# Effect of Suction on the Resilient Modulus of Compacted Fine-Grained Subgrade Soils

by

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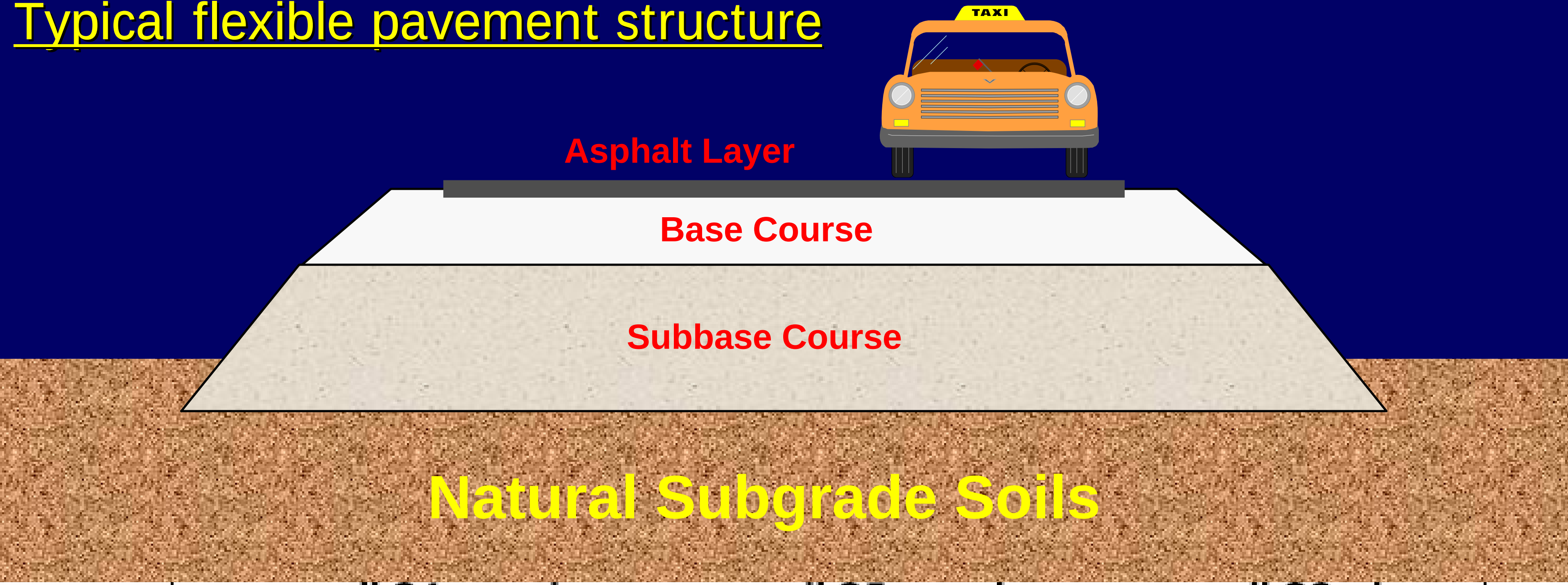
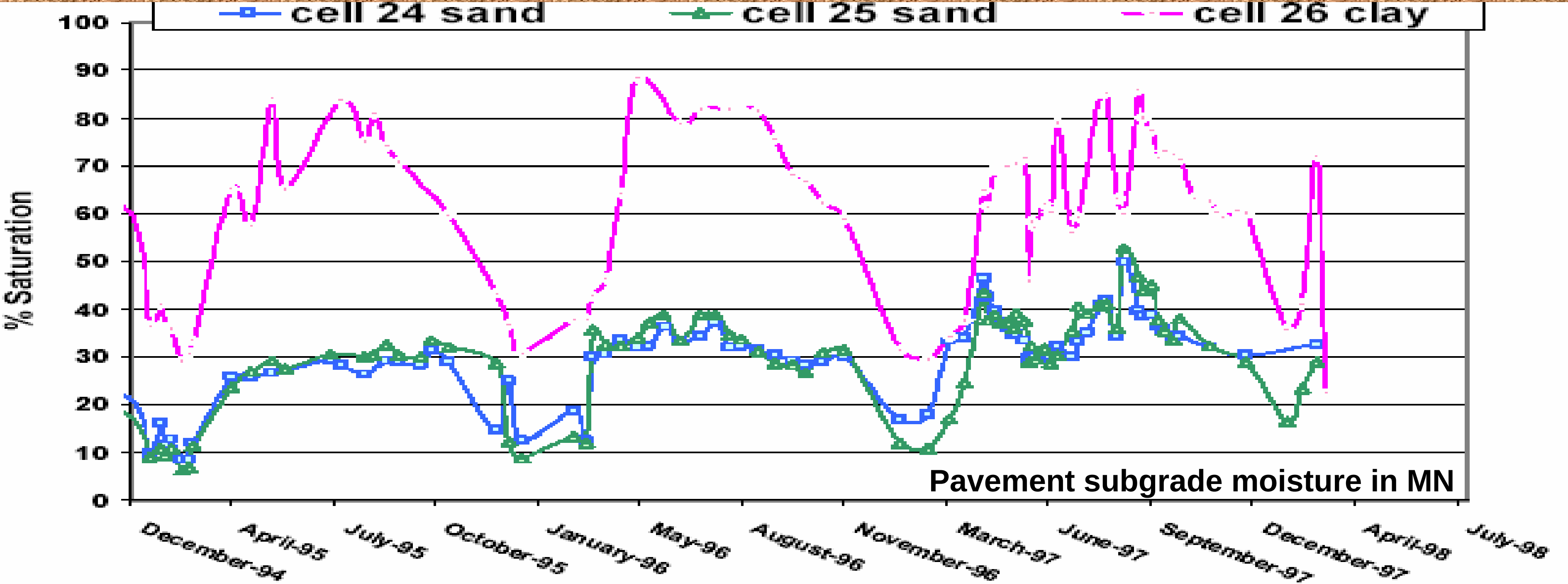
# Outline

- Introduction
- Test Materials
- Testing Program
- Results & Analysis
- Conclusions

# Typical flexible pavement structure

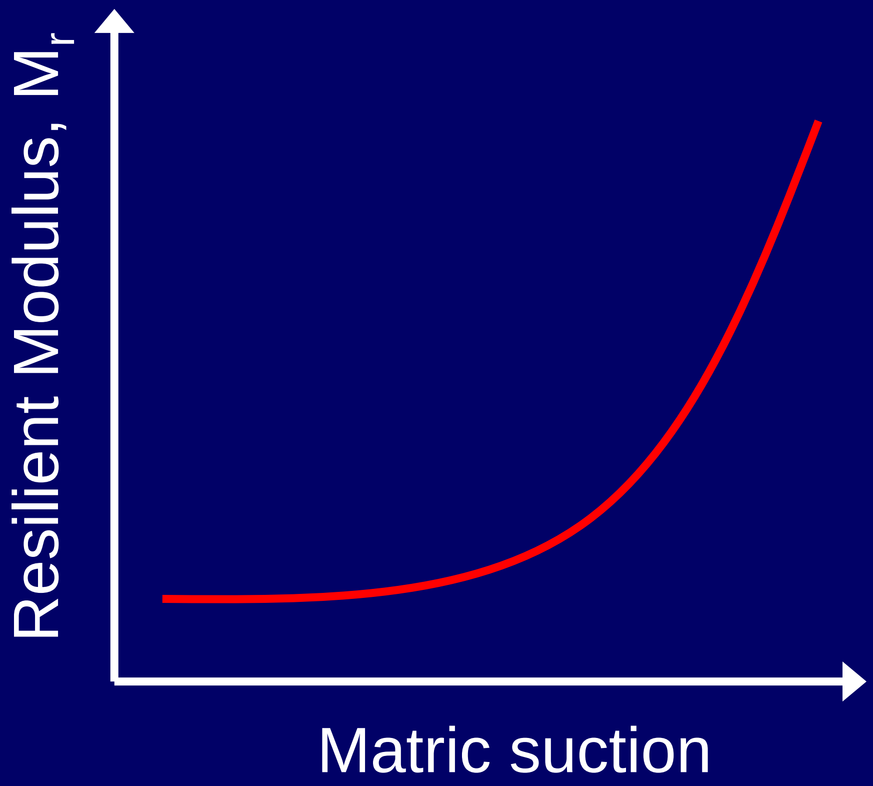


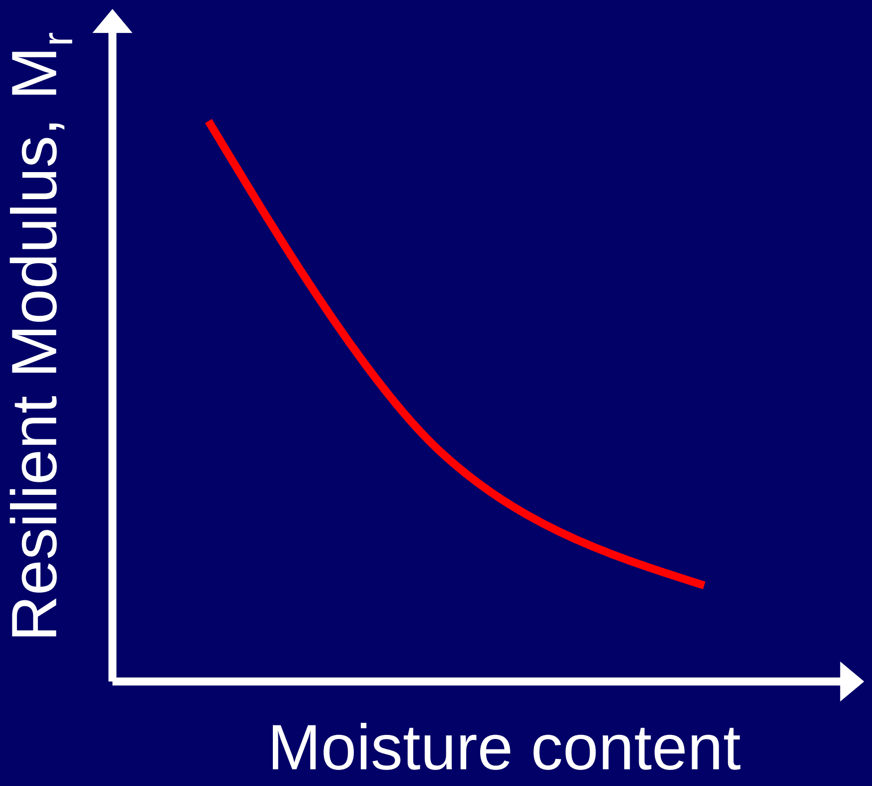



# Introduction

- NCHRP 1-37A addresses this issue by employing the resilient modulus ($M_r$) at an equilibrium degree of saturation for pavement design, and provides a model to predict changes in modulus due to changes in moisture content.

# Conceptual Relationship



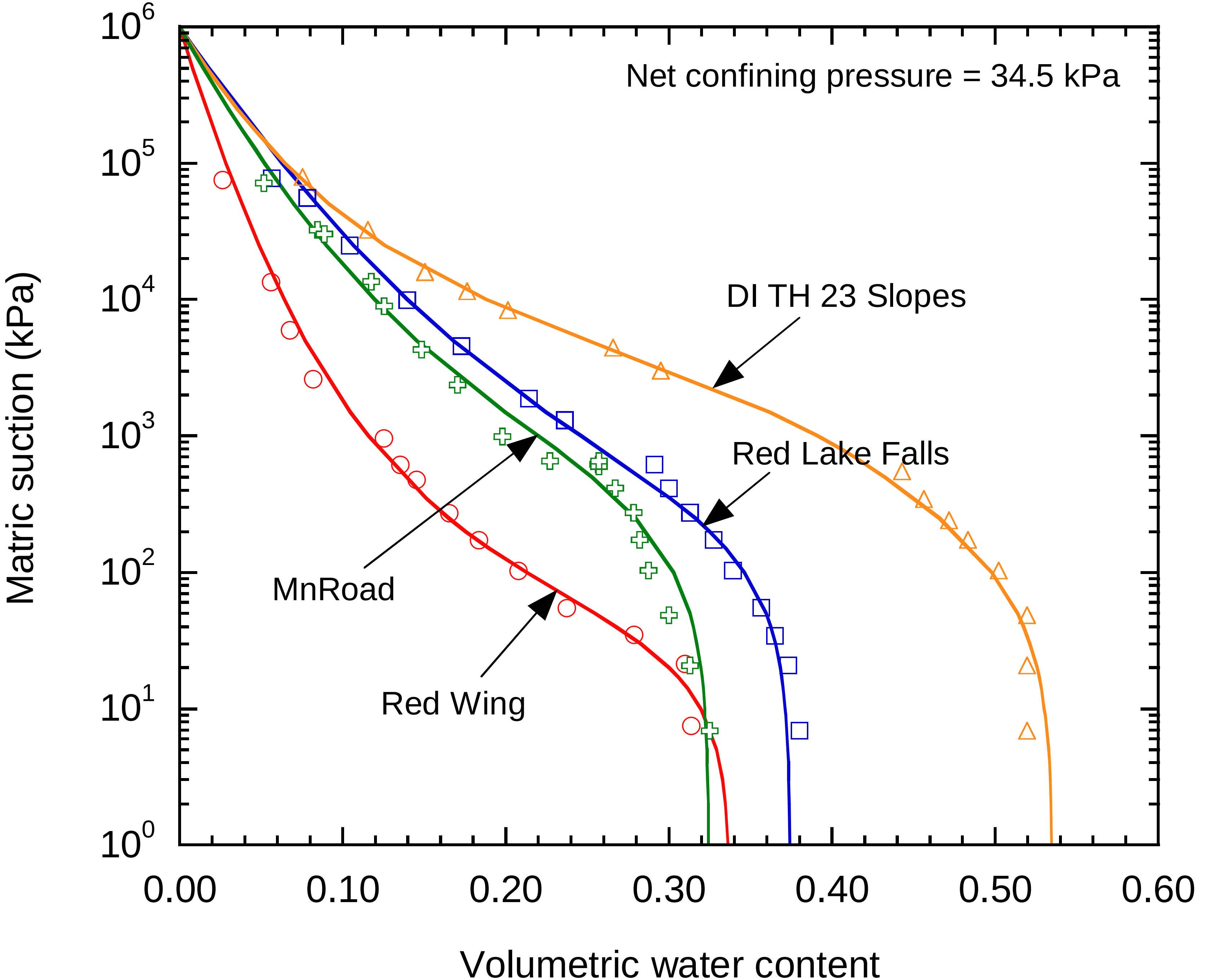




Modulus of unsaturated soils is strongly influenced by matric suction, particularly for compacted fine-grained soils. However, simple predictive relationships between $M_r$ and matric suction have not been defined.

# Objectives

- To investigate $M_r$ of compacted fine-grained subgrade soils having a wide range of plasticity index over a range of matric suctions
- To develop empirical relationships between $M_r$ and matric suction

| Soil Properties | Red Wing, MN | Red Lake Falls, MN | MnRoad, MN | Duluth TH 23 Slopes, MN |
|---|---|---|---|---|
| USCS | ML | CL | CL | CH |
| % Sand | 11.9 | 8.9 | 36.3 | 3.1 |
| % Clay | 5.7 | 27.3 | 14.5 | 75.2 |
| % Fine | 88.1 | 91.1 | 59.7 | 96.4 |
| LL | 28 | 42 | 26 | 85 |
| PI | 11 | 24 | 9 | 52 |
| $G_s$ | 2.69 | 2.69 | 2.66 | 2.75 |
| O.M.C. (%) | 13.5 | 22.0 | 16.0 | 27.5 |
| $\rho_{d,max}$ (t/m$^3$) | 1.79 | 1.58 | 1.77 | 1.44 |



Net confining pressure = 34.5 kPa
DI TH 23 Slopes
Red Lake Falls
MnRoad
Red Wing
Matric suction (kPa)
Volumetric water content
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
0.00
0.10
0.20
0.30
0.40
0.50
0.60

# Testing Program

Phase I: Suction Conditioning

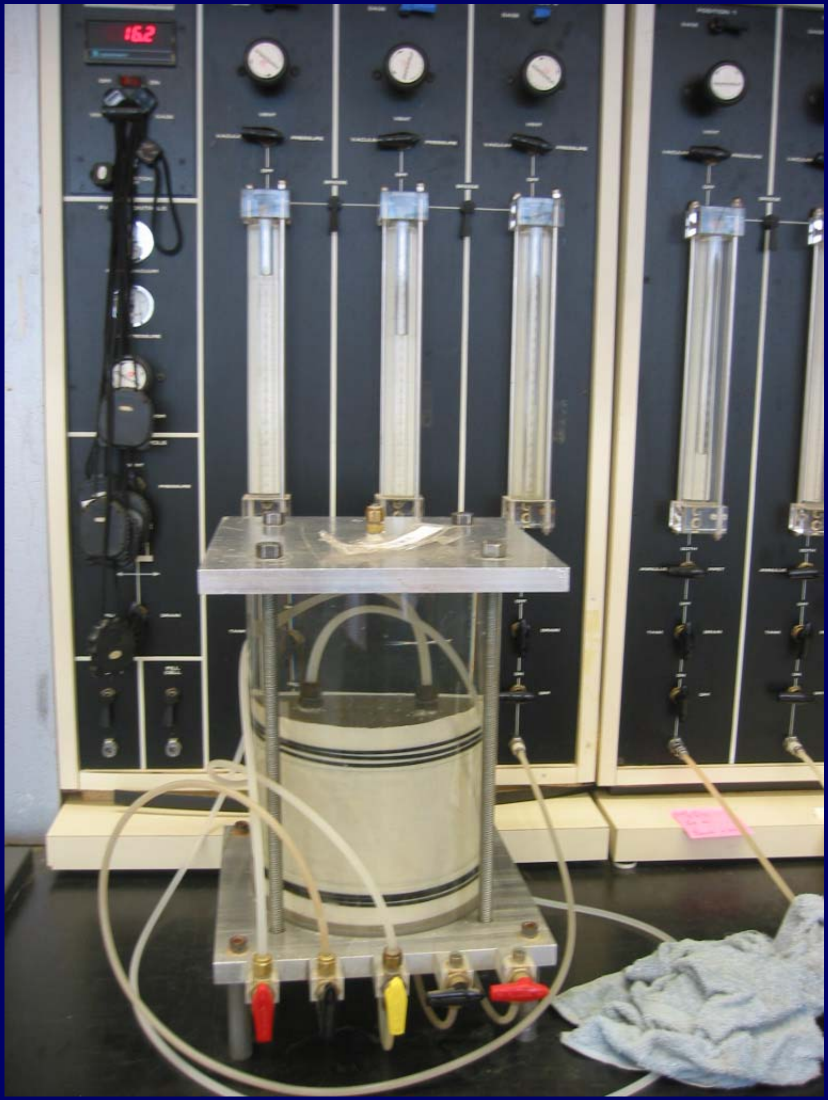
- Saturation (zero suction)
- Inducing Target Suction (154 and 350 kPa)

Phase II: Resilient Modulus ($M_r$) Testing

- Tests were conducted in accordance with NCHRP 1-28A using Procedure II for soils with at least 35% fines

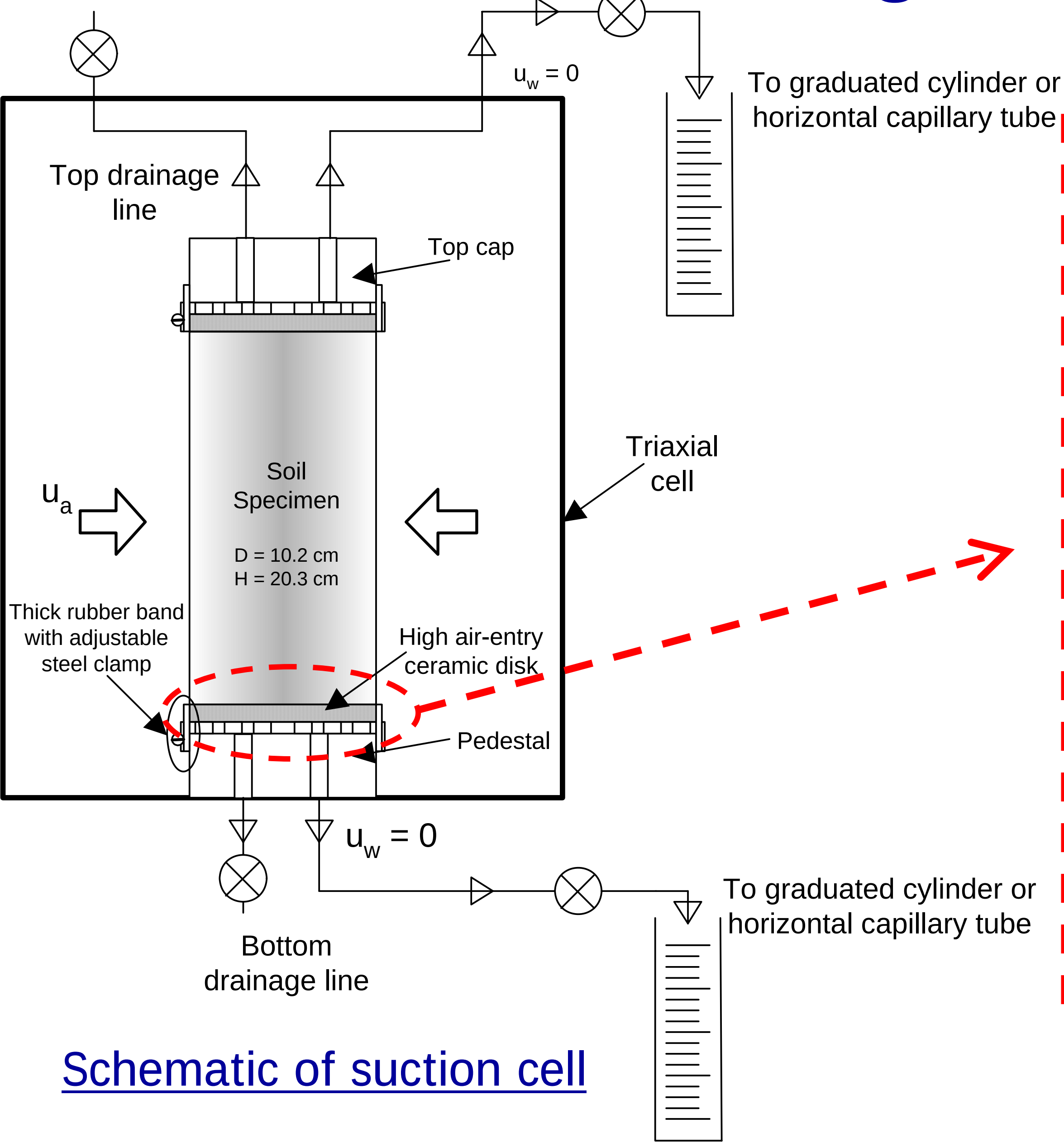
Phase III: Post-Test Measurement of Matric Suction

# Phase I: Saturation

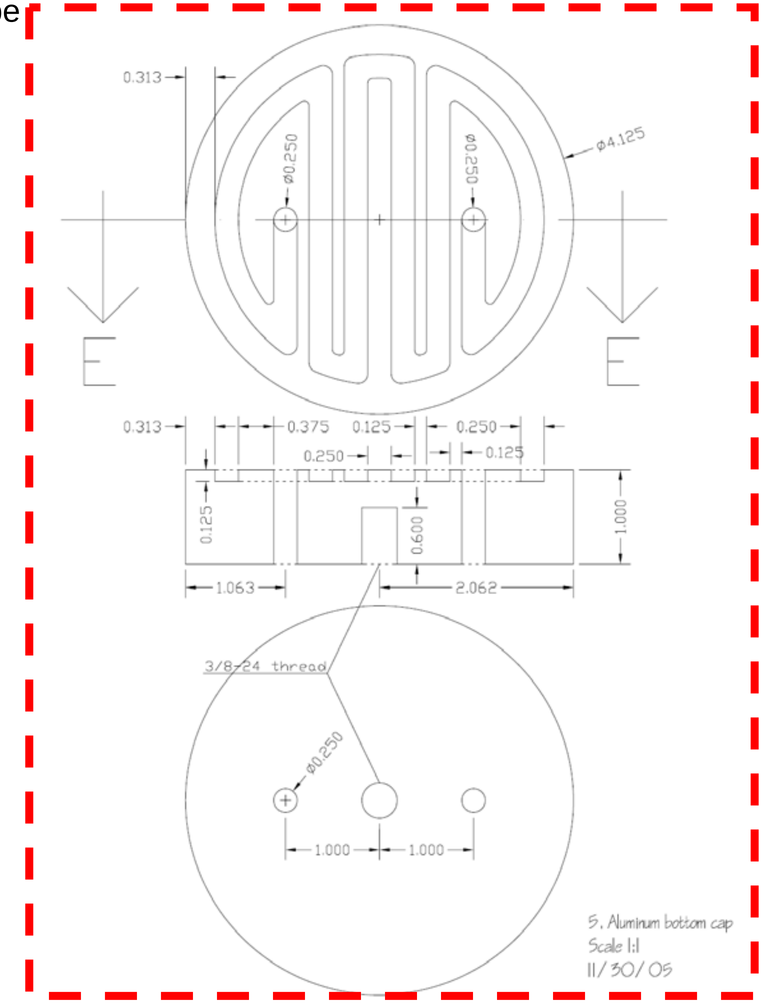


- Followed ASTM D 5084 (ASTM 2004)
- B-check (not less than 90%)
- ~ 2-6 weeks saturation time

# Phase I: Inducing Target Suction




Schematic of suction cell

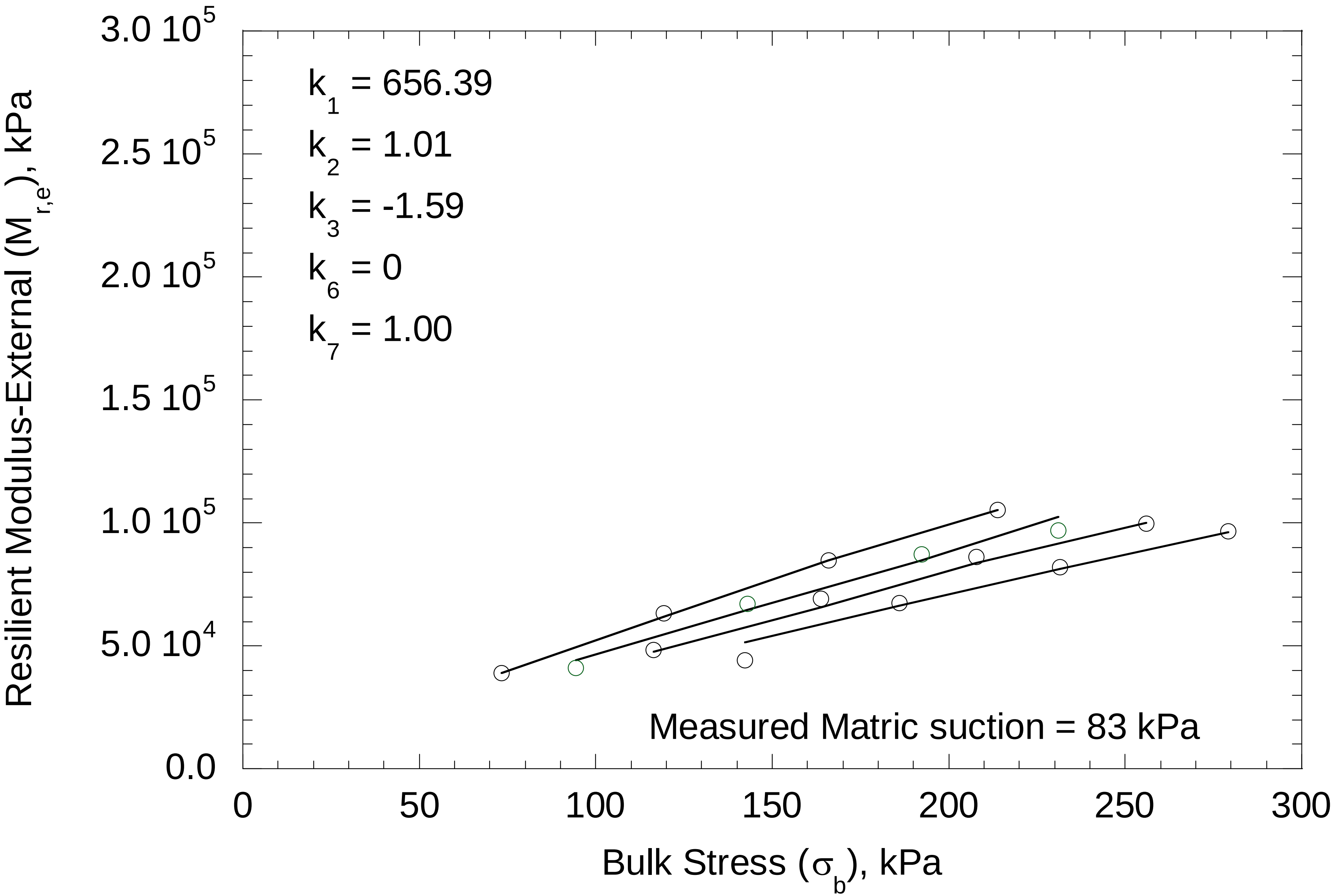



Drawing of pedestal

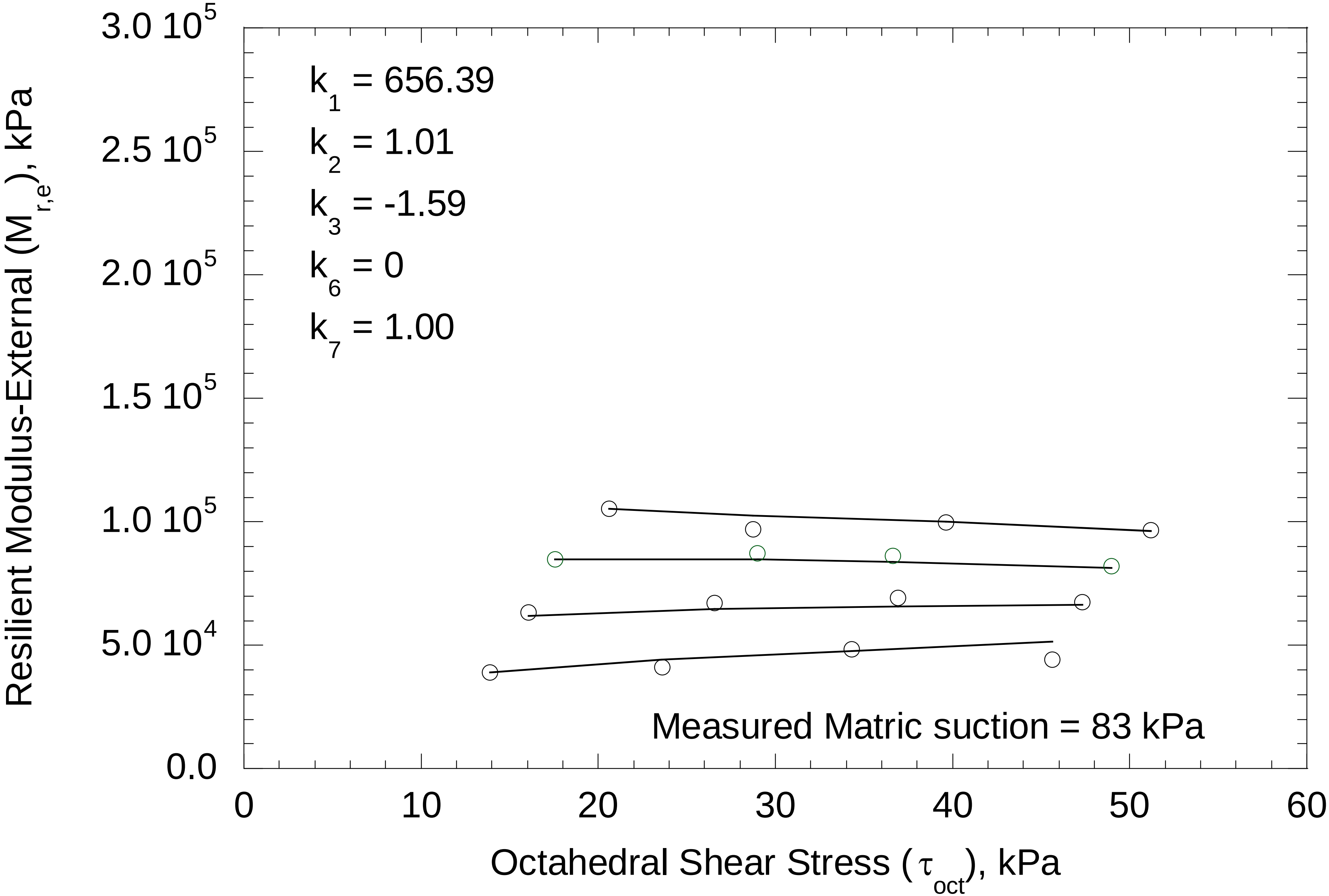
# Phase II: Resilient Modulus ($M_r$) Testing

- Five-parameter power function:

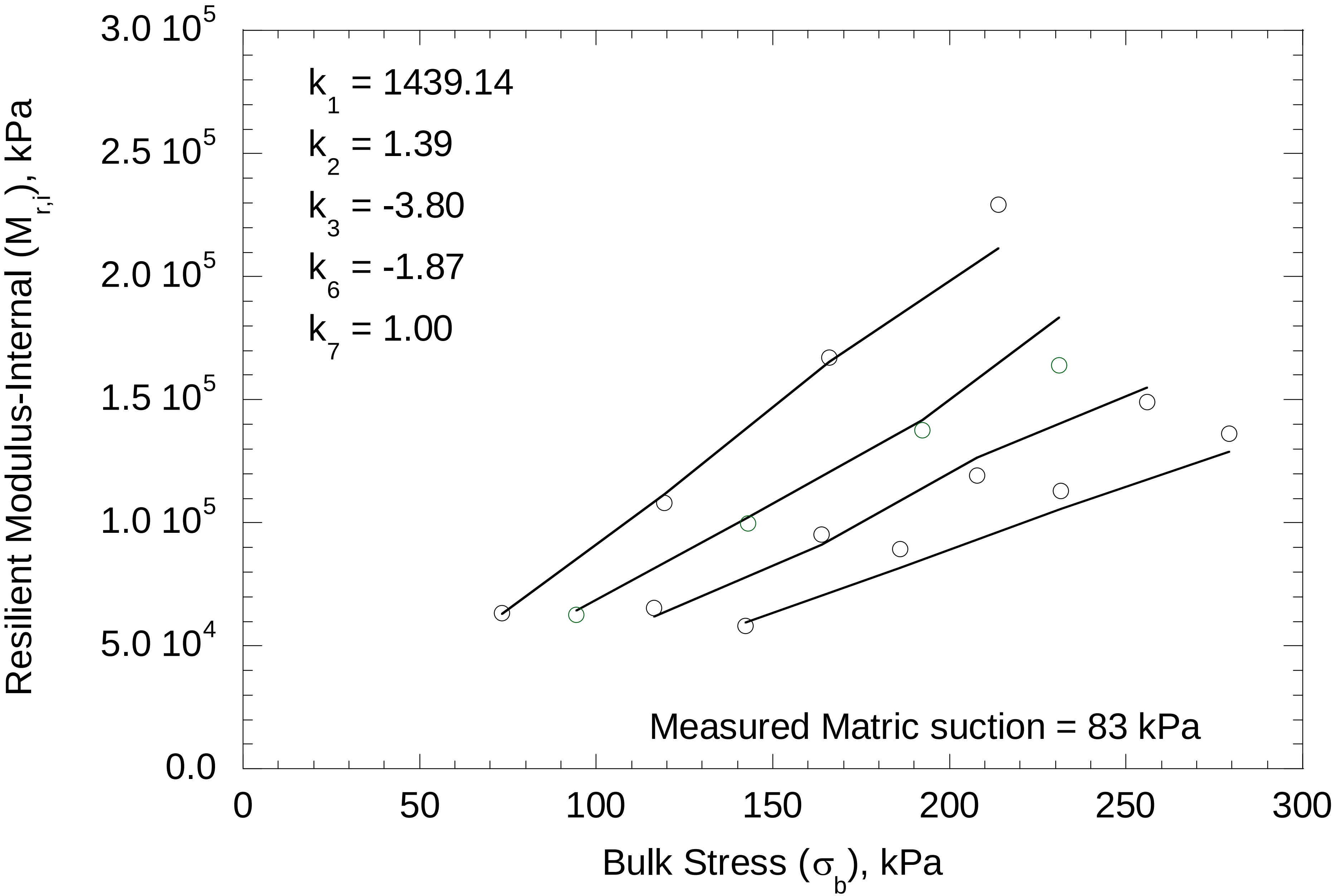
$$M_r = k_1 p_a \left( \frac{\sigma_b - 3k_6}{p_a} \right)^{k_2} \left( \frac{\tau_{oct}}{p_a} + k_7 \right)^{k_3}$$



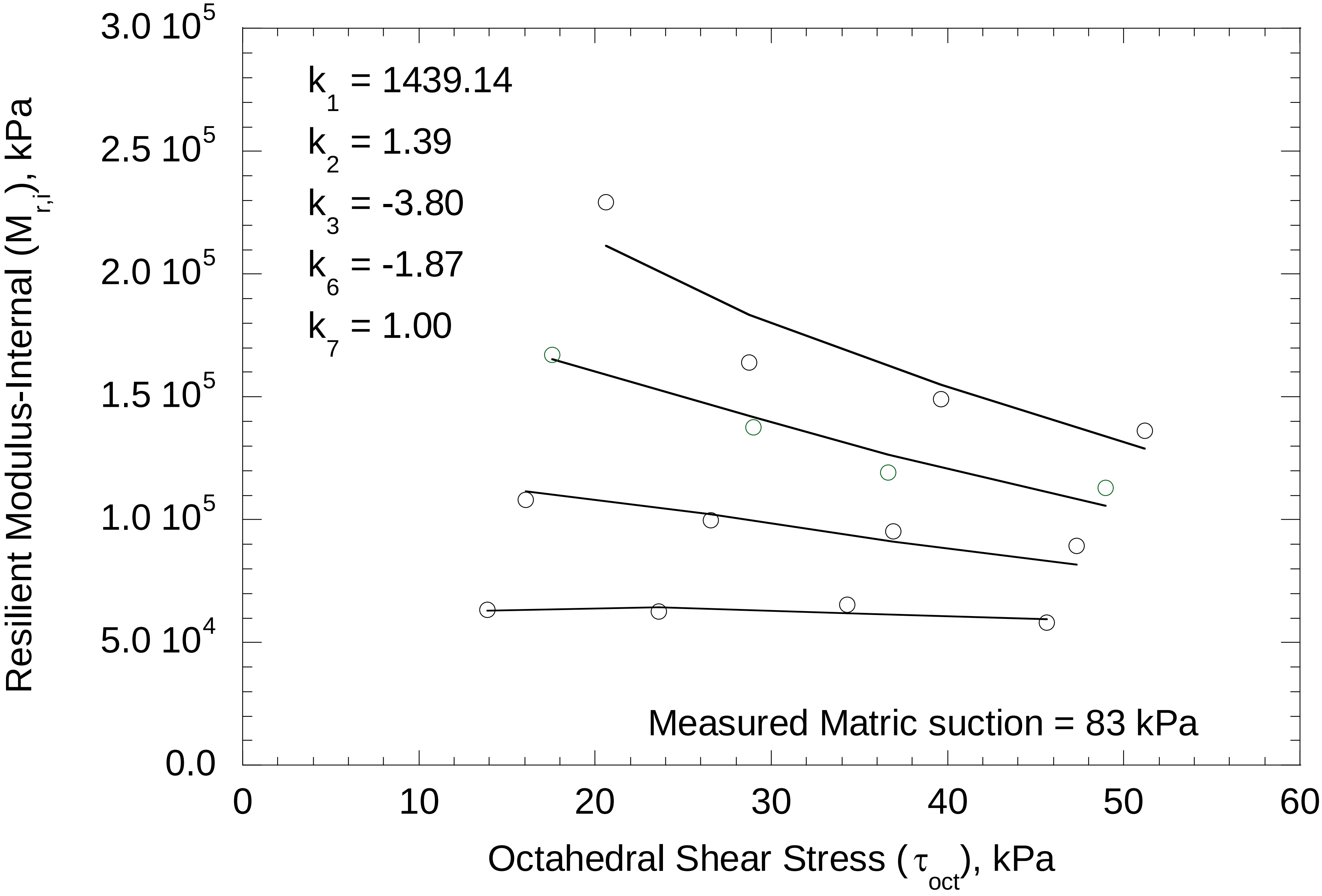
k1 = 656.39
k2 = 1.01
k3 = -1.59
k6 = 0
k7 = 1.00
Measured Matric suction = 83 kPa
Resilient Modulus-External (Mr,e), kPa
Bulk Stress (σb), kPa
3.0 10^5
2.5 10^5
2.0 10^5
1.5 10^5
1.0 10^5
5.0 10^4
0.0
0
50
100
150
200
250
300



k1 = 656.39
k2 = 1.01
k3 = -1.59
k6 = 0
k7 = 1.00
Measured Matric suction = 83 kPa
Resilient Modulus-External (Mr,e), kPa
Octahedral Shear Stress (τoct), kPa
0.0
5.0 10^4
1.0 10^5
1.5 10^5
2.0 10^5
2.5 10^5
3.0 10^5
0
10
20
30
40
50
60



$k_1$ = 1439.14
$k_2$ = 1.39
$k_3$ = -3.80
$k_6$ = -1.87
$k_7$ = 1.00
Measured Matric suction = 83 kPa
Resilient Modulus-Internal ($M_{r,i}$), kPa
Bulk Stress ($\sigma_b$), kPa
3.0 $10^5$
2.5 $10^5$
2.0 $10^5$
1.5 $10^5$
1.0 $10^5$
5.0 $10^4$
0.0
0
50
100
150
200
250
300



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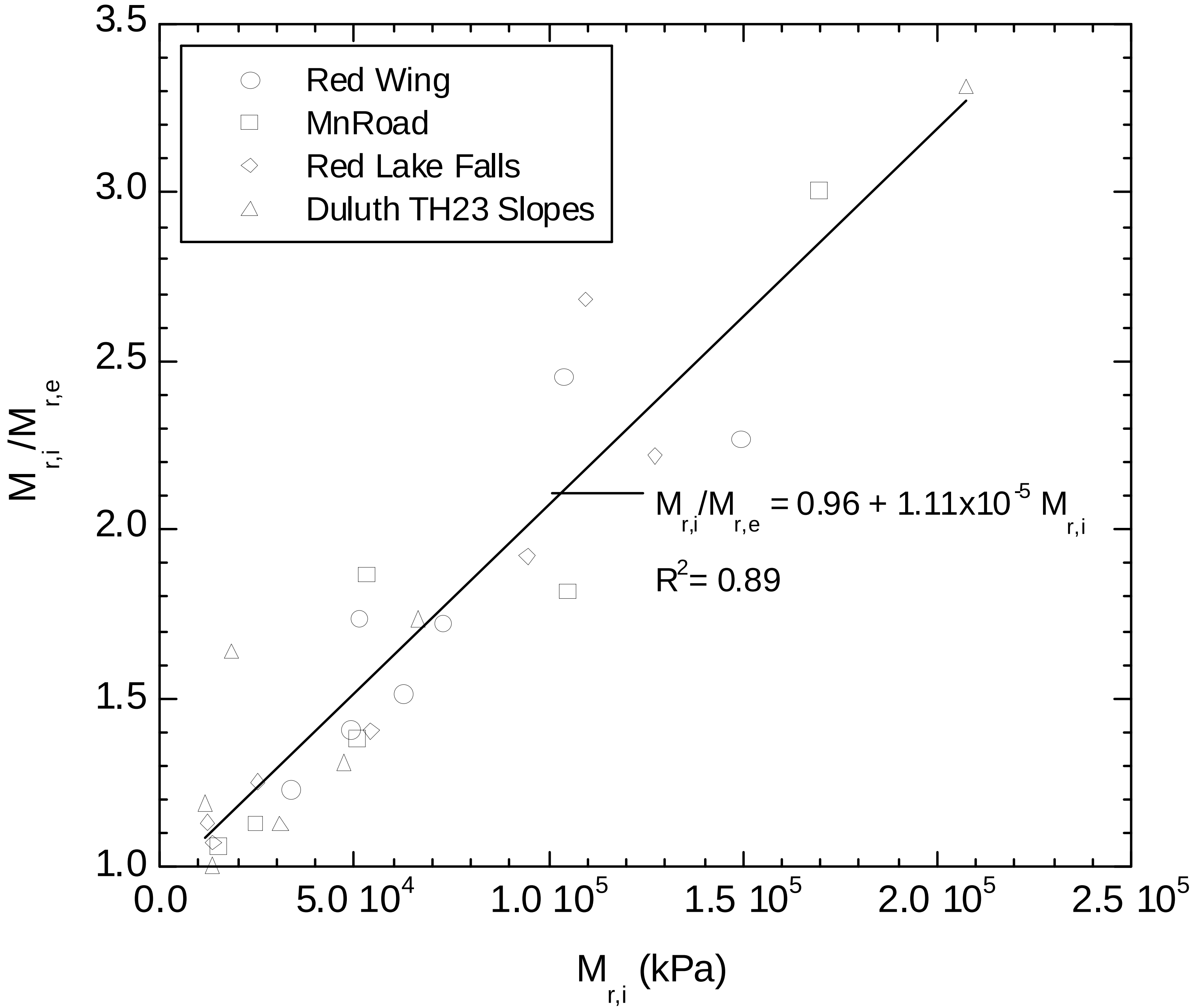
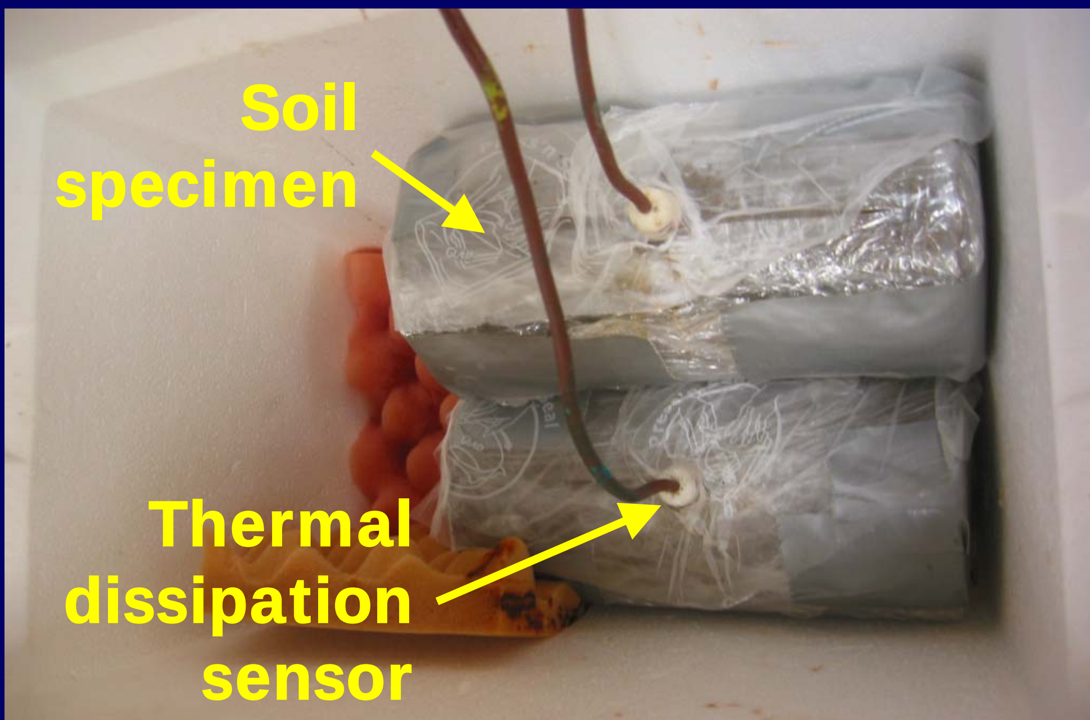
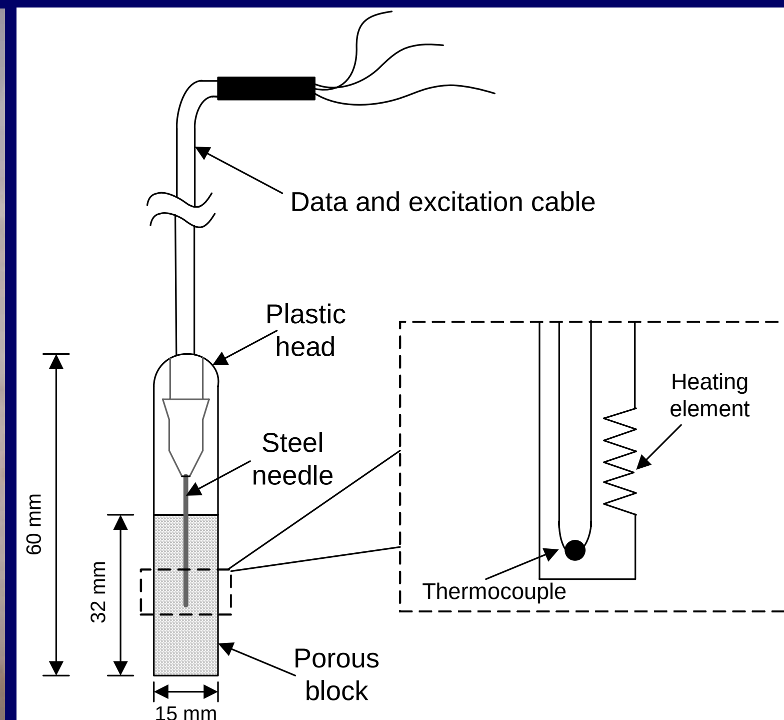
$k_6$ = -1.87
$k_7$ = 1.00
Measured Matric suction = 83 kPa
Resilient Modulus-Internal ($M_{r,i}$), kPa
Octahedral Shear Stress ($\tau_{oct}$), kPa
0.0
5.0 $10^4$
1.0 $10^5$
1.5 $10^5$
2.0 $10^5$
2.5 $10^5$
3.0 $10^5$
0
10
20
30
40
50
60



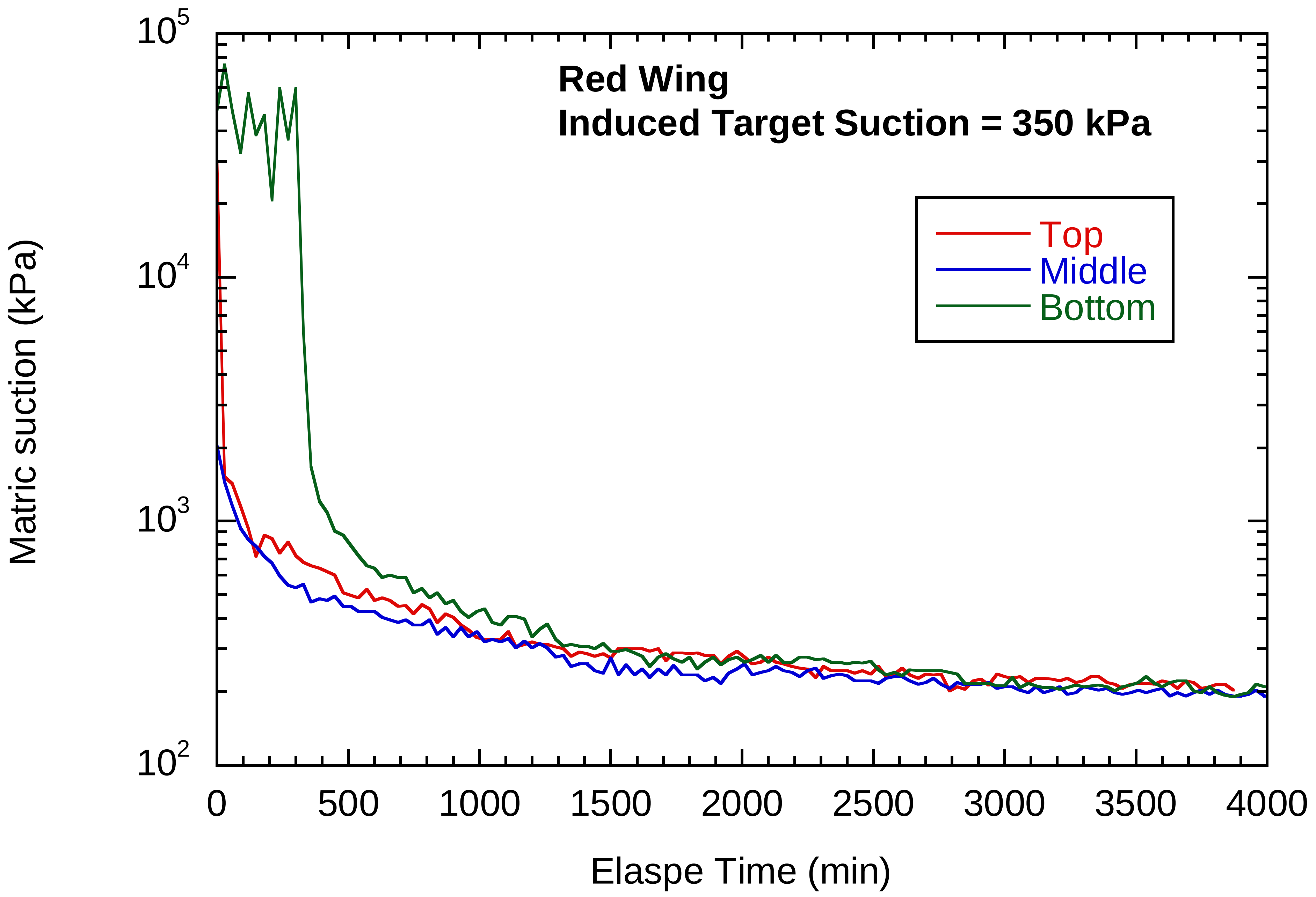
Red Wing
MnRoad
Red Lake Falls
Duluth TH23 Slopes
$M_{r,i}/M_{r,e} = 0.96 + 1.11x10^{-5} M_{r,i}$
$R^2= 0.89$
$M_{r,i}/M_{r,e}$
$M_{r,i}$ (kPa)
3.5
3.0
2.5
2.0
1.5
1.0
0.0
5.0 $10^4$
1.0 $10^5$
1.5 $10^5$
2.0 $10^5$
2.5 $10^5$

# Phase III: Post-Test Measurement of Matric Suction



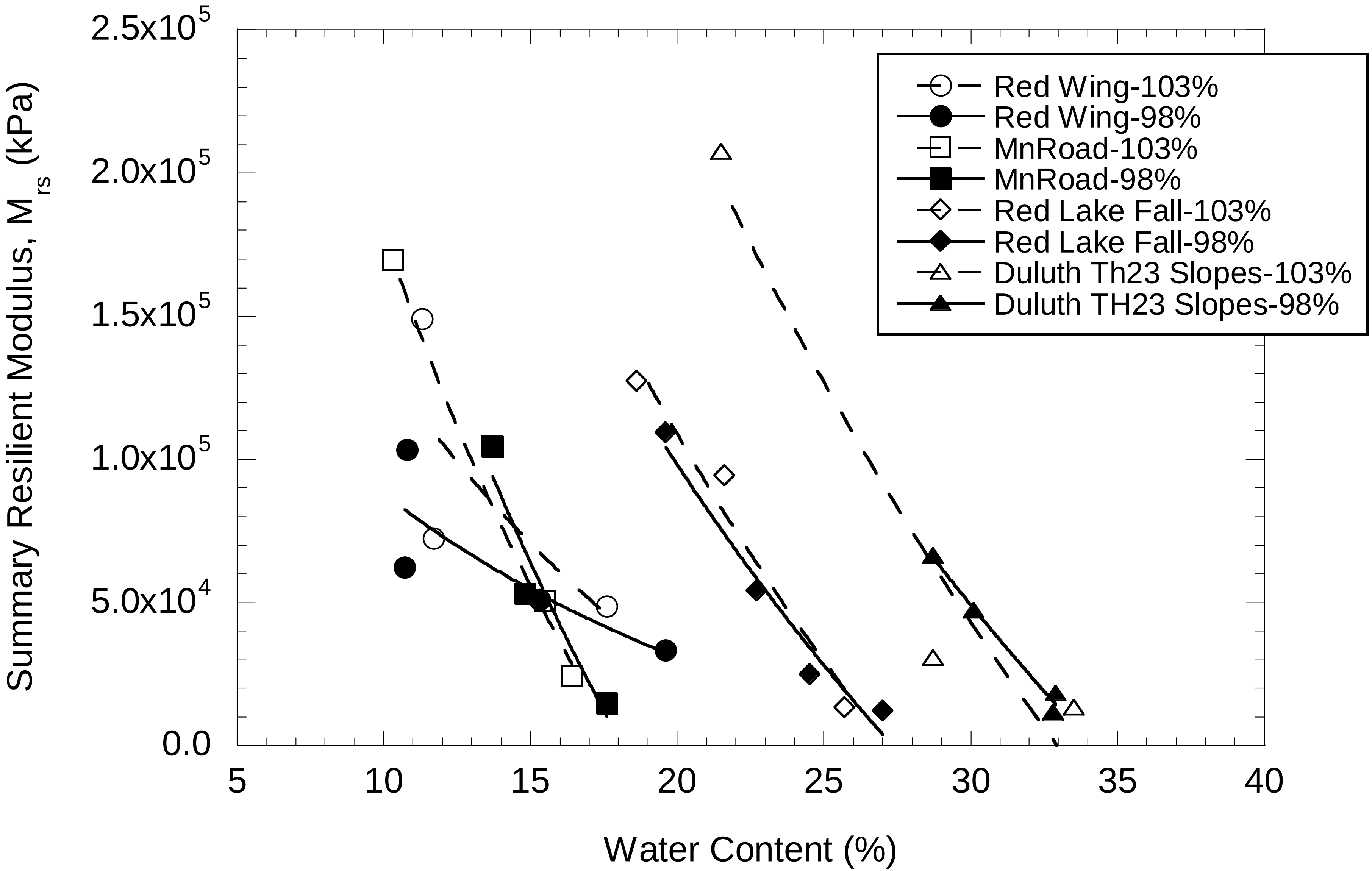




**Schematic of Thermal Dissipation Sensor – Model 229 by Campbell Scientific Inc.**

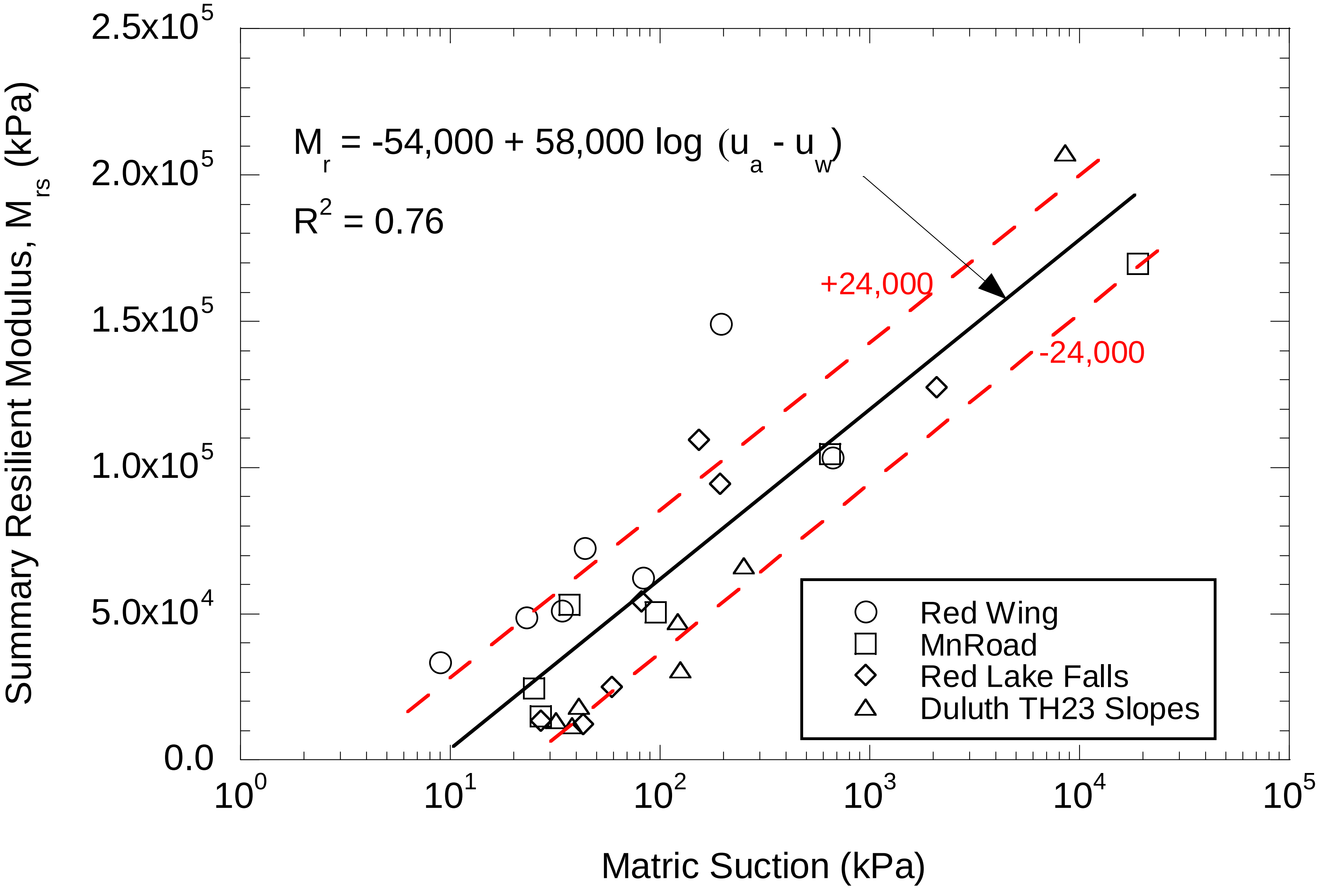


Red Wing
Induced Target Suction = 350 kPa
Top
Middle
Bottom
Matric suction (kPa)
Elaspe Time (min)
$10^5$
$10^4$
$10^3$
$10^2$
0
500
1000
1500
2000
2500
3000
3500
4000

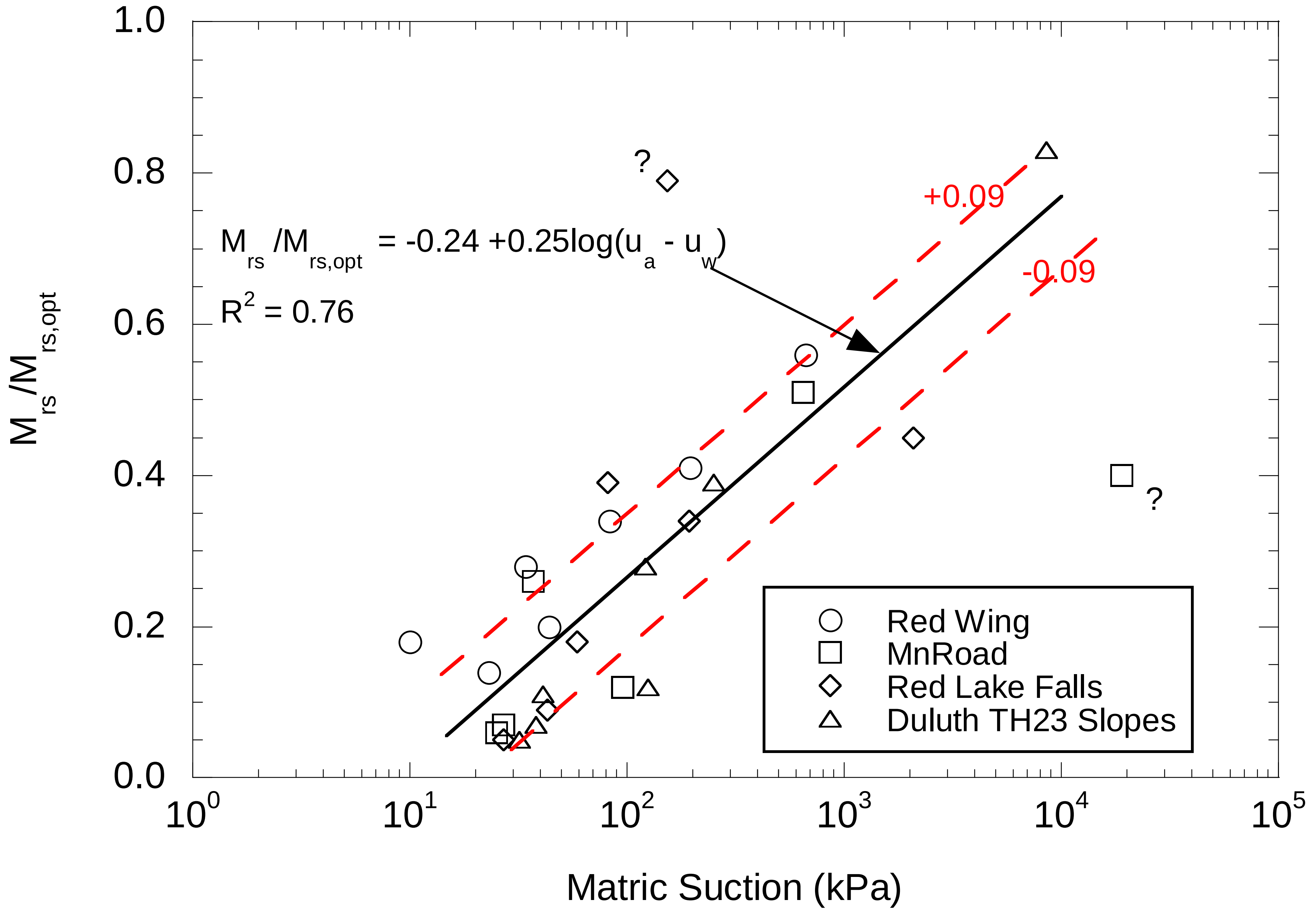
# Results & Analysis



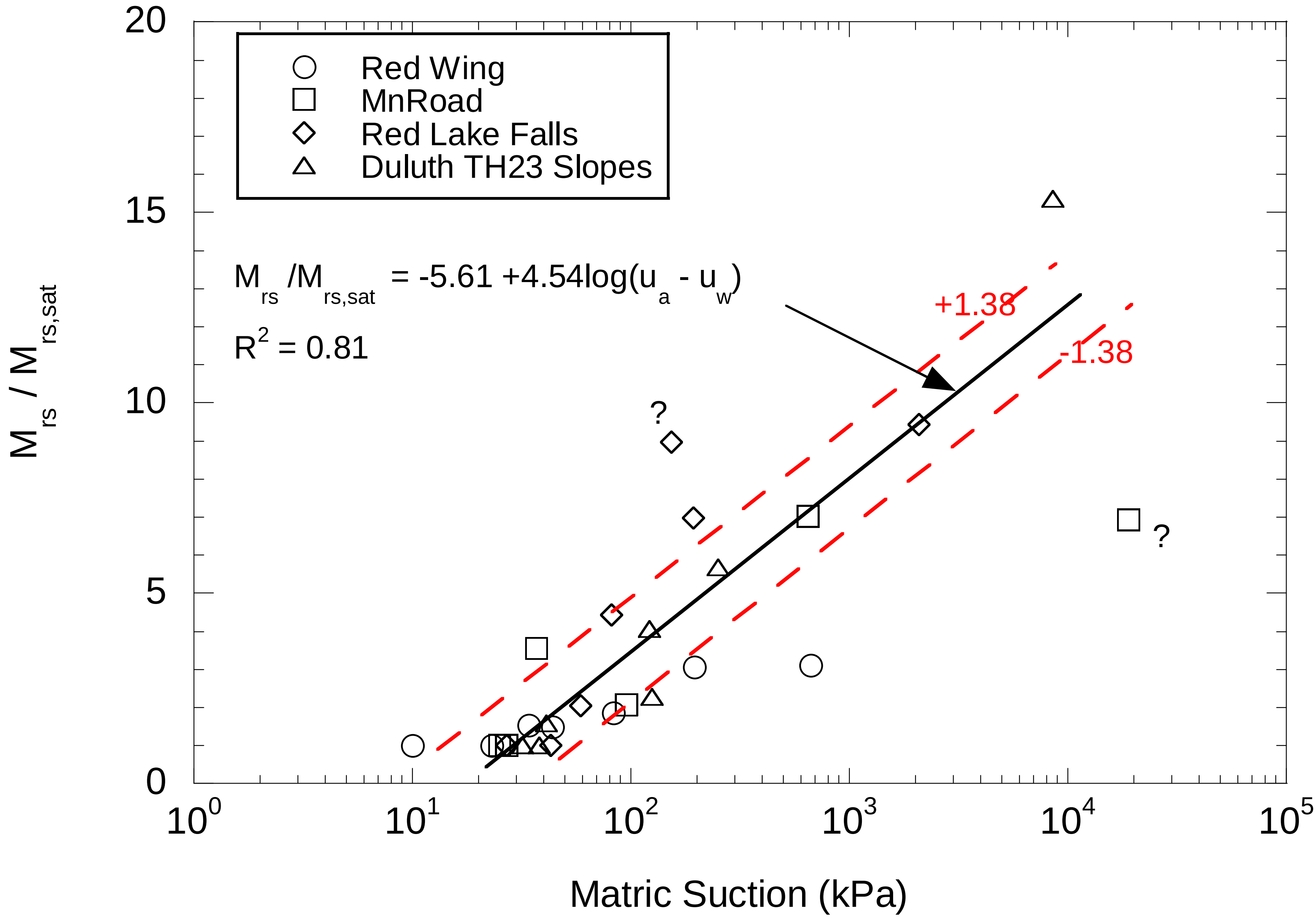
Summary Resilient Modulus, $M_{rs}$ (kPa)
Water Content (%)
0.0
$5.0x10^4$
$1.0x10^5$
$1.5x10^5$
$2.0x10^5$
$2.5x10^5$
5
10
15
20
25
30
35
40
Red Wing-103%
Red Wing-98%
MnRoad-103%
MnRoad-98%
Red Lake Fall-103%
Red Lake Fall-98%
Duluth Th23 Slopes-103%
Duluth TH23 Slopes-98%



$M_r$ = -54,000 + 58,000 log ($u_a$ - $u_w$)
$R^2$ = 0.76
+24,000
-24,000
Red Wing
MnRoad
Red Lake Falls
Duluth TH23 Slopes
Summary Resilient Modulus, $M_{rs}$ (kPa)
Matric Suction (kPa)
0.0
$5.0x10^4$
$1.0x10^5$
$1.5x10^5$
$2.0x10^5$
$2.5x10^5$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$



1.0
0.8
0.6
0.4
0.2
0.0
$M_{rs}/M_{rs,opt}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
Matric Suction (kPa)
$M_{rs}/M_{rs,opt} = -0.24 + 0.25\log(u_a - u_w)$
$R^2 = 0.76$
+0.09
-0.09
?
?
Red Wing
MnRoad
Red Lake Falls
Duluth TH23 Slopes



Red Wing
MnRoad
Red Lake Falls
Duluth TH23 Slopes
$M_{rs}/M_{rs,sat} = -5.61 + 4.54\log(u_a - u_w)$
$R^2 = 0.81$
+1.38
-1.38
?
?
0
5
10
15
20
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
Matric Suction (kPa)
$M_{rs} / M_{rs,sat}$

# Conclusions

- A series of tests was conducted on four fine-grained subgrade soils representing a wide range of plasticity to evaluate how $M_r$ is affected by matric suction.
- $M_r$ test was conducted on each specimen after matric suction conditioning using methods described in NCHRP 1-28A.
- After $M_r$ test, target matric suction was checked using thermal dissipation sensors.
- Independent direct measurement of matric suction obtained with thermal dissipation sensors was used to define relationship between modulus and suction.

# Conclusions

- Summary $M_r$ of all four soils increased with increasing matric suction within a narrow band.
- A “modulus ratio (MR)” was computed as the ratio of the summary $M_r$ at any suction to a reference summary $M_r$.
- Two reference moduli were considered: summary $M_r$ at optimum compaction conditions and summary $M_r$ at saturation.
- MR varied linearly with logarithm of matric suction in a relatively narrow band for all soils and using both normalization schemes.

# Conclusions

- These trends can be used to estimate summary $M_r$ of a well compacted sample at a given suction if the summary $M_r$ at optimum compaction conditions or at saturation is known.

# Acknowledgments

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- Help and support of Mr. John Siekemier of the MnDOT.