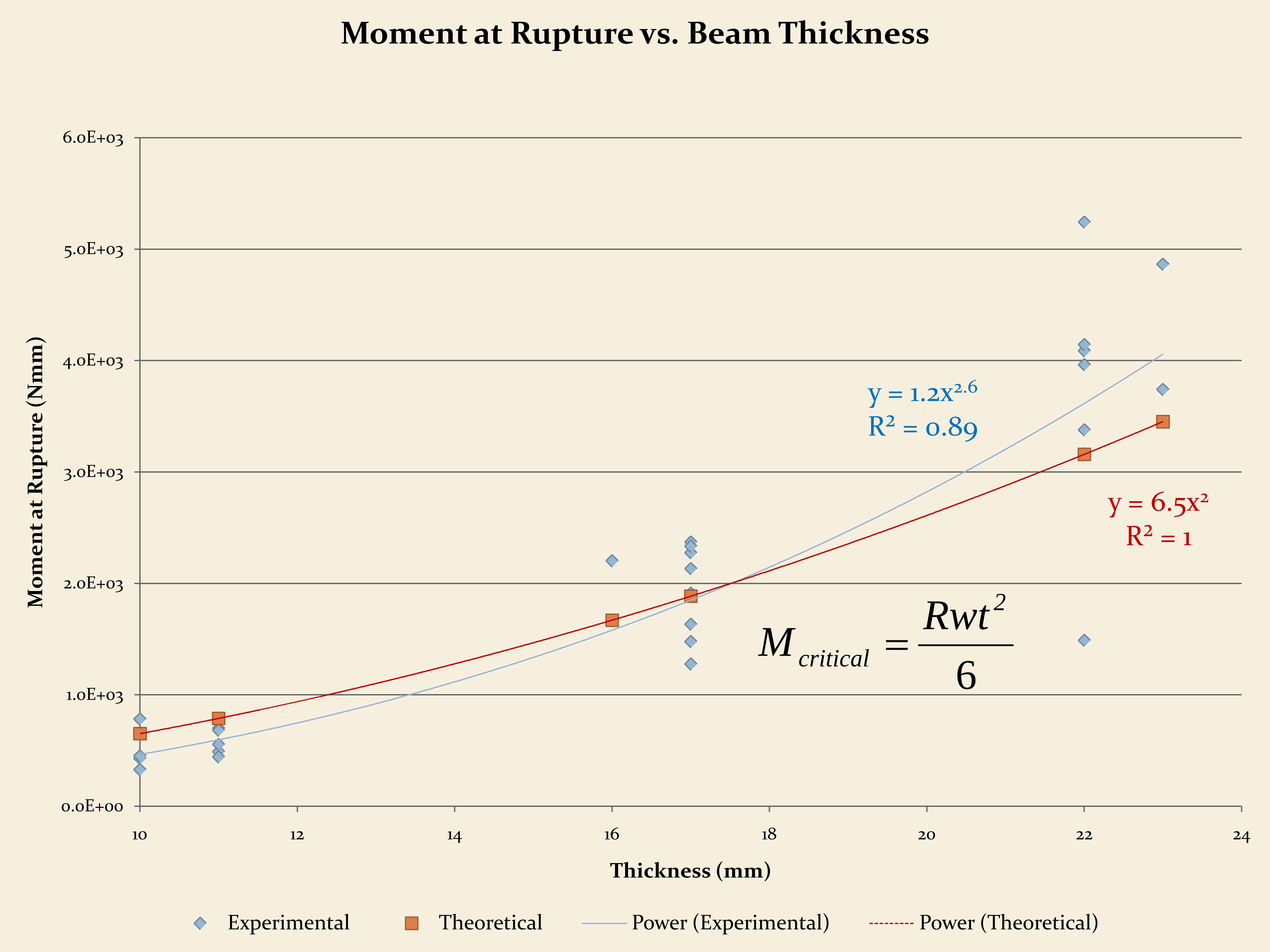
Recipe #	Probability that R < .45 Mpa
13	0.000000
14	0.0026
7	0.0074
8	0.000019
10	0.00010
9	0.000012
1	0.0088
2	0.0067
11	0.000000
3	0.00083
4	0.0021
12	0.000004
6	0.042
5	0.026

Questions

- How do the Observed Bending Strengths Compare to Common Loading Conditions?
  - The expected bending loads are far below the lower bound of the mean bending strength of the tested recipes (weakest mix: 1 Mpa > 0.45 Mpa)
  - The maximum probability of failure under expected loading conditions is 0.042 (4.2%). Rate of breakage reported in Ghana is 0.11 (11%).

Questions

- How Does Thickening the Lip Affect the Maximum Allowable Moment?


Moment at Rupture vs. Beam Thickness
Moment at Rupture (Nmm)
6.0E+03
5.0E+03
4.0E+03
3.0E+03
2.0E+03
1.0E+03
0.0E+00
10
12
14
16
18
20
22
24
Thickness (mm)
y = 1.2x2.6
R2 = 0.89
y = 6.5x2
R2 = 1
Mcritical = Rwt2 / 6
Experimental
Theoretical
Power (Experimental)
Power (Theoretical)

Comparison of Allowable Moment for Samples of Varying Thickness, 95% Confidence

Test	t	$T_{.05}$	$t>T_{.05}$?
$M_{max,medium}>M_{max,thin}$	9.8	1.746	TRUE
$M_{max,thick}>M_{max,medium}$	4.7	1.746	TRUE

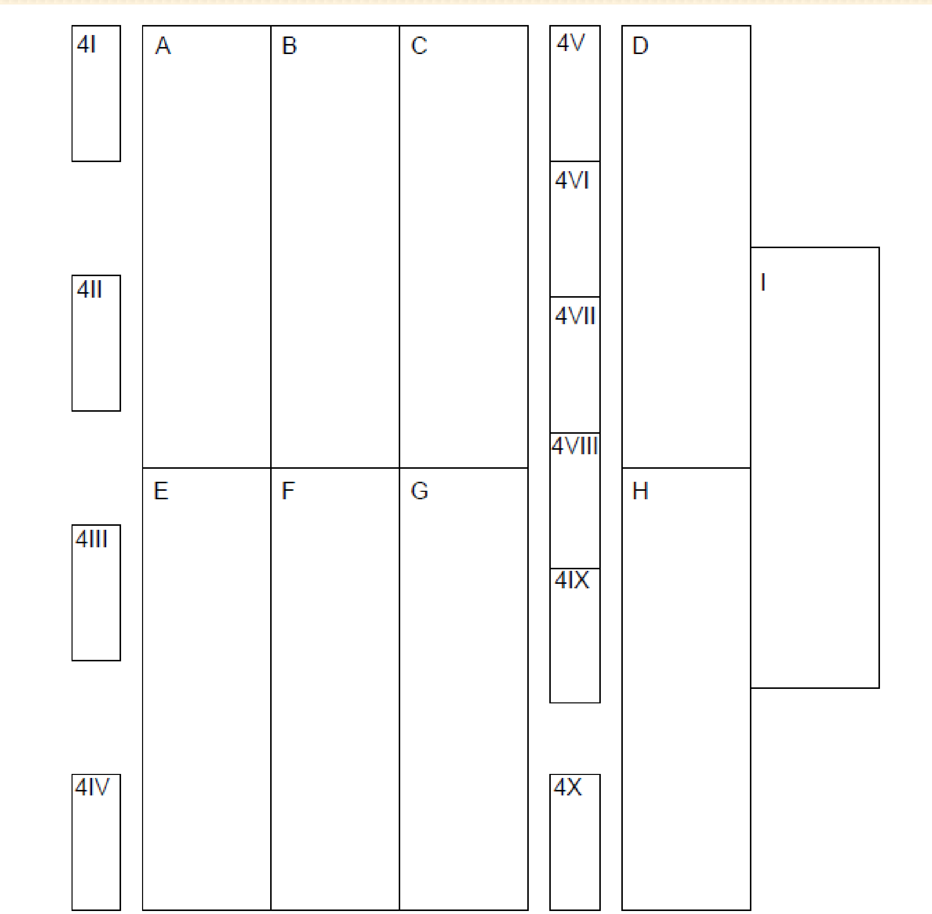
Questions

- How Does Thickening the Lip Affect the Maximum Allowable Moment?
  - The maximum allowable moment increases with *at least* the square of the thickness

Questions

- What is the Effect of Kiln Position on Bending Strength?

Schematic of Kiln Loading (Left) and Photograph of Pyrometric Cones after Firing with Relative Positions Preserved (Right)




Modulus of Rupture vs. Combustible Mass: Organized by Kiln Position
Modulus of Rupture
6.0E+00
5.0E+00
4.0E+00
3.0E+00
2.0E+00
1.0E+00
0.0E+00
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Combustible Mass (kg)
Linear (A)
Linear (B)
Linear (C)
Linear (D)
Linear (E)
Linear (F)
Linear (G)
Linear (H)
Linear (I)

Questions

- What is the Effect of Kiln Position on Bending Strength?
  - Samples fired to a higher maturity exhibit generally greater bending strength than samples fired to a lesser maturity.
  - In a particularly dramatic case, recipe #1 exhibited a 3.6-fold increase in strength in position E as compared to position H

Recommendations

- Geometry
  - It is recommended that the filter lip be thickened to 25mm. This will increase shear capacity by 66% and moment capacity by 180% with a 10% material increase.
- Firing
  - After first four hours, witness cones in door and spyhole must be checked hourly. Once guide cone bends, cones must be checked every fifteen minutes.
  - Communication must be maintained with consultant Manny Hernandez to alter kiln configuration until sufficiently even heating is attained.
  - Being that shear and bending are well beyond the expected loads, control of this variable may be key to filter durability

Outline

- Project Overview
- Filter Performance
  - Goal
  - Study Design
  - Results
- Filter Durability
  - Questions
  - Results
  - Recommendations
- **Combined Recommendations**
- Paraboloid Filter Flow
  - Goal
  - Study Design
  - Results

Design Variables and Parameters

Key:
+ Variable increases parameter
-- Variable decreases parameter
o No effect

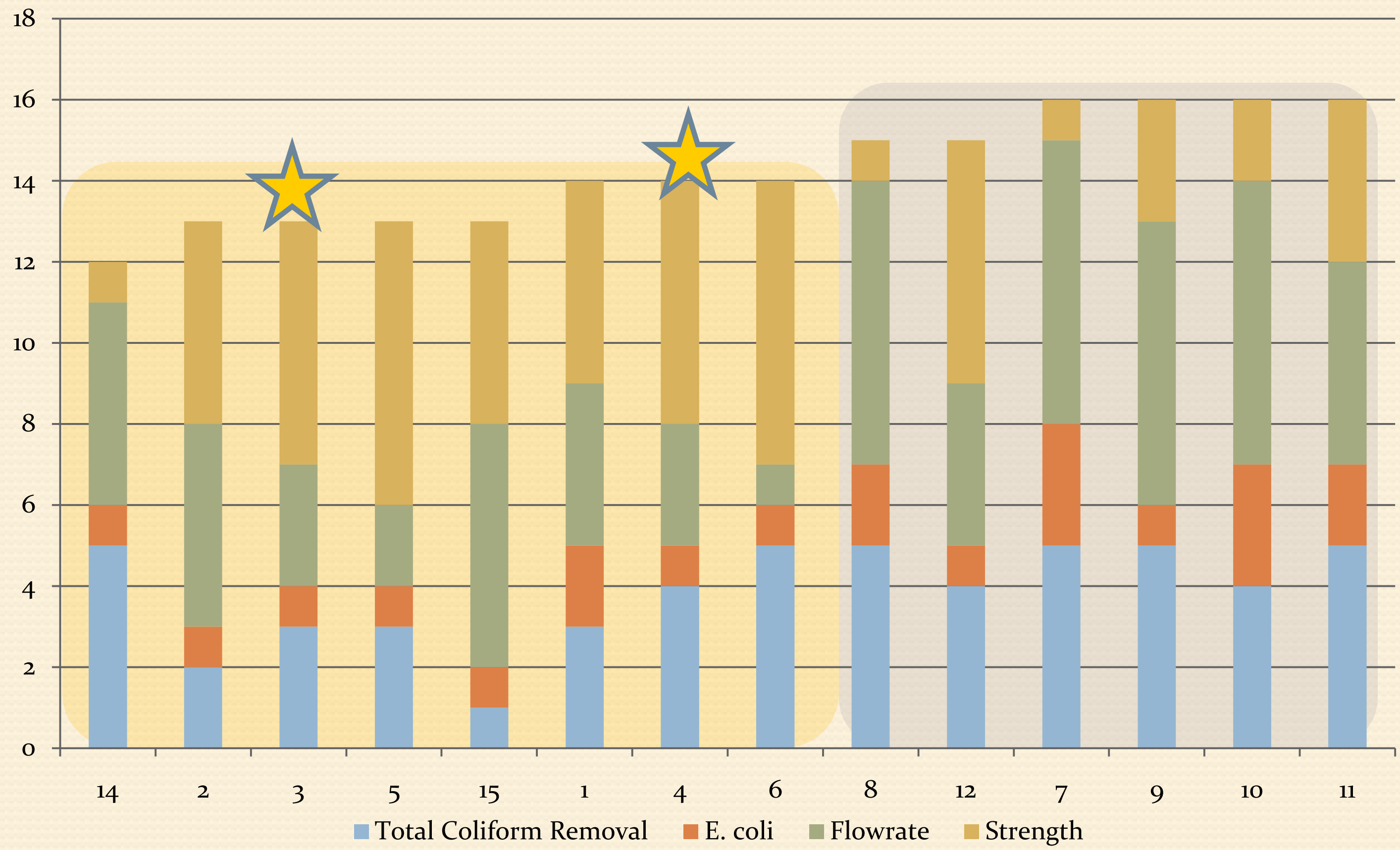
Variable \ Parameter		*E. Coli* Removal	Total Coliform Removal	Flowrate	Turbidity Removal	Strength	**Sum**
Combustible Type	Rice Husk	--	+	+	--	Higher, stronger	**+ + -- --**
	Sawdust	+	--	--	+	Lower, stronger	**+ + -- --**
Addition of Grog	Grog	o	o	o	o	o	**o**
	No Grog	o	o	o	o	o	**o**
Combustible Volume	Low : 43-47%	o	o	--	o	+	**+ --**
	Med: 51-54%	o	o	o	o	o	**o**
	High: 50-56%	o	o	+	o	--	**+ --**
Additional Variables	Sifting	o	o	--	o	+	**+ --**
	Shape	o	o		o	NA	

Design Variables and Parameters

Key:
+ Variable increases parameter
-- Variable decreases parameter
o No effect

Variable \ Parameter		*E. Coli* Removal	Total Coliform Removal	Flowrate	Turbidity Removal	Strength	Sum
Combustible Type	Rice Husk	--	+	+	--	Higher, stronger	+ + --
	Sawdust	+	--	--	+	Lower, stronger	+ -- --
Addition of Grog	Grog	o	o	o	o	o	o
	No Grog	o	o	o	o	o	o
Combustible Volume	Low : 43-47%	o	o	--	o	+	+ --
	Med: 51-54%	o	o	o	o	o	o
	High: 50-56%	o	o	+	o	--	+ --
Additional Variables	Sifting	o	o	--	o	+	+ --
	Shape	o	o		o	NA	

Combined Ranking System



Combined Ranking System

- Tier 1 &2 Filters: 2, 3, 5 and 14
  - Flowrate: 5>3>2>14
  - Filter 14 difficult to make due to sifting
  - Filter 5 is weak
  - Choose Filter 3
- Tier 3 Filters: 1, 4, 6, 15
  - Flowrate: 6>4>1>15
  - Filter 6 is weak
  - Choose Filter 4
    - Paraboloid shape of 15 acceptable

Recommendations to PHW

- Filter design, based on 3 and 4
  - Rice Husk
    - Medium Volume
      - 51%-54% of total mix volume
    - Hammer-milled only
      - Not sifted
  - ~10% Grog by mass if desired by potters for shrinkage
      - No effect
  - Paraboloid or Flower Pot filters
- Coagulate to remove further turbidity

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- Leah Nation – partner in factory construction
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- Gbalhai women potters – Abiba, Semata, Selamatu

The End.