Determining Pavement Design Criteria for Recycled Aggregate Base and Large Stone Subbase

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MnDOT Project TPF-5(341)

Monthly Meeting

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RESEARCH TEAM

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AGENCY MEMBERS

- MnDOT
- Caltrans
- MDOT
- IDOT
- LRRB
- MoDOT
- WisDOT
- NDDOT
- Iowa DOT

ASSOCIATE MEMBERS

- Aggregate & Ready Mix of MN
- Asphalt Pavement Alliance (APA)
- Braun Intertec
- Infrasense
- Diamond Surface Inc.
- Flint Hills Resources
- International Grooving & Grinding Association (IGGA)
- Midstate Reclamation & Trucking
- MN Asphalt Pavement Association
- Minnesota State University - Mankato
- National Concrete Pavement Technology Center
- Roadscanners
- University of Minnesota - Duluth
- University of New Hampshire
- Mathy Construction Company
- Michigan Tech Transportation Institute (MTTI)
- University of Minnesota
- National Center for Asphalt Technology (NCAT) at Auburn University
- GSE Environmental
- Helix Steel
- Ingios Geotechnics
- WSB
- Cargill
- PITT Swanson Engineering
- University of California Pavement Research Center
- Collaborative Aggregates LLC
- American Engineering Testing, Inc.
- Center for Transportation Infrastructure Systems (CTIS)
- Asphalt Recycling & Reclaiming Association (ARRA)
- First State Tire Recycling
- BASF Corporation
- Upper Great Plains Transportation Institute at North Dakota State University
- 3M
- Pavia Systems, Inc.
- All States Materials Group
- Payne & Dolan, Inc.
- Caterpillar
- The Dow Chemical Company
- The Transtec Group
- Testquip LLC
- Hardrives, Inc.
- Husky Energy
- Asphalt Materials & Pavements Program (AMPP)
- Concrete Paving Association of MN (CPAM)
- MOBA Mobile Automation
- Geophysical Survey Systems
- Leica Geosystems
- University of St. Thomas
- Trimble

OUTLINE

- Follow-up
- Test cells
- Task 4 – Laboratory testing
- Summary
- Future study

FOLLOW-UP

- **Task 1** – Literature review and recommendations
- **Task 2** – Tech transfer "state of practice"
- **Task 3** – Construction monitoring and reporting
- **Task 4** – Laboratory testing
- **Task 5** – Performance monitoring and reporting
- **Task 6** – Instrumentation
- **Task 7** – Pavement design criteria
- **Task 8 & 9** – Draft/final report

Green – Completed
Red – In Progress

TEST CELLS

Recycled Aggregate Base				Large Stone Subbase		Large Stone Subbase with Geosynthetics				
185	186	188	189	127	227	328	428	528	628	728
3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave	3.5 in Superpave
12 in Coarse RCA	12 in Fine RCA	12 in Limestone	12 in RCA+RAP	6 in Class 6 Aggregate	6 in Class 6 Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate	6 in Class 5Q Aggregate
3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	3.5 in S. Granular Borrow	18 in LSSB (1 lift)	18 in LSSB (1 lift)	9 in LSSB TX	9 in LSSB TX+GT	9 in LSSB BX+GT	9 in LSSB BX	9 in LSSB
Sand	Sand	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam

S. Granular Borrow = Select Granular Borrow

TX = Triaxial Geogrid
BX = Biaxial Geogrid
GT = Nonwoven Geotextile

TASK 4

Task 4 - Laboratory Testing

Green – Completed
Red – In Progress

Iowa State University

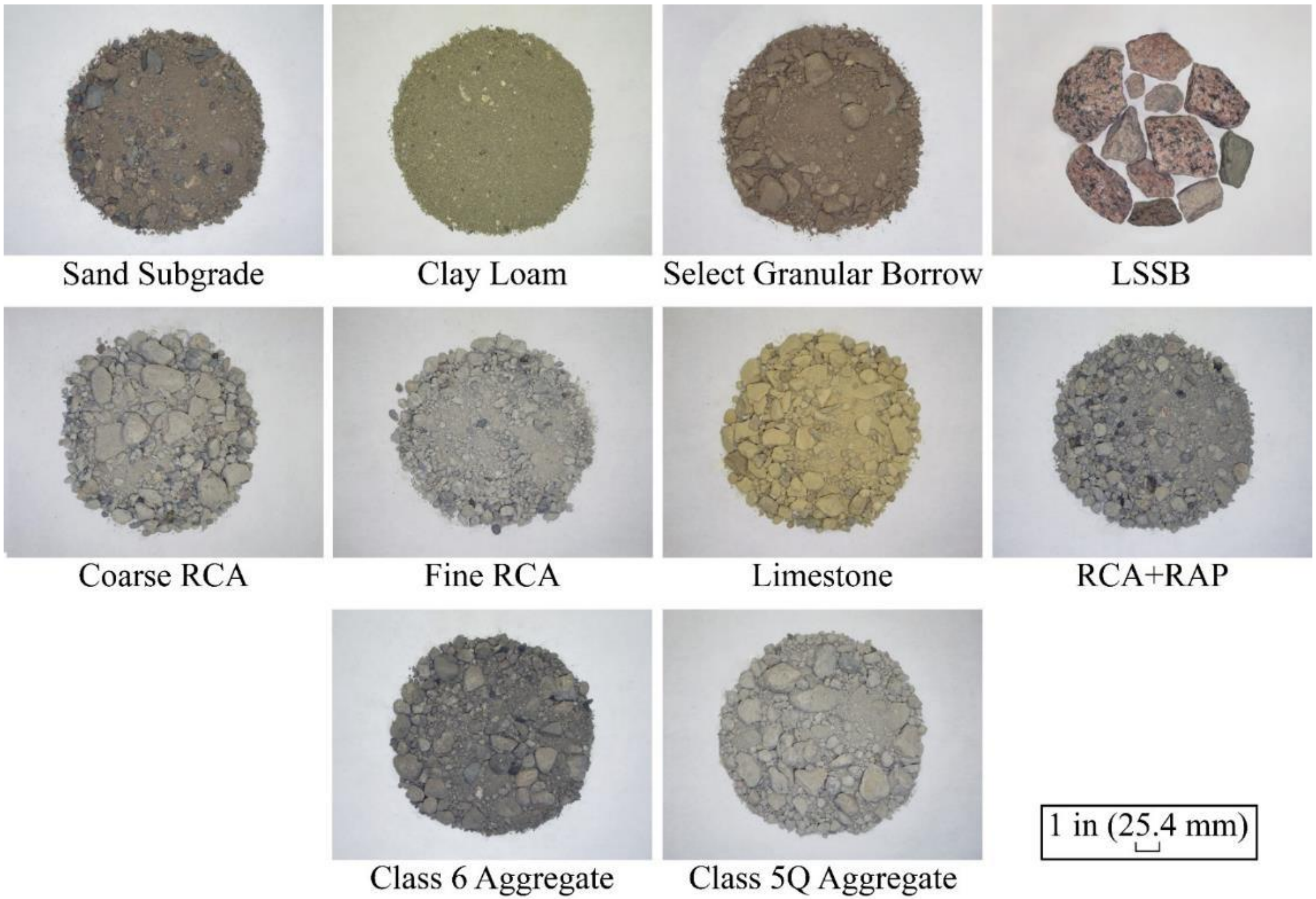
- Sieve analysis & hydrometer test
- Atterberg limits
- Proctor compaction
- Specific gravity & absorption
- Image analysis
- Asphalt & cement content determination
- Gyratory compaction & percent crushing
- Contact angle measurement

University of Wisconsin-Madison

- Permeability
- Soil-water characteristic curve

TASK 4

Test Materials



TASK 4

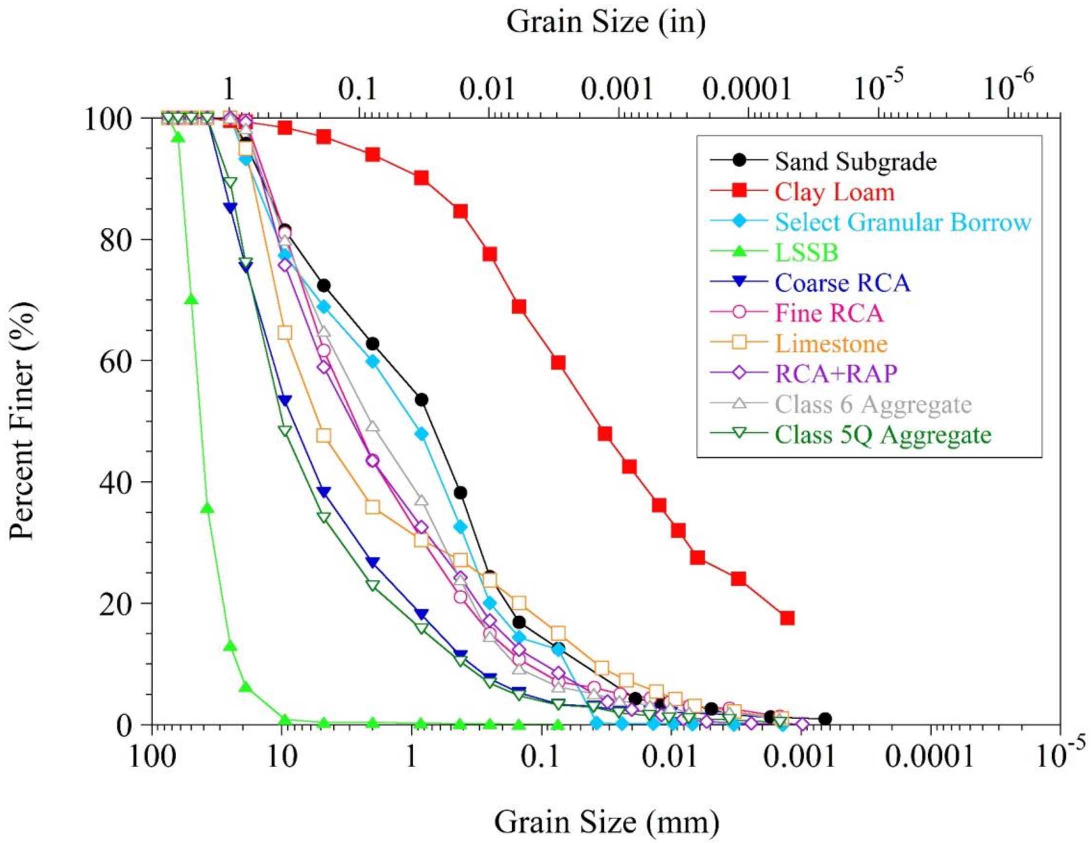
Deleterious Material Content

- Visual identification
  - Plant roots & leaves
  - Wood chips
  - Plastic
  - Fabric
- No reinforcing steel in RCA
  - Magnetization
- Weight of the deleterious materials < 0.1% by dry weight
- Suitability for the quality requirements (MnDOT 2018)
- RAP particles in all the materials
  - No removal

TASK 4

Particle Size Distribution

- ASTM C136 & D6913 – Sieve analysis
- ASTM D7928 – Hydrometer test



TASK 4

Classification

Material	Gravel (%)	Sand (%)	Fines (%)	C_u (ASTM D2487)	C_c (ASTM D2487)	LL (BS 1377-2)	PL (ASTM D4318)	PI (ASTM D4318)	USCS (ASTM D2487)		AASHTO M 145
									Symbol	Definition	
Sand Subgrade	27.6	59.8	12.6	33.1	1.24	19.9	NA	NP	SM	Silty Sand with Gravel	A-1-b
Clay Loam	3.1	37.2	59.7	NA	NA	36.3	23.9	12.4	CL	Sandy Lean Clay	A-6
Select Granular Borrow	31.1	56.5	12.4	30.3	1.10	18.9	NA	NP	SM	Silty Sand with Gravel	A-1-b
LSSB	99.6	0.3	0.1	2.08	1.14	NA	NA	NA	GP	Poorly-Graded Gravel	A-1-a
Coarse RCA	61.7	34.9	3.4	34.5	1.75	NA	NA	NP	GW	Well-Graded Gravel with Sand	A-1-a
Fine RCA	38.3	54.6	7.1	33.9	1.12	32.7	NA	NP	SW-SM	Well-Graded Sand with Silt and Gravel	A-1-a
Limestone	52.3	32.6	15.1	211.3	1.91	17.9	NA	NP	GM	Silty Gravel with Sand	A-1-b
RCA+RAP	41	50.4	8.6	49.4	0.98	27.4	NA	NP	SP-SM	Poorly-Graded Sand with Silt and Gravel	A-1-a
Class 6 Aggregate	35.1	58.6	6.3	23.8	0.60	27.4	NA	NP	SP-SM	Poorly-Graded Sand with Silt and Gravel	A-1-a
Class 5Q Aggregate	65.9	30.9	3.2	33.7	2.60	NA	NA	NP	GW	Well-Graded Gravel with Sand	A-1-a

Fines = silt and clay; C_u = coefficient of uniformity; C_c = coefficient of curvature; LL = liquid limit; PL = plastic limit; PI = plasticity index; NA = not available; NP = non-plastic; USCS = Unified Soil Classification System; AASHTO = American Association of State Highway and Transportation Officials

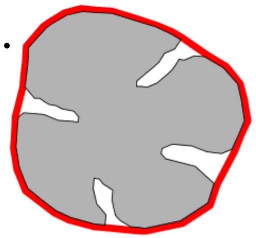
TASK 4

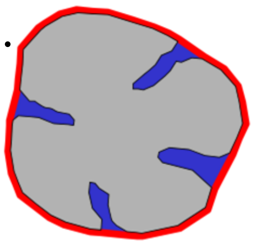
Specific Gravity & Absorption

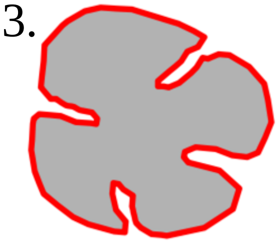
- ASTM C127 – For coarse aggregates
- ASTM C128 – For fine aggregates
- ASTM D854 – For soil solids

Material	Oven-Dry G_s	Saturated-Surface-Dry G_s	Apparent G_s	Absorption (%)
Sand Subgrade	2.60	2.64	2.72	1.84
Clay Loam	2.68	NA	NA	NA
Select Granular Borrow	2.62	2.66	2.72	1.53
LSSB	2.60	2.61	2.63	0.36
Coarse RCA	2.25	2.40	2.64	6.97
Fine RCA	2.17	2.35	2.64	8.65
Limestone	2.66	2.71	2.79	1.72
RCA+RAP	2.28	2.38	2.52	4.34
Class 6 Aggregate	2.35	2.44	2.58	3.86
Class 5Q Aggregate	2.28	2.42	2.65	6.32

G_s = specific gravity; NA = not available

1.

Dry aggregate
Bulk volume

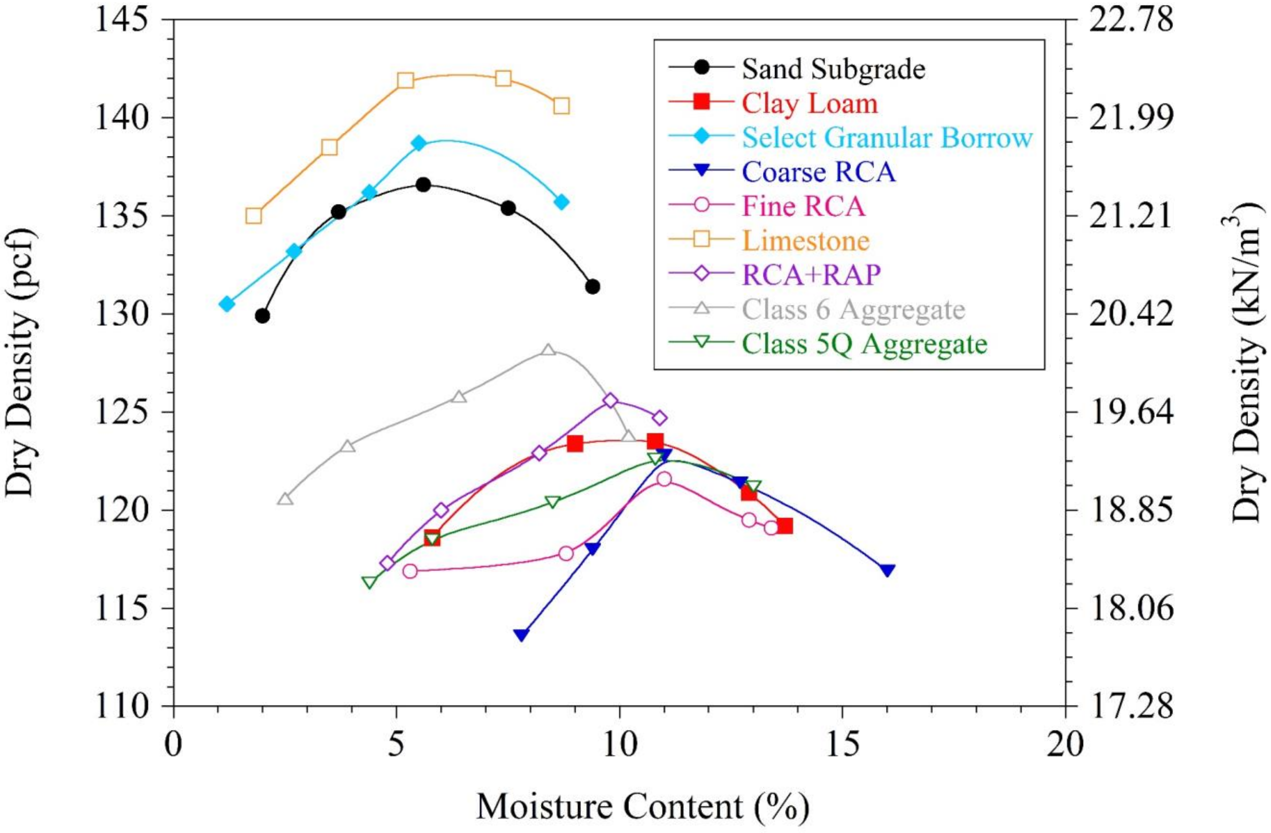
2.

SSD aggregate
Bulk volume

3.

Dry aggregate
Net volume

TASK 4

Proctor Compaction

- ASTM D1557 – Modified Proctor



TASK 4

Proctor Compaction

- ASTM D4718 – Correction for materials containing oversize particles

Material	Proctor Compaction Test Results			Corrected for Oversize Particles		
	MDD		OMC	Corrected MDD		Corrected
	(pcf)	(kN/m^3)	(%)	(pcf)	(kN/m^3)	OMC (%)
Sand Subgrade	136.6	21.46	5.7	137.7	21.63	5.6
Clay Loam	123.9	19.46	10	124.9	19.62	10.0
Select Granular Borrow	138.6	21.77	5.4	140.3	22.03	5.3
LSSB	NA	NA	NA	NA	NA	NA
Coarse RCA	122.9	19.31	11.3	128.6	20.19	9.5
Fine RCA	121.6	19.10	11.1	121.7	19.12	11.1
Limestone	142.2	22.34	6.2	143.2	22.49	6.3
RCA+RAP	125.6	19.73	10	125.8	19.76	10.0
Class 6 Aggregate	128.2	20.14	8.3	128.5	20.19	8.3
Class 5Q Aggregate	122.6	19.26	11	128.0	20.11	9.6

MDD = maximum dry density; OMC = optimum moisture content; NA = not available.

TASK 4

Asphalt Binder Content

Material	Ignition Method (AASHTO T 308)	Quantitative Extraction (AASHTO T 164)
Coarse RCA	2.02	0.10
Fine RCA	2.98	0.38
Limestone	1.61	0.35
RCA+RAP	3.18	1.58
Class 6 Aggregate	3.17	1.77
Class 5Q Aggregate	2.15	0.28


Asphalt Content Ignition Furnace

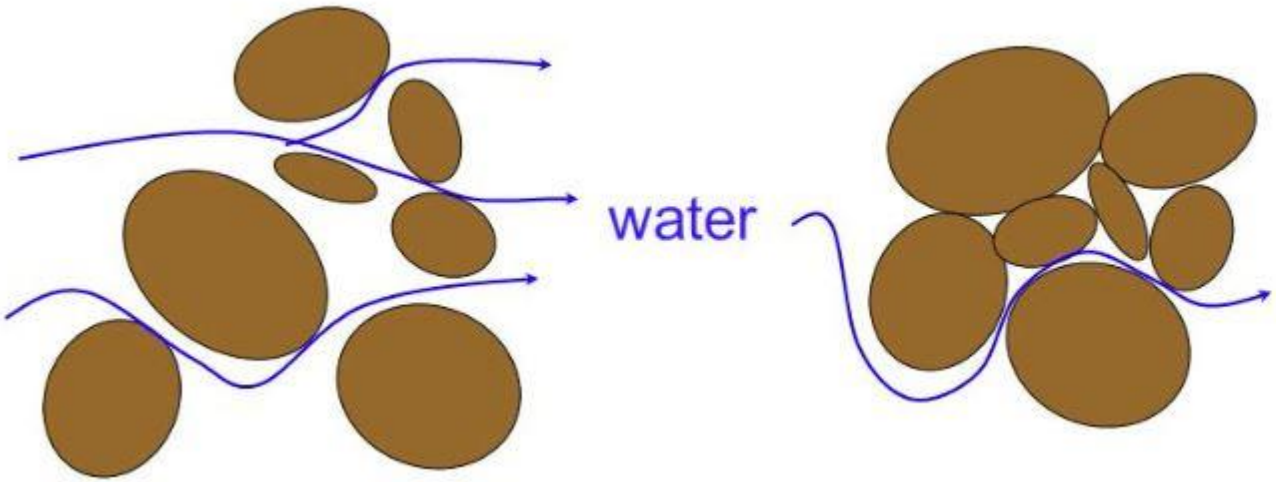

Asphalt Extraction Bowl

Asphalt Centrifuge Extractor

TASK 4

Permeability Test

- ASTM 5084 – Flexible wall permeameter
  - Constant head permeability test
  - Falling head permeability test



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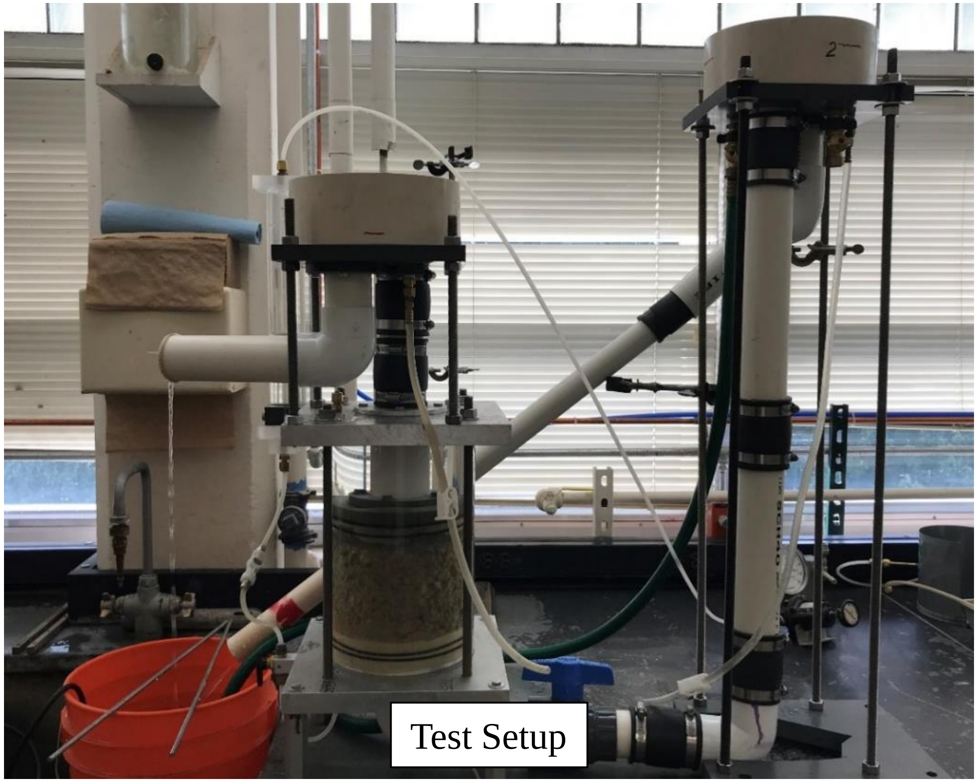
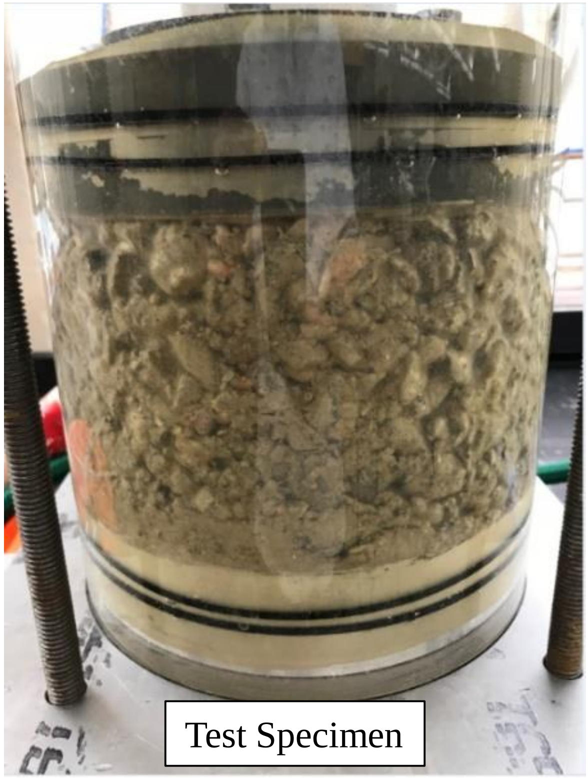
TASK 4

Constant Head Permeability Test

- 6-in diameter and 4-in height specimens
- In the membrane by light hammering



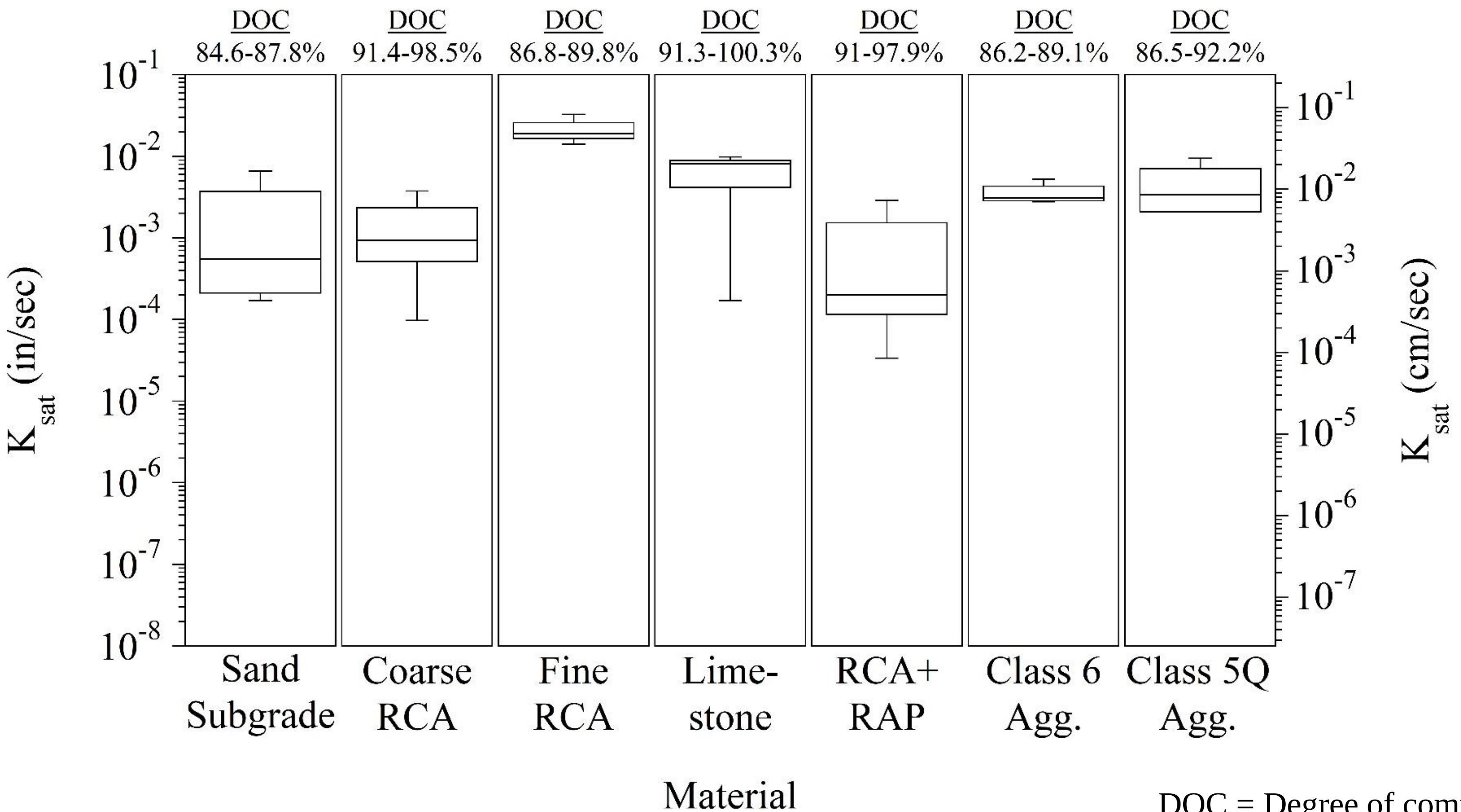
Test Setup



Test Specimen

TASK 4

Constant Head Permeability Test



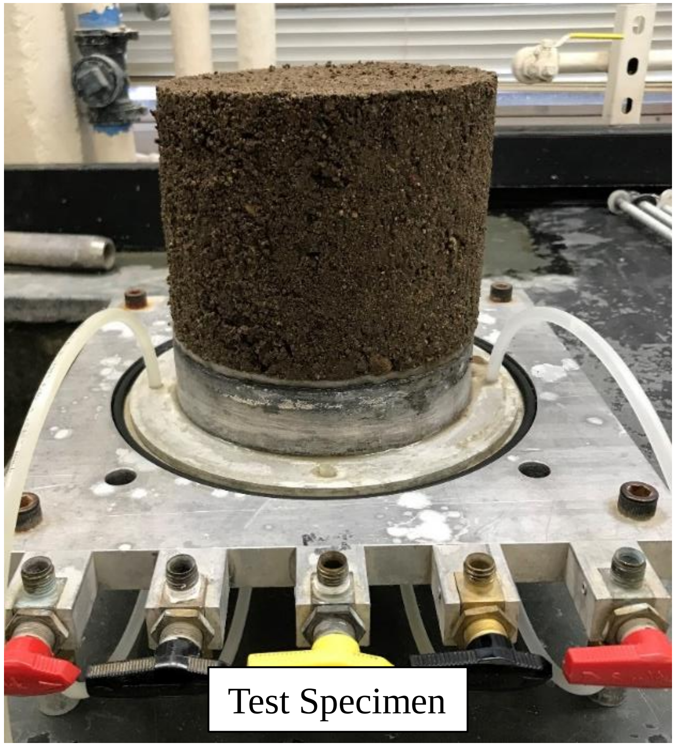
DOC = Degree of compaction

TASK 4

Falling Head Permeability Test

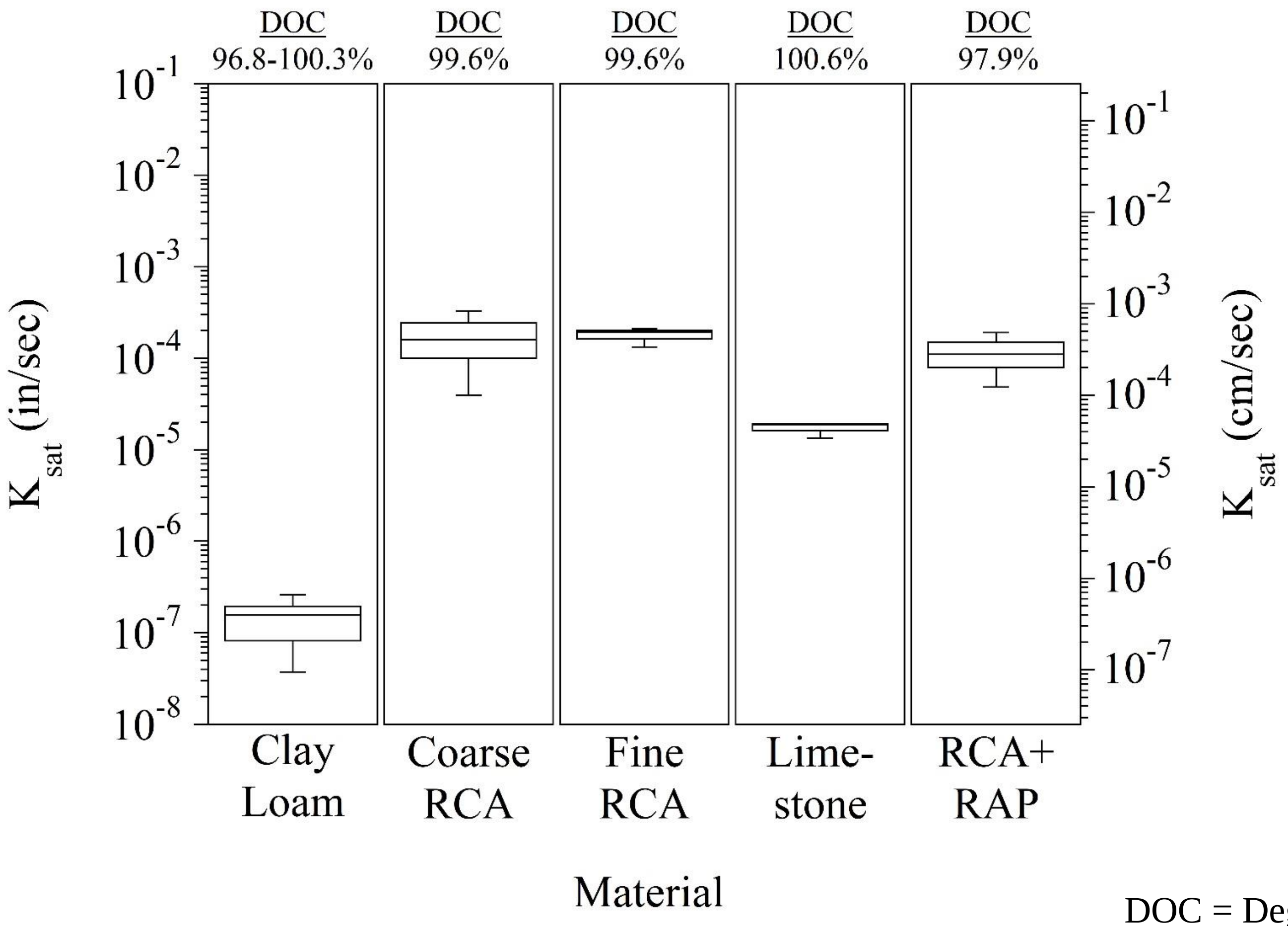
- 6-in diameter and 4-in height specimens
- In the compaction mold


Test Setup


Test Specimen

TASK 4

Falling Head Permeability Test

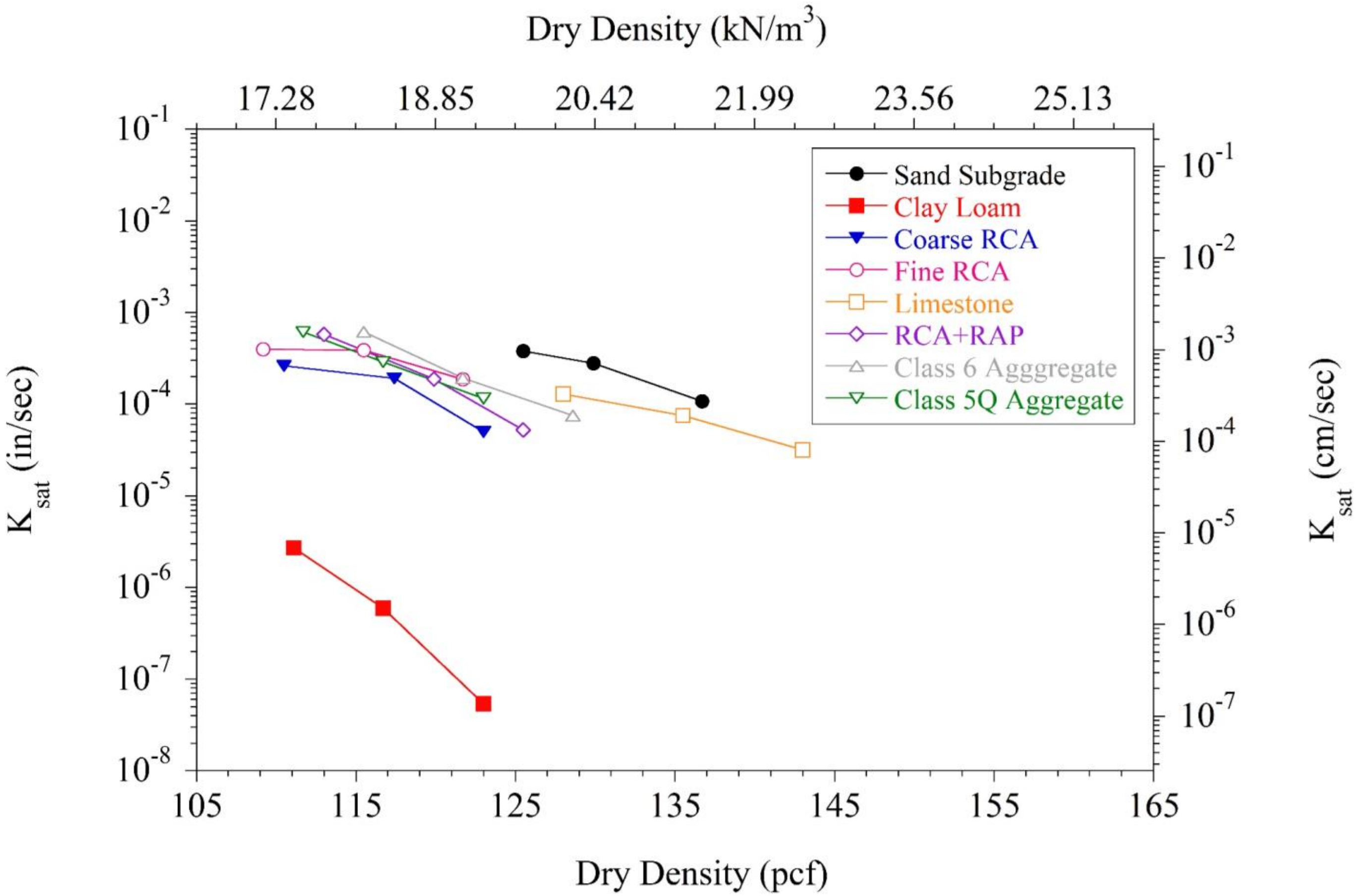


DOC = Degree of compaction

TASK 4

Falling Head Permeability Test

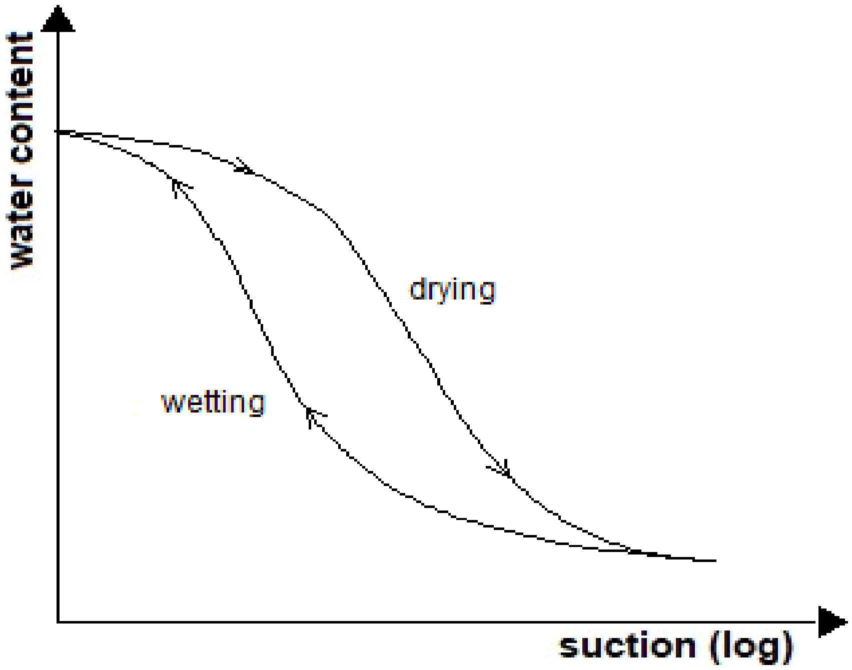
- Degree of compaction

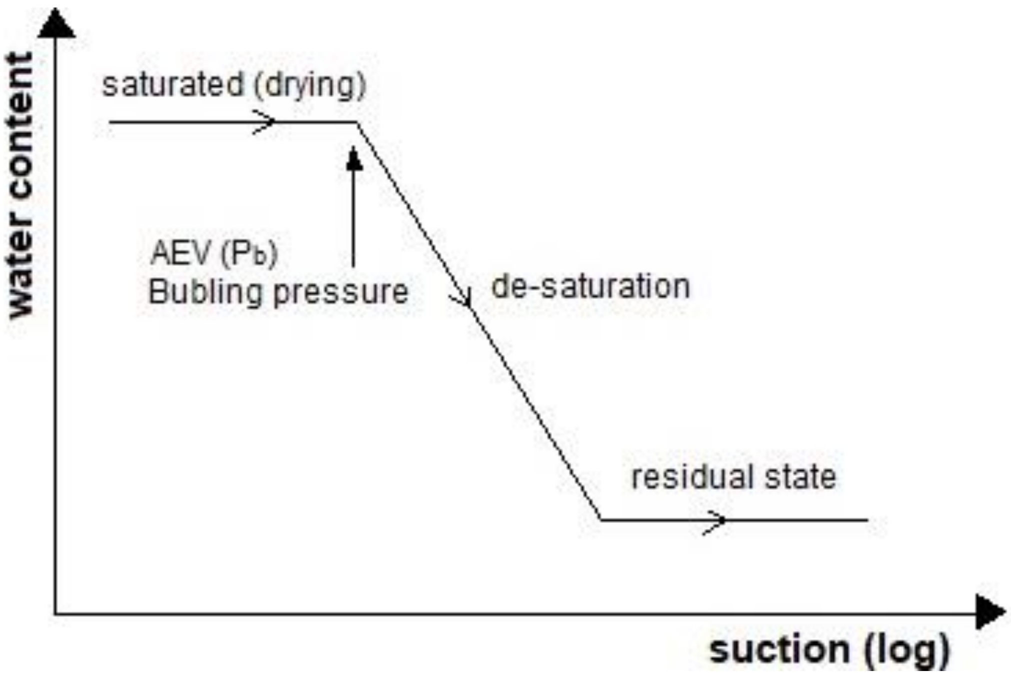


TASK 4

Soil-Water Characteristic Curve (SWCC)

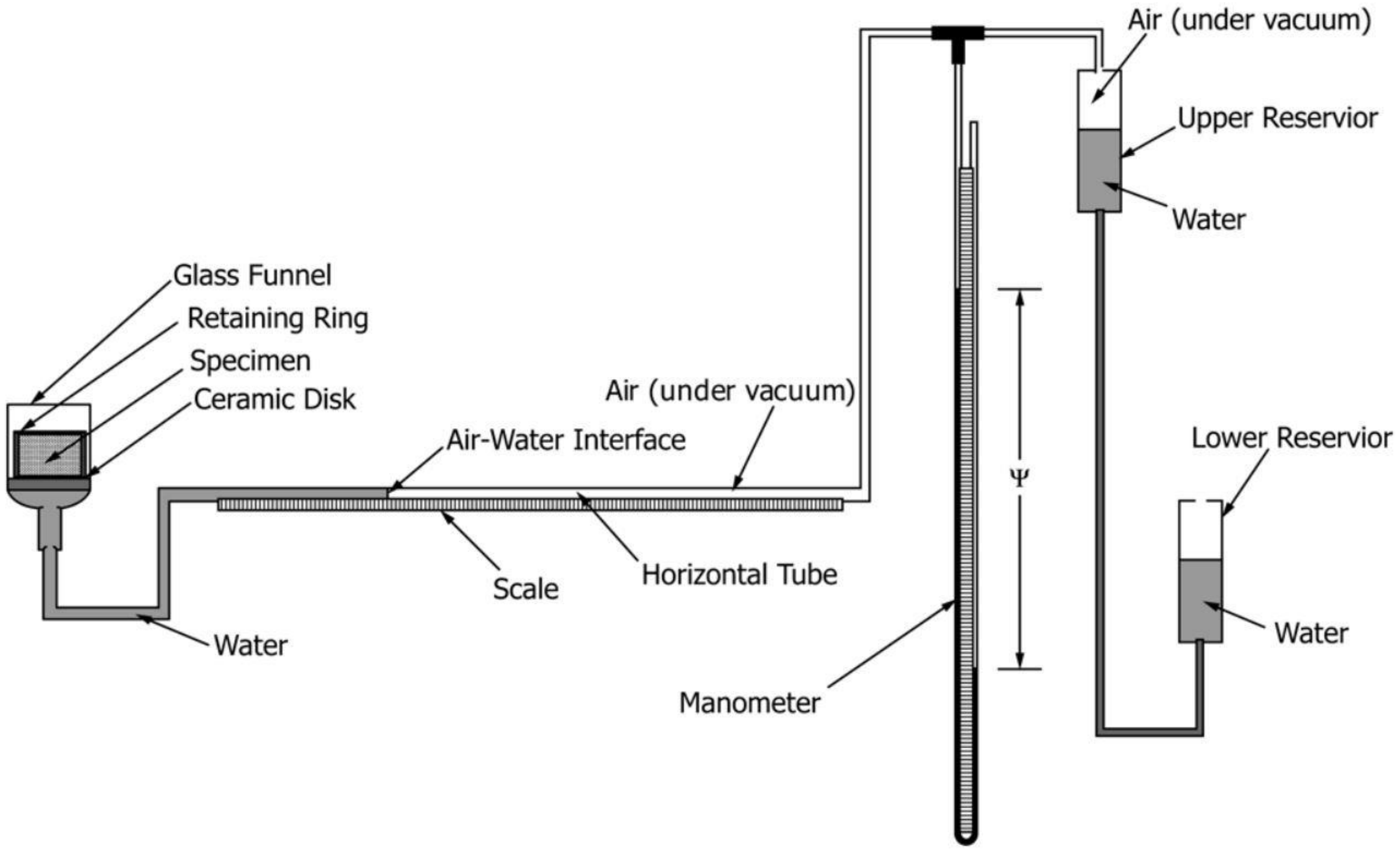
- ASTM D6836
  - Hanging column test
  - Pressure plate and activity meter test





TASK 4

Hanging Column Test

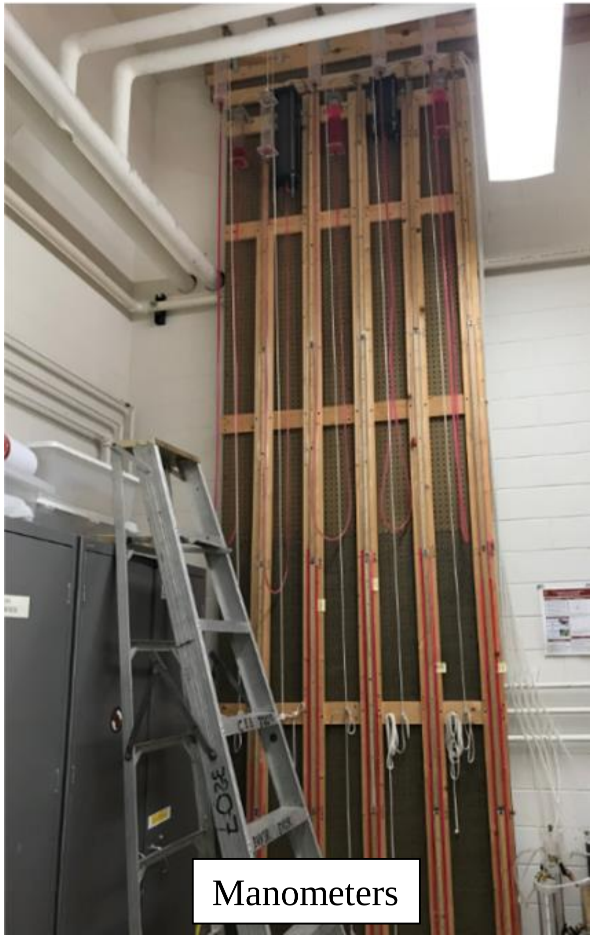


TASK 4

Hanging Column Test

Glass Funnel

Horizontal Tube



Manometers

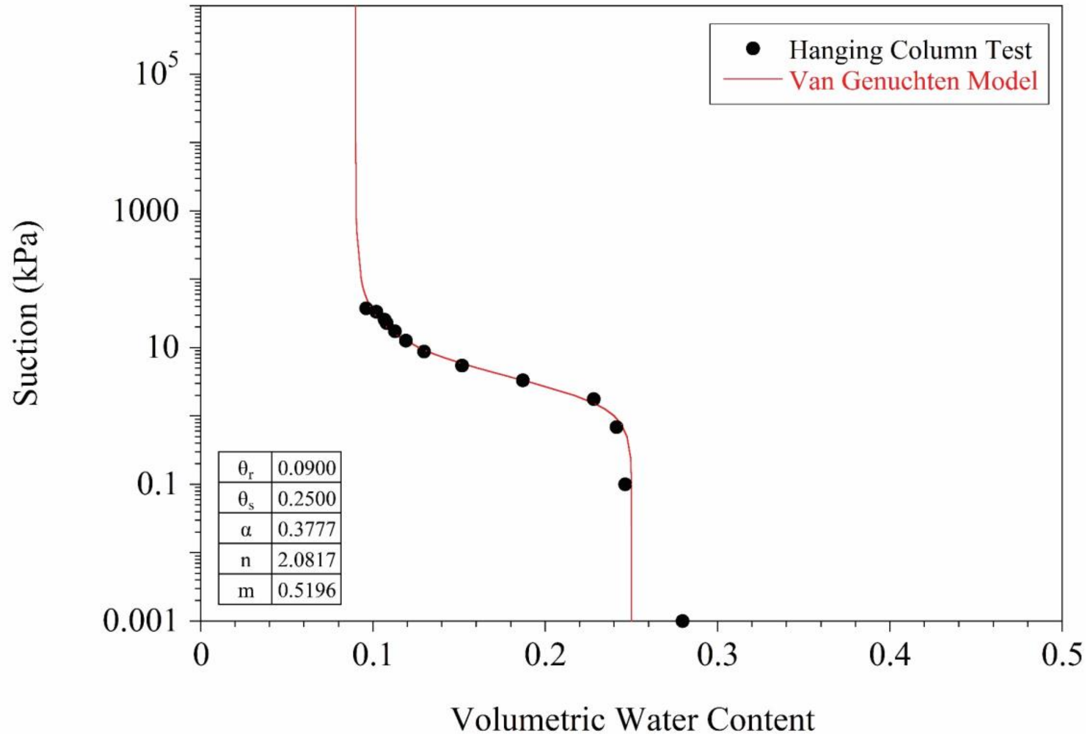
TASK 4

Hanging Column Test

- van Genuchten (1980) model

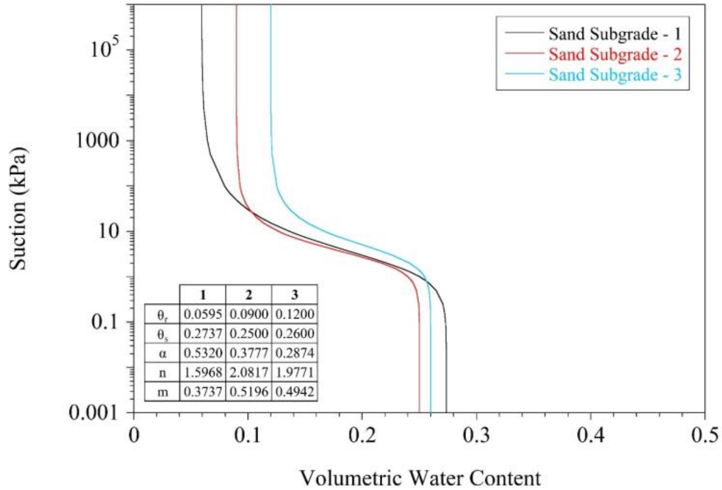
$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha\psi)^n}\right]^m$$

Θ = Normalized volumetric water content
θ = Soil volumetric water content
θ_r = Residual volumetric water content
θ_s = Saturated volumetric water content
Ψ = Matric suction
α, n, and m = van Genuchten fitting parameters

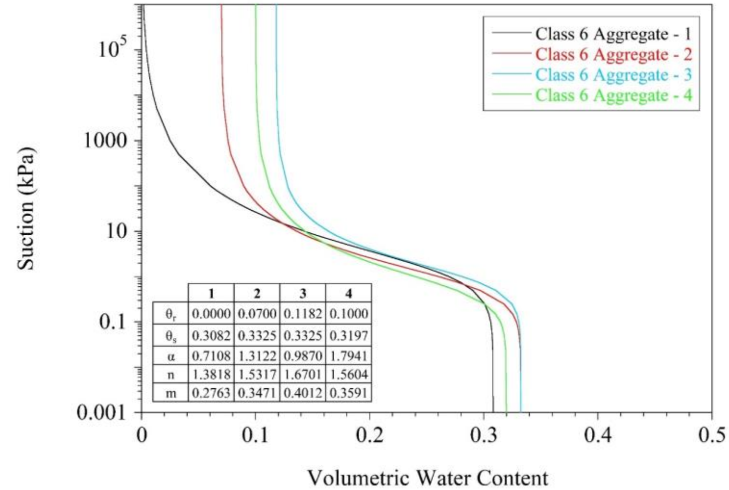


TASK 4

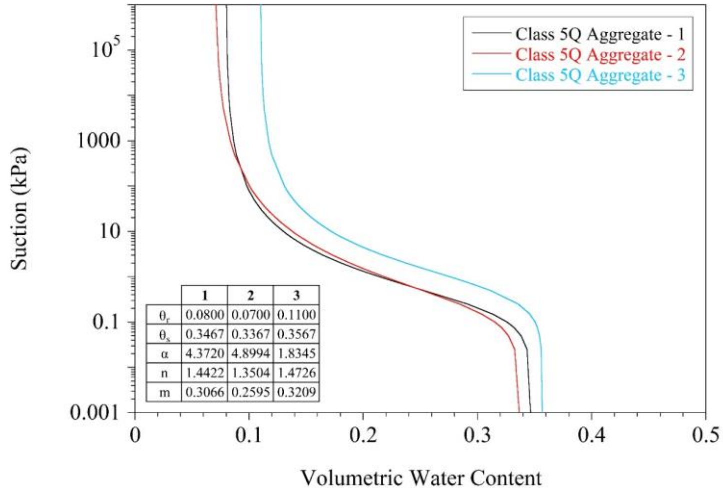
Hanging Column Test



	1	2	3
θ_r	0.0595	0.0900	0.1200
θ_s	0.2737	0.2500	0.2600
α	0.5320	0.3777	0.2874
n	1.5968	2.0817	1.9771
m	0.3737	0.5196	0.4942



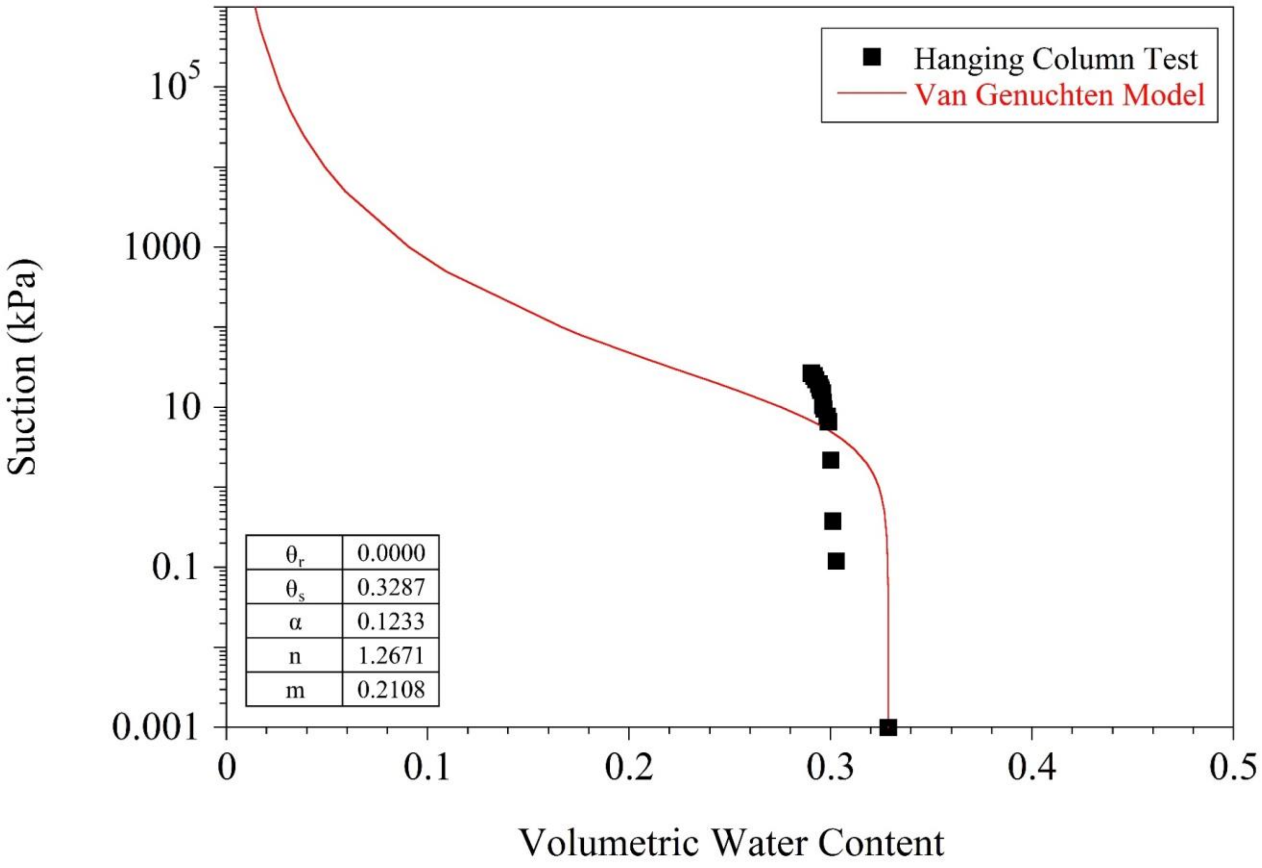
	1	2	3	4
θ_r	0.0000	0.0700	0.1182	0.1000
θ_s	0.3082	0.3325	0.3325	0.3197
α	0.7108	1.3122	0.9870	1.7941
n	1.3818	1.5317	1.6701	1.5604
m	0.2763	0.3471	0.4012	0.3591

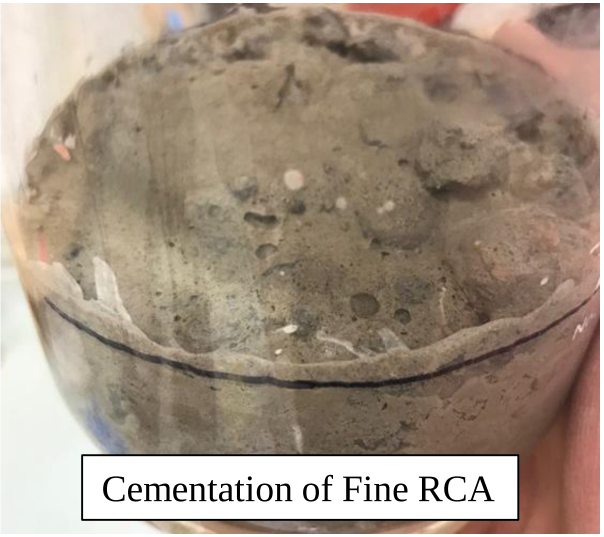


	1	2	3
θ_r	0.0800	0.0700	0.1100
θ_s	0.3467	0.3367	0.3567
α	4.3720	4.8994	1.8345
n	1.4422	1.3504	1.4726
m	0.3066	0.2595	0.3209

TASK 4

Hanging Column Test

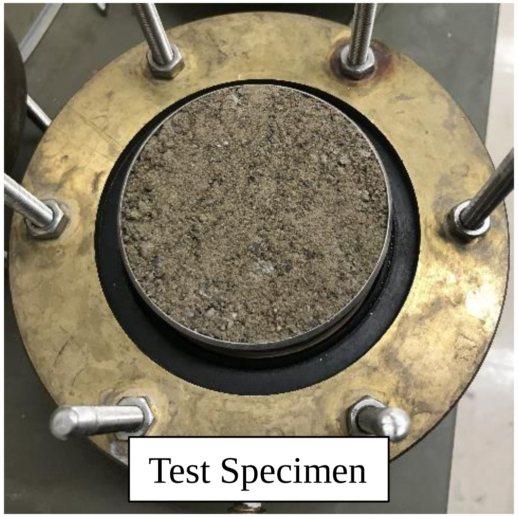




TASK 4

Pressure Plate and Activity Meter Test

Single-Specimen Pressure Chambers



Test Specimen

Activity Meter Device

TASK 4

Pressure Plate and Activity Meter Test

- van Genuchten (1980) model

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha\psi)^n}\right]^m$$

Θ = Normalized volumetric water content

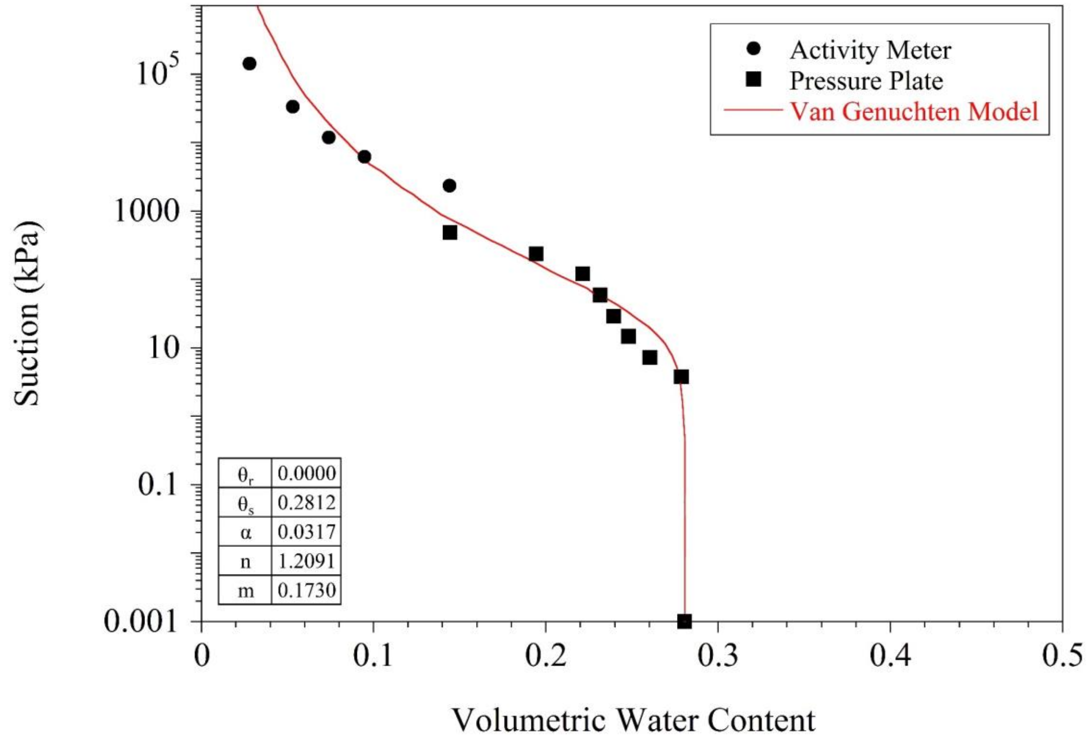
θ = Soil volumetric water content

θ_r = Residual volumetric water content

θ_s = Saturated volumetric water content

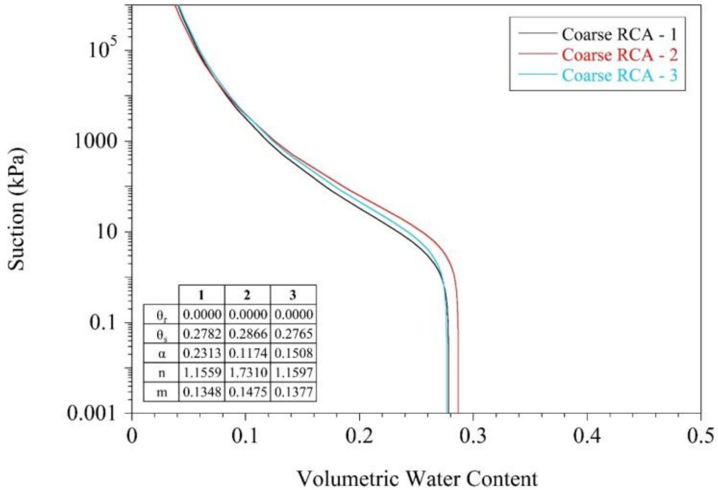
Ψ = Matric suction

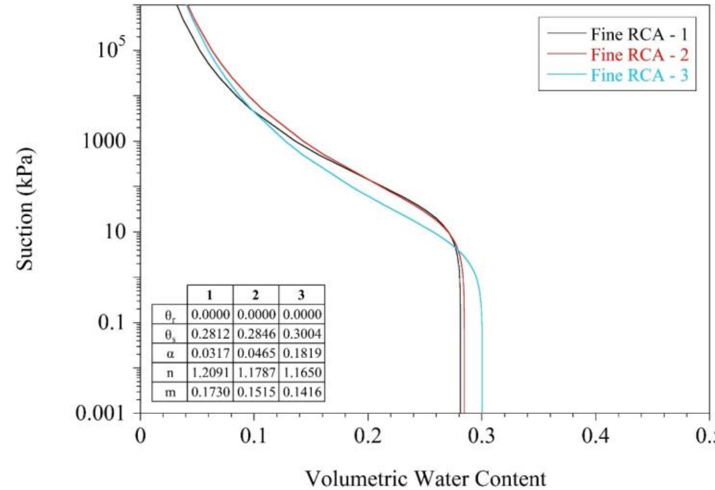
α, n, and m = van Genuchten fitting parameters

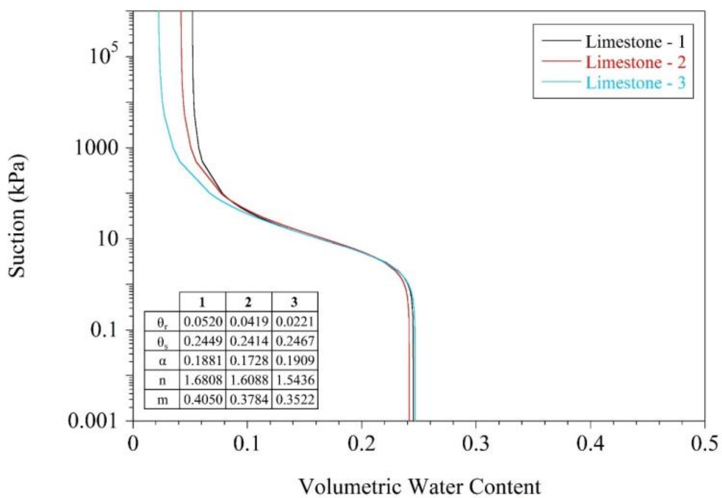


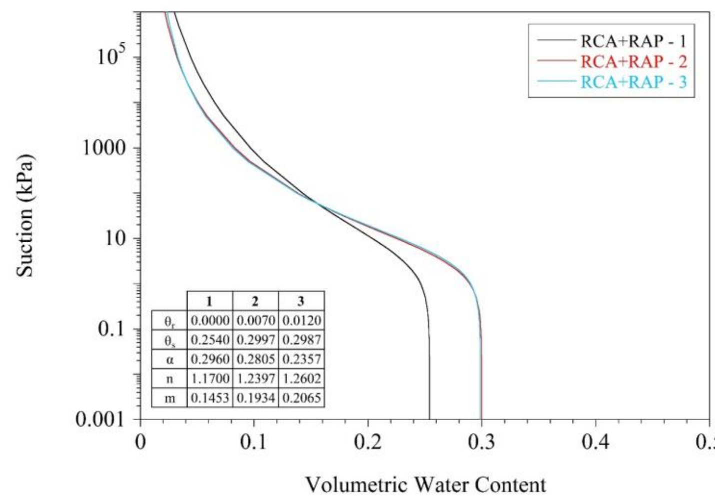
TASK 4

Pressure Plate and Activity Meter Test



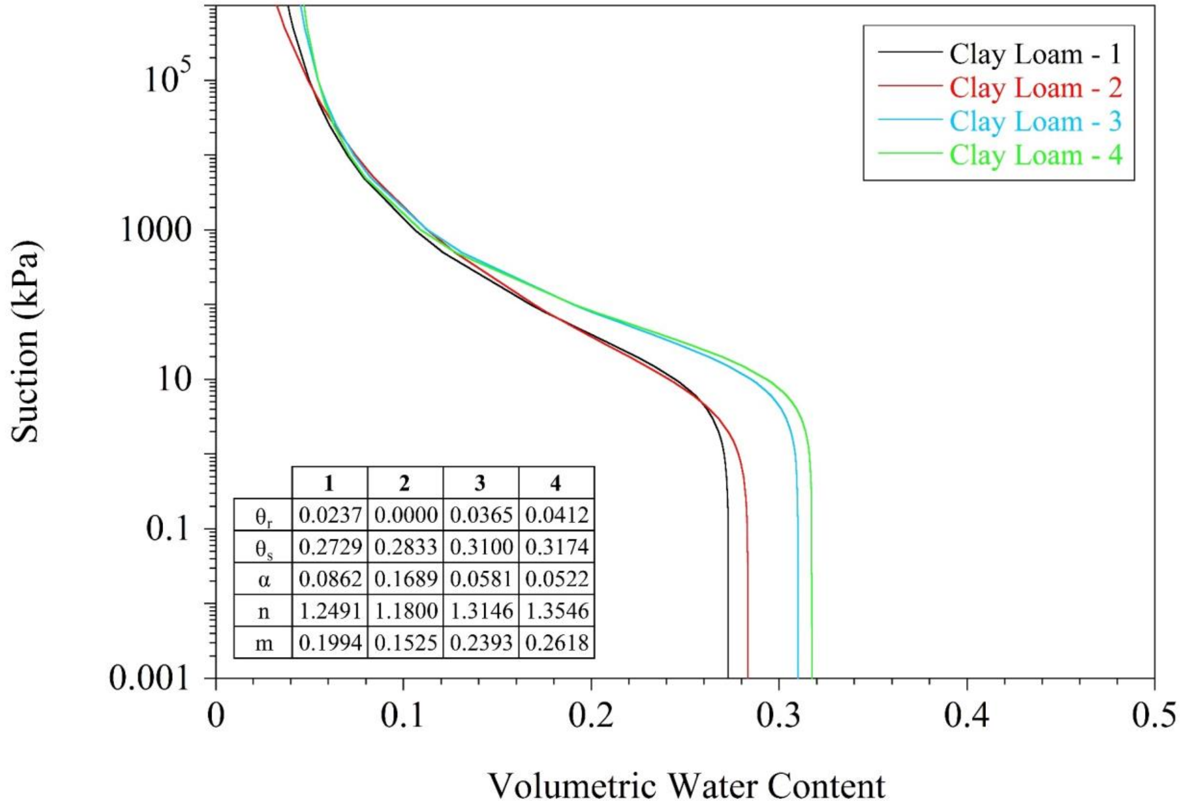






TASK 4

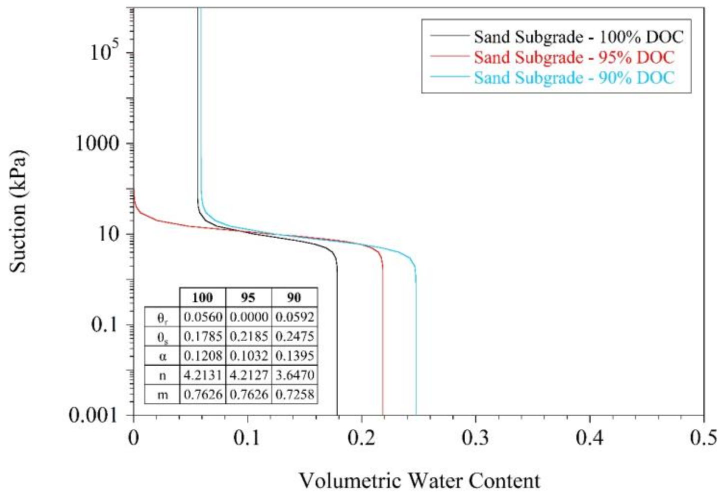
Pressure Plate and Activity Meter Test

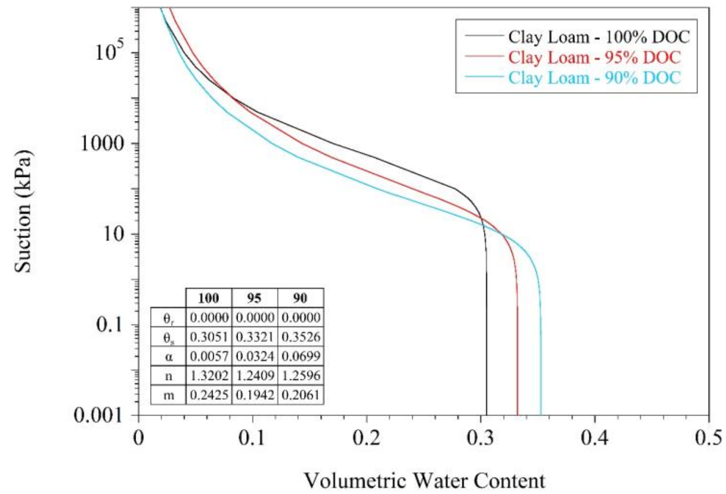


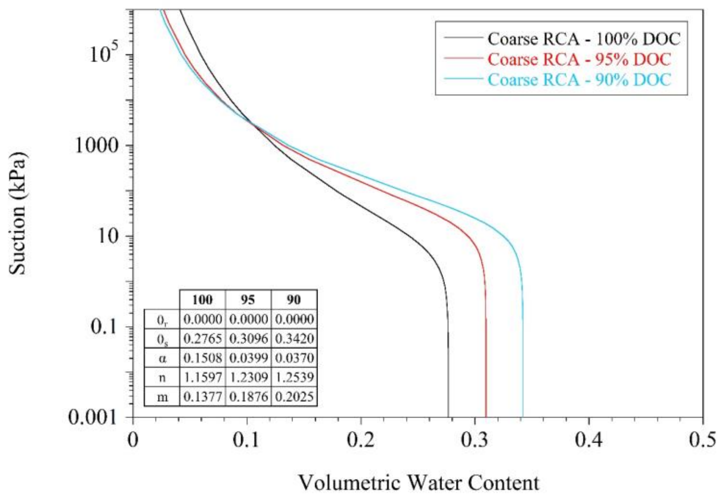
	1	2	3	4
θ_r	0.0237	0.0000	0.0365	0.0412
θ_s	0.2729	0.2833	0.3100	0.3174
α	0.0862	0.1689	0.0581	0.0522
n	1.2491	1.1800	1.3146	1.3546
m	0.1994	0.1525	0.2393	0.2618

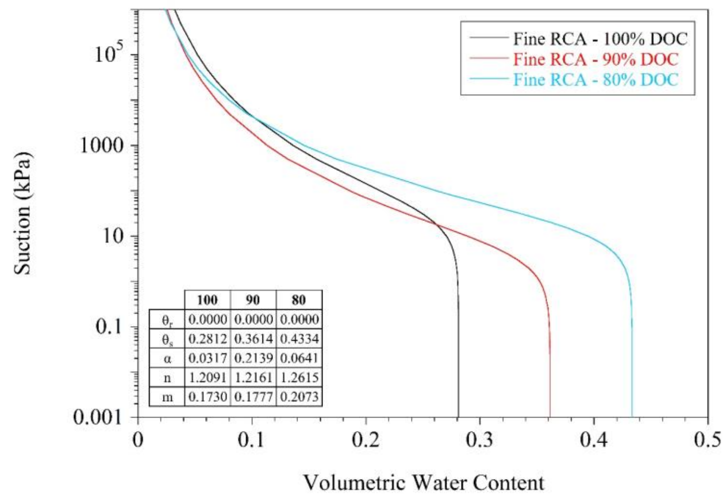
TASK 4

Pressure Plate and Activity Meter Test



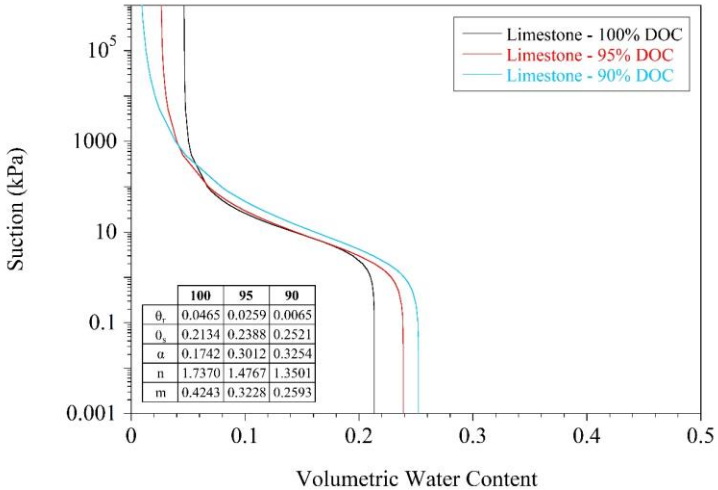




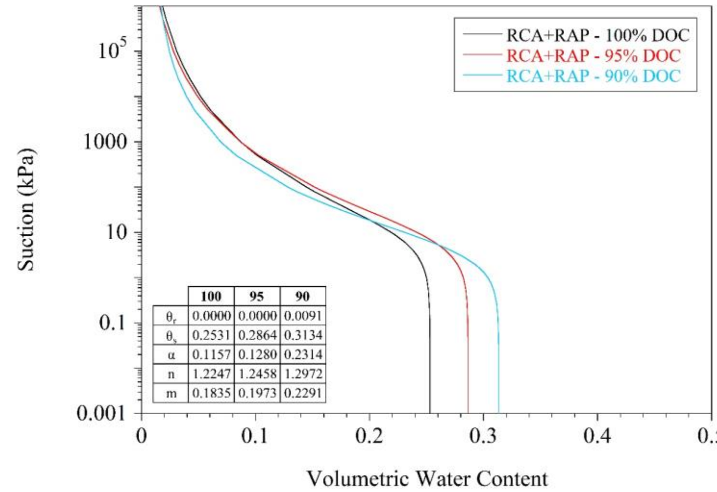


TASK 4

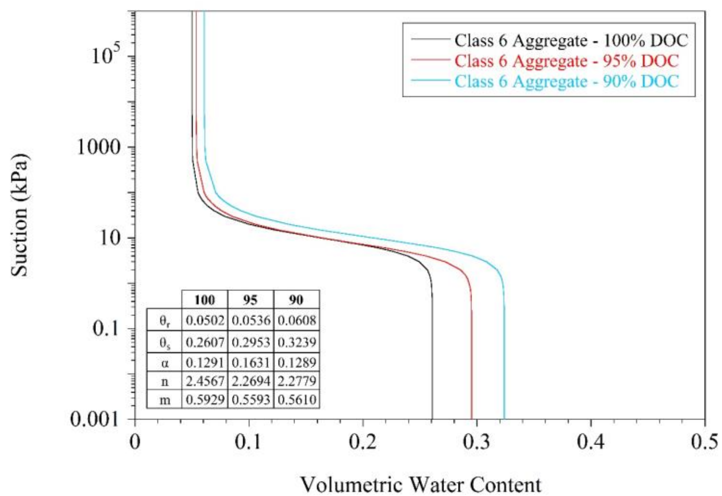
Pressure Plate and Activity Meter Test



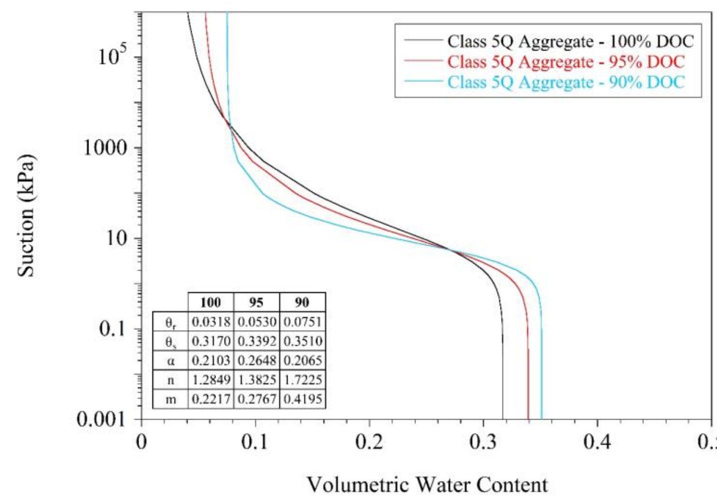
	100	95	90
θ_r	0.0465	0.0259	0.0065
θ_s	0.2134	0.2388	0.2521
α	0.1742	0.3012	0.3254
n	1.7370	1.4767	1.3501
m	0.4243	0.3228	0.2593



	100	95	90
θ_r	0.0000	0.0000	0.0091
θ_s	0.2531	0.2864	0.3134
α	0.1157	0.1280	0.2314
n	1.2247	1.2458	1.2972
m	0.1835	0.1973	0.2291



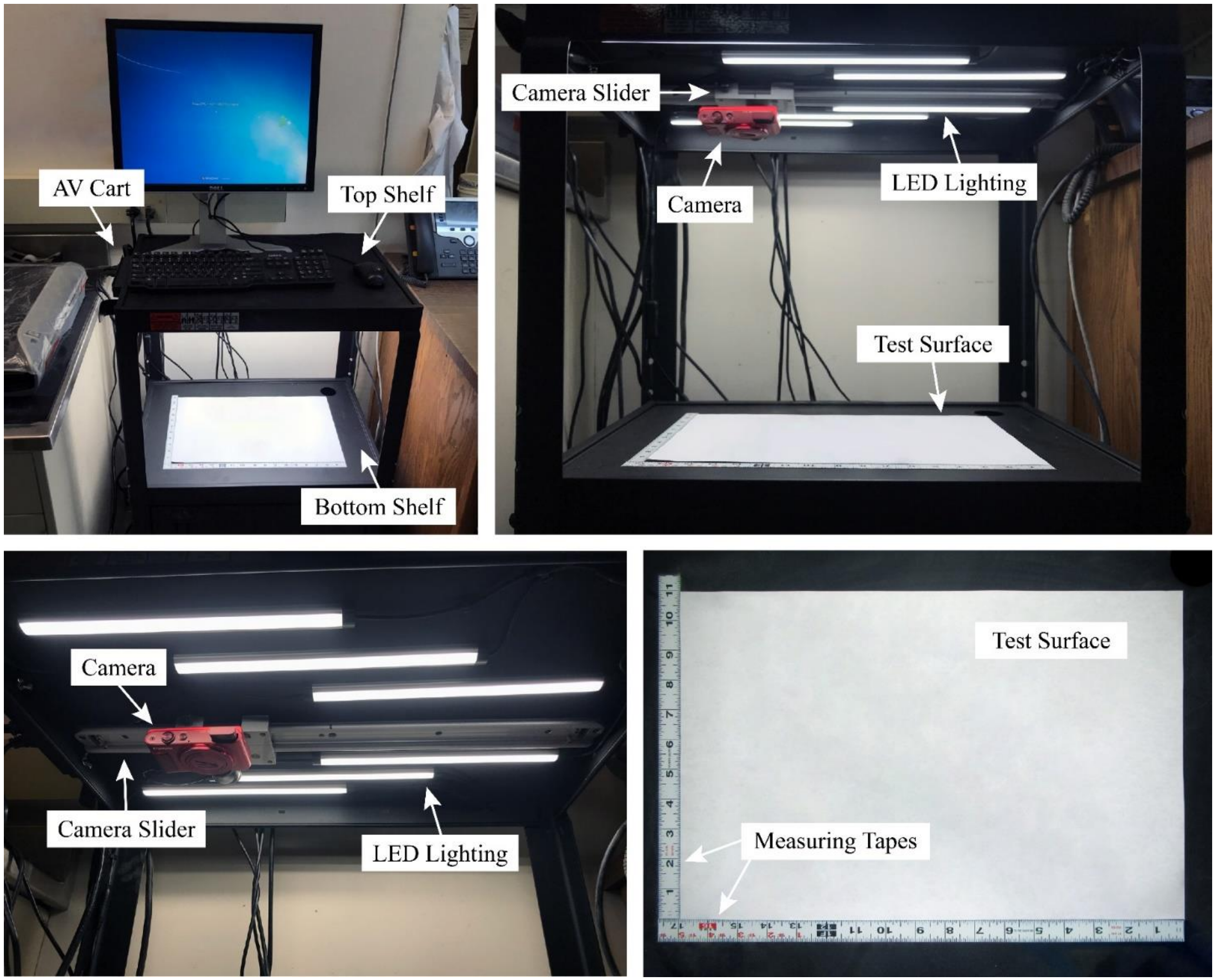
	100	95	90
θ_r	0.0502	0.0536	0.0608
θ_s	0.2607	0.2953	0.3239
α	0.1291	0.1631	0.1289
n	2.4567	2.2694	2.2779
m	0.5929	0.5593	0.5610



	100	95	90
θ_r	0.0318	0.0530	0.0751
θ_s	0.3170	0.3392	0.3510
α	0.2103	0.2648	0.2065
n	1.2849	1.3825	1.7225
m	0.2217	0.2767	0.4195

TASK 4

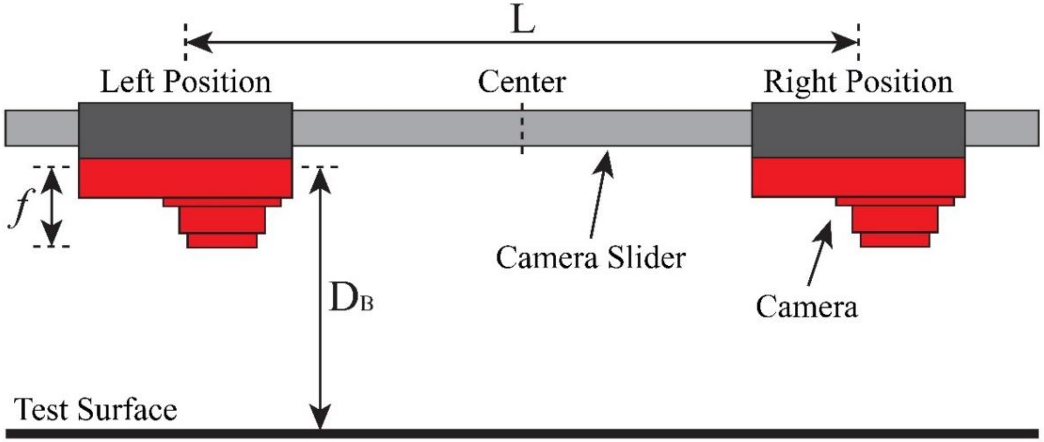
Stereophotography



TASK 4

Stereophotography

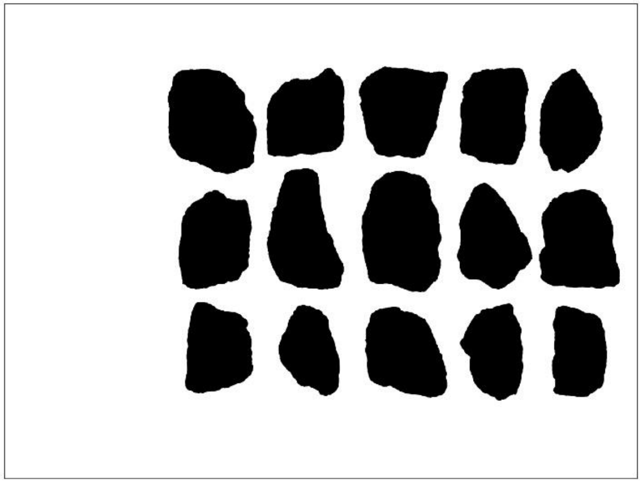
- Parameters
  - D_B = vertical distance between the camera center and the test surface
  - L = camera separation distance
  - f = focal length of the camera



TASK 4

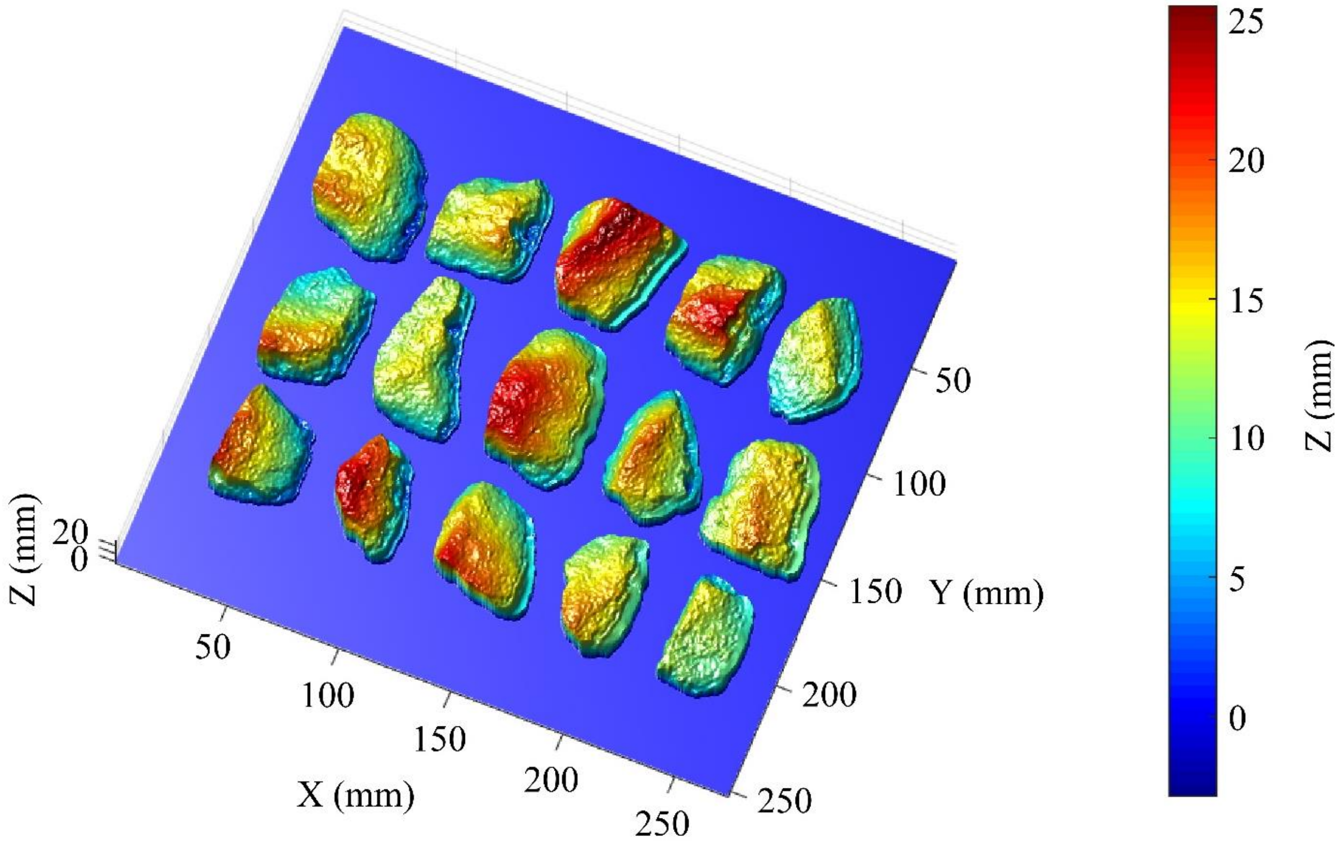
Stereophotography





TASK 4

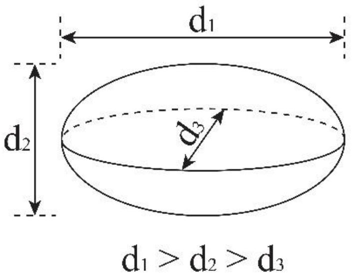
Stereophotography

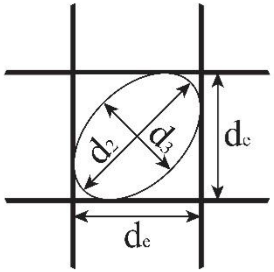


TASK 4

Stereophotography

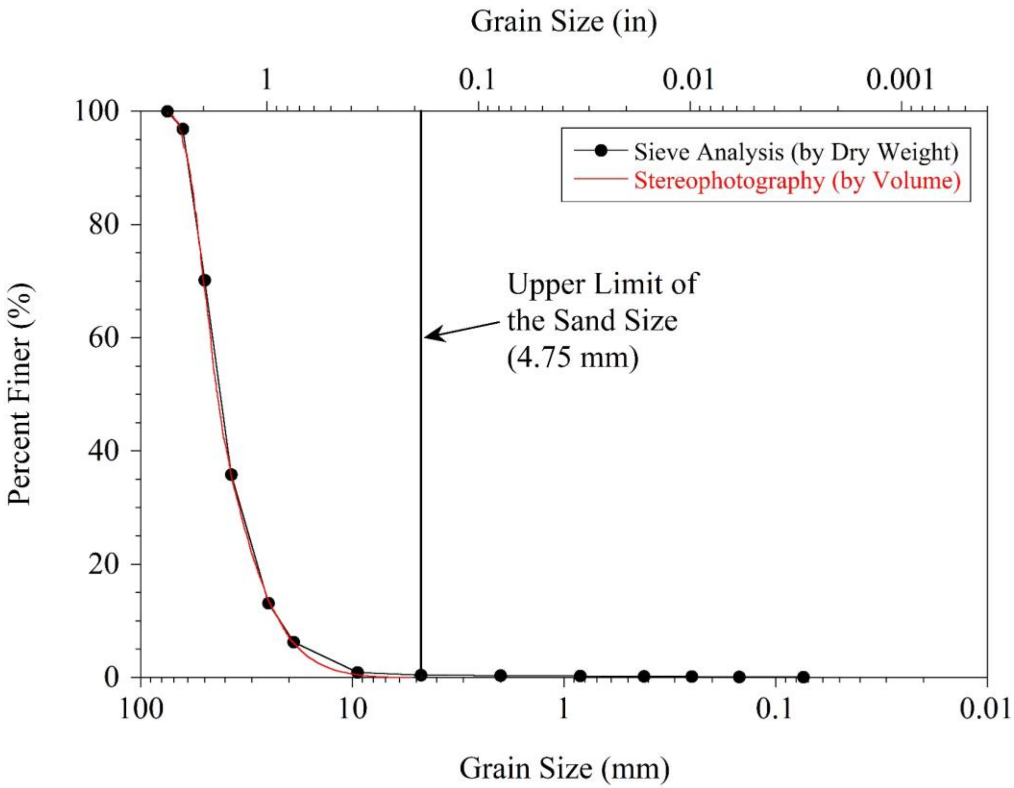
- Ellipsoidal particle model





$$d_e = \sqrt{\frac{d_2^2 + d_3^2}{2}}$$

$$V = d_1 \text{ x } d_2 \text{ x } d_3$$



TASK 4

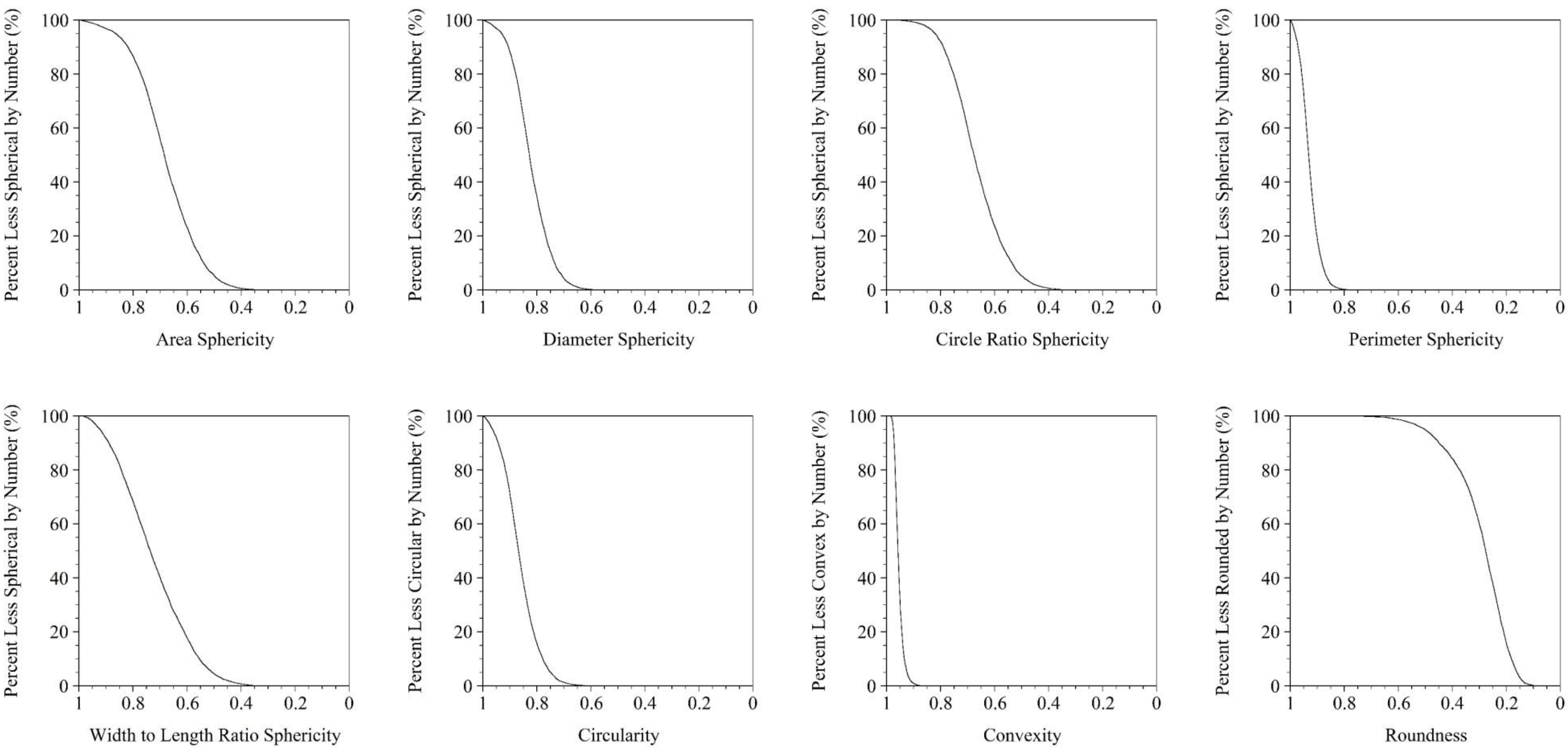
Stereophotography

- Shape parameters
  - Area sphericity
  - Diameter sphericity
  - Circle ratio sphericity
  - Perimeter sphericity
  - Width to length ratio sphericity
  - Circularity
  - Convexity
  - Roundness

Parameter	Formula	Description	Reference
Area Sphericity	$S_A = \frac{A}{A_{cir}}$	The ratio of the area of the particle (A) to the area of the smallest circumscribing circle (A_{cir}).	Riley (1941)
Diameter Sphericity	$S_D = \frac{D_e}{D_{cir}}$	The ratio of the diameter of a circle having the same area as the original particle (D_e) to the diameter of the minimum circumscribing circle (D_{cir}).	Wadell (1935)
Circle Ratio Sphericity	$S_C = \frac{D_{ins}}{D_{cir}}$	The ratio of the diameter of the largest inscribed circle of the particle (D_{ins}) to the smallest circumscribing circle of the particle (D_{cir}).	Santamarina and Cho (2000)
Perimeter Sphericity	$S_P = \frac{P_e}{P}$	The ratio of the perimeter of the circle having the same area as the particle (P_e) to the real perimeter of the particle (P).	Kuo and Freeman (2000)
Width-to-Length Ratio Sphericity (Aspect Ratio, Elongation)	$AR = \frac{W}{L}$	The ratio of the width of the particle (W) to the length of the particle (L).	Krumbein and Sloss (1951)
Circularity	$C = \frac{4\pi A}{P^2}$	The ratio of the area of the particle (A) to the area of the circle having the same perimeter as the particle ($P^2/4\pi$).	ISO (2008)
Convexity (Solidity)	$C_x = \frac{A}{A_c}$	The ratio of the area of the particle (A) to the area of the minimum convex boundary circumscribing the particle (A_c).	Mora and Kwan (2000)
Roundness (Angularity)	$R = \frac{\sum_{i=1}^{N} r_i / N}{r_{ins}}$	The ratio of the average radius of corner circles of the particles (r_i is the radius of i-th corner and N is the number of corners) to the radius of the maximum inscribed circle (r_{ins}).	Wadell (1932, 1933, and 1935)

TASK 4

Stereophotography



TASK 4

Gyratory Compaction

- ASTM D6925
- 4500 g of each material
- 100, 300, and 500 gyrations

Parameter	Value
Compaction Mold Diameter	6 in (150 mm)
Specimen Height	6 - 7.25 in (150 – 185 mm)
Vertical Applied Pressure	12,530 psf (600 kPa)
Number of Gyrations	100, 300[a], 500[b]
Angle of Gyration	1.25° ± 0.02
Frequency of Gyration	30 ± 0.5 gyrations/min
Number of Dwell Gyrations	2

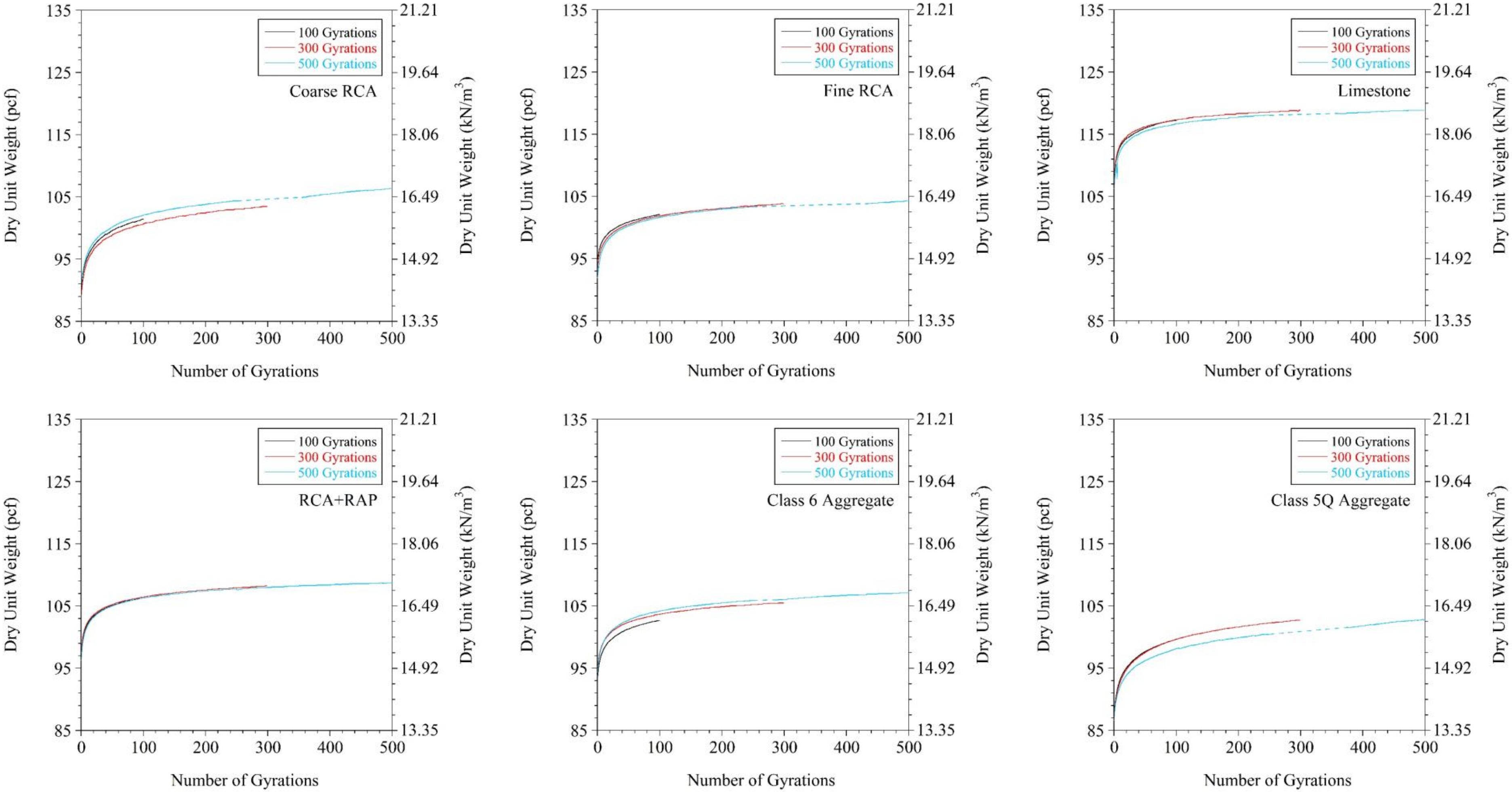
[a]In fact, 299 gyrations (maximum number of gyrations that can be applied per test) were applied. However, the number is rounded to 300 for simplicity.
[b]Applied in two consecutive tests with 250 gyrations each.

TASK 4

Gyratory Compaction

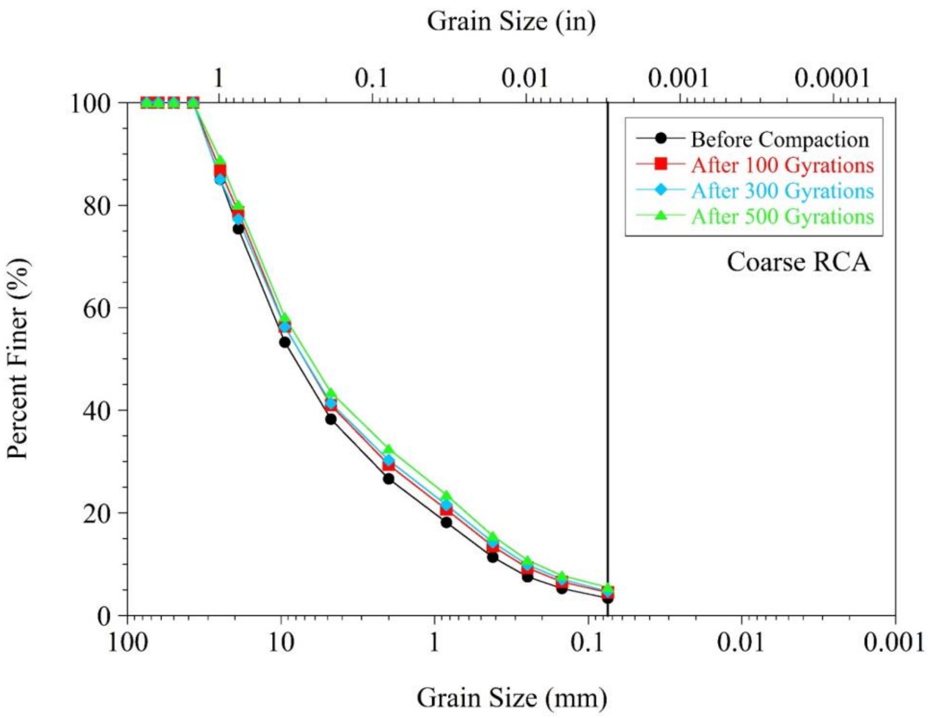
TASK 4

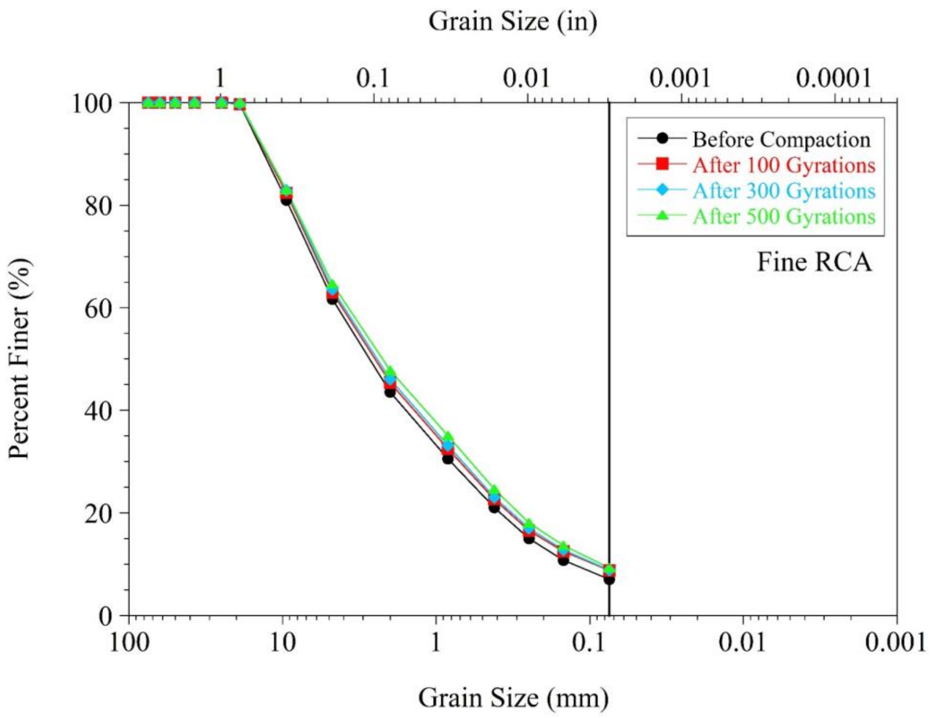
Gyratory Compaction



TASK 4

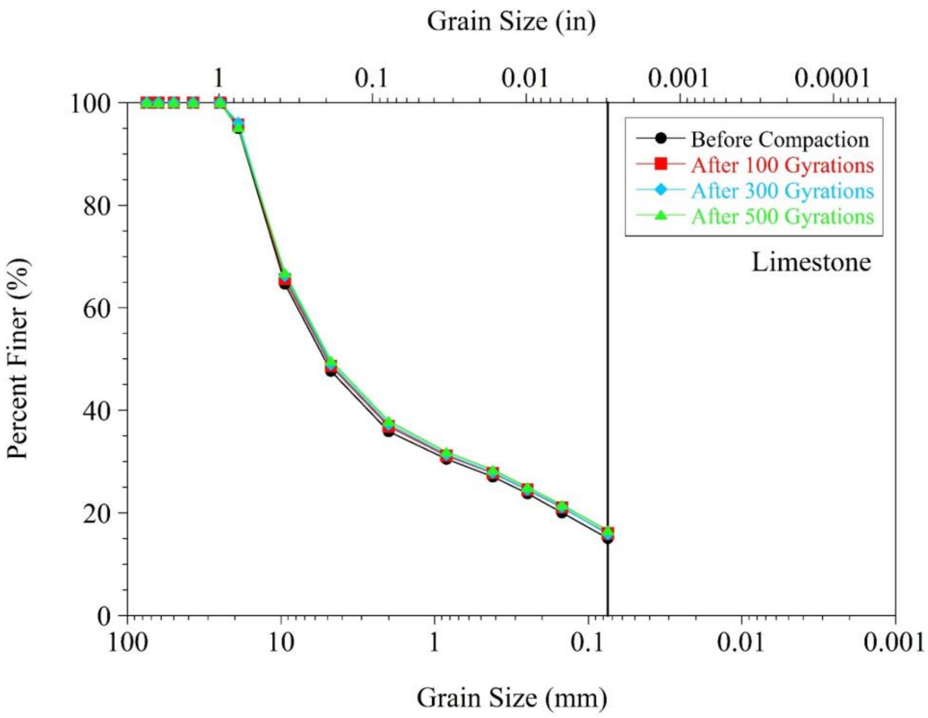
Gyratory Compaction

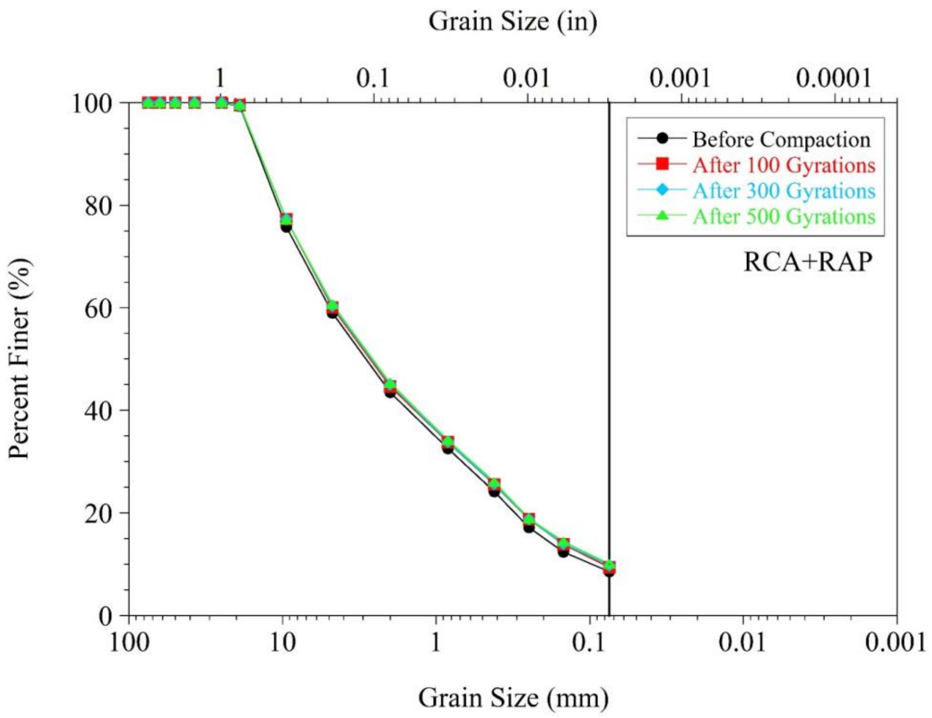




TASK 4

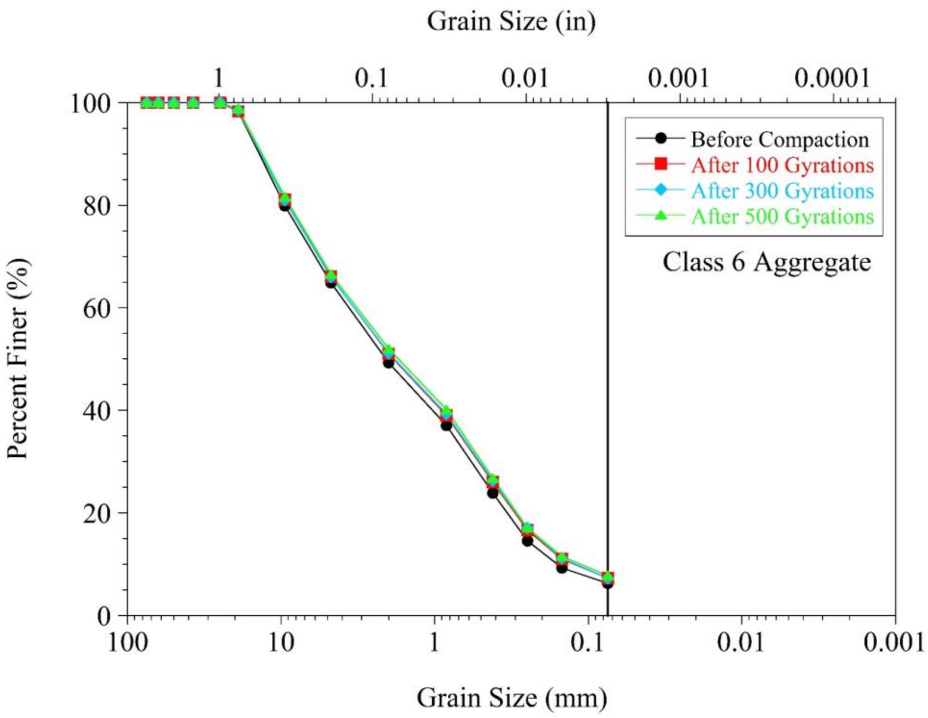
Gyratory Compaction

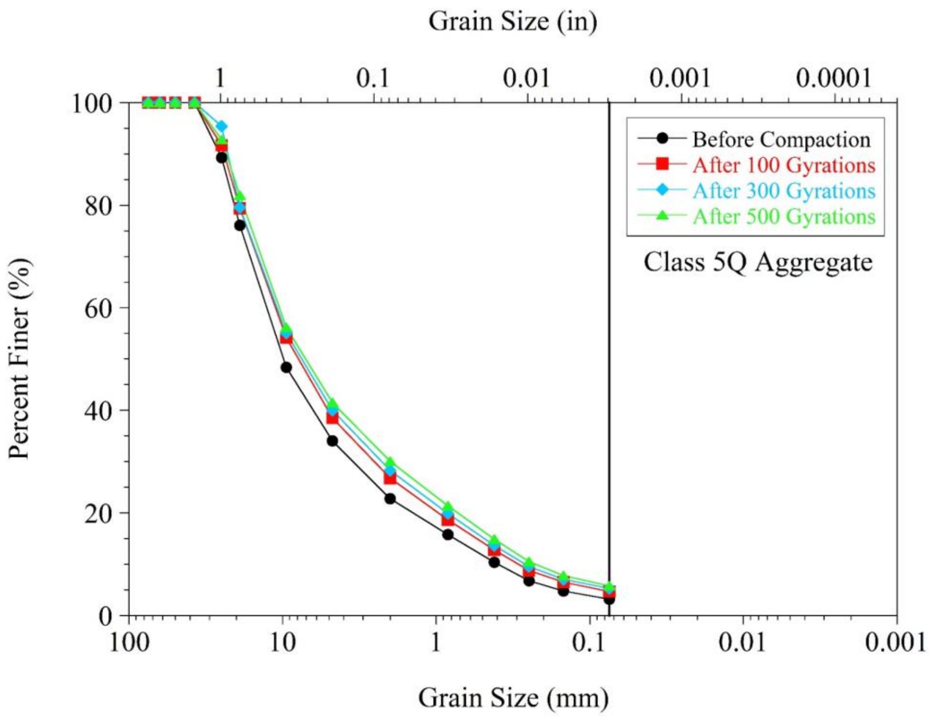




TASK 4

Gyratory Compaction

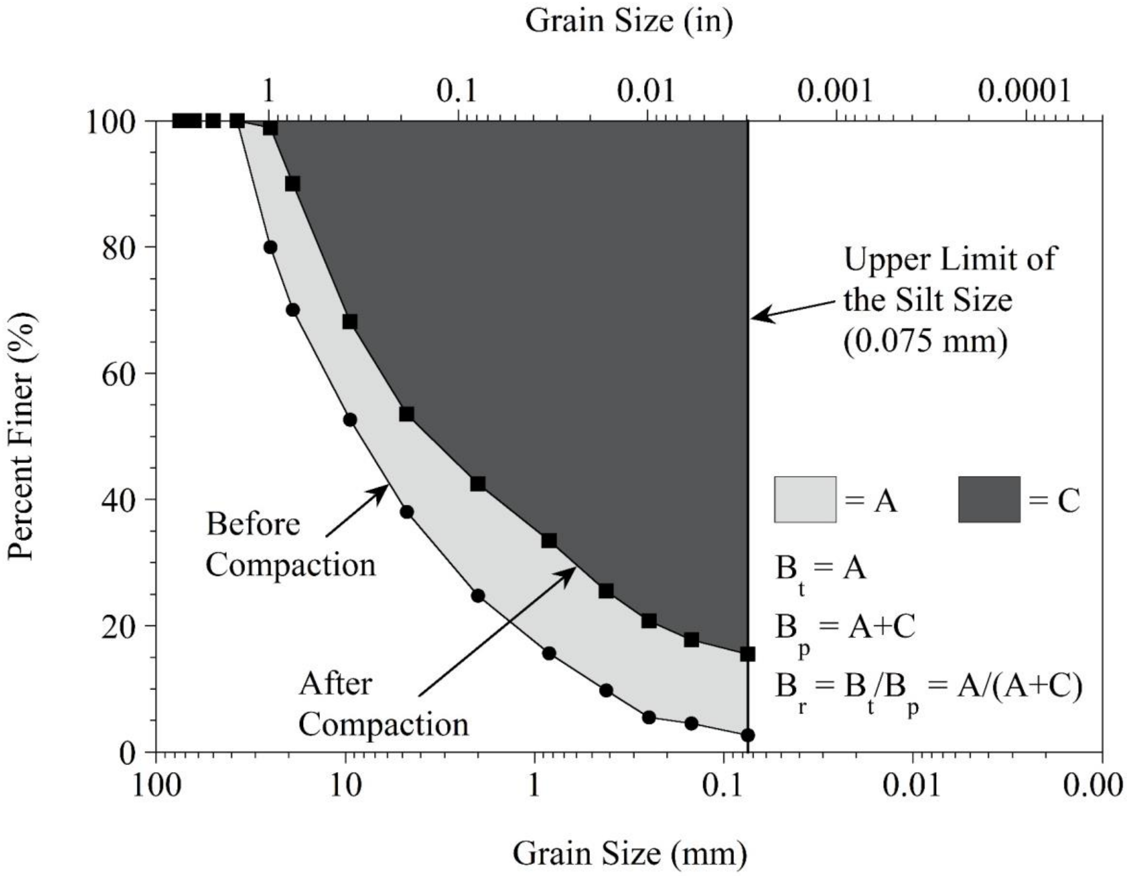




TASK 4

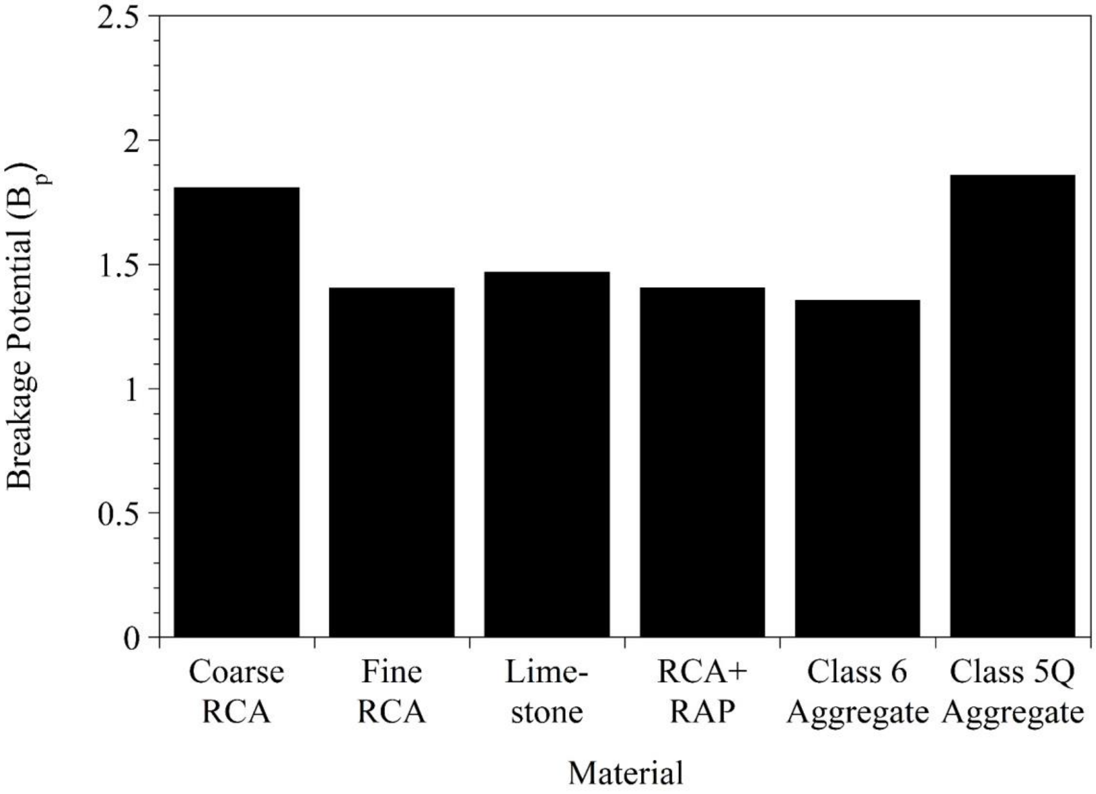
Gyratory Compaction

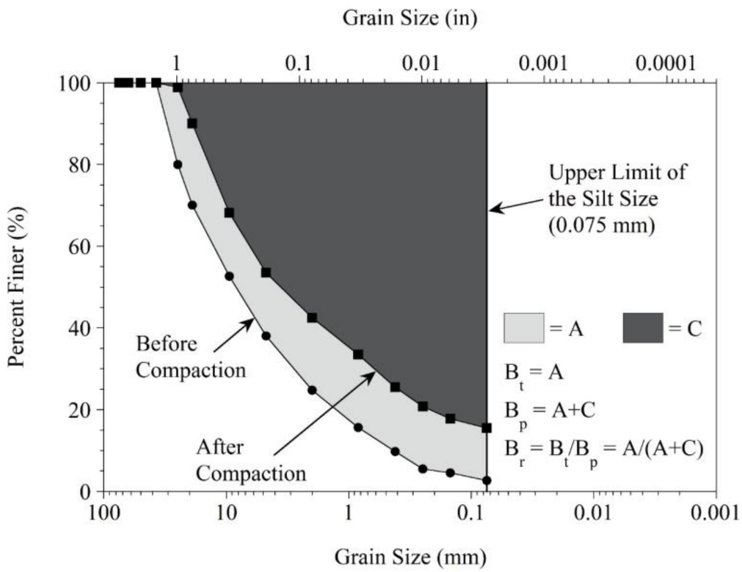
- Hardin (1985)
  - Breakage potential (B_p)
  - Total breakage (B_t)
  - Relative Breakage (B_r)



TASK 4

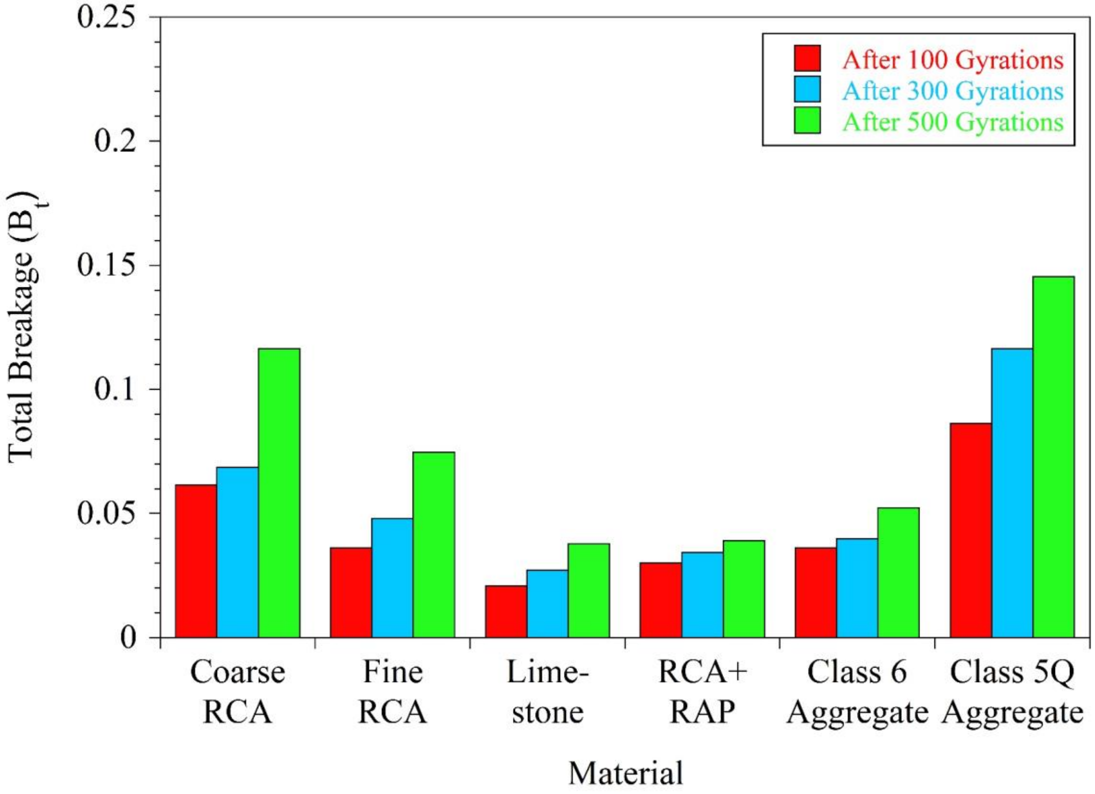
Gyratory Compaction

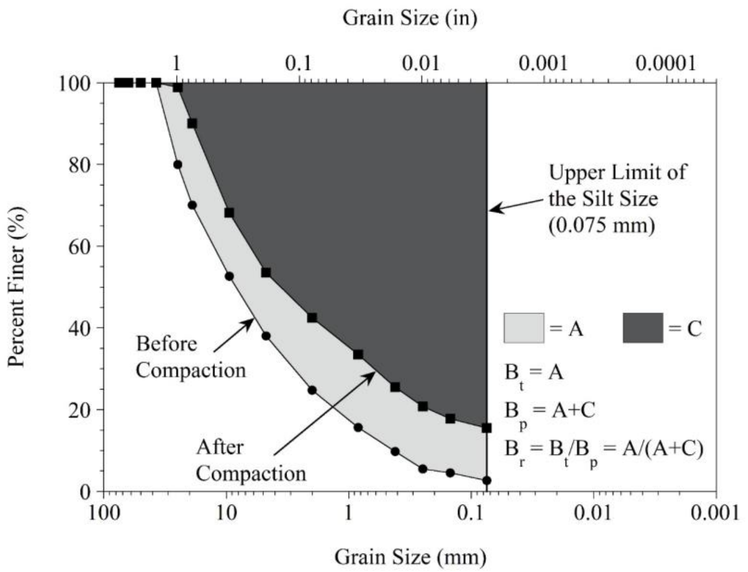




TASK 4

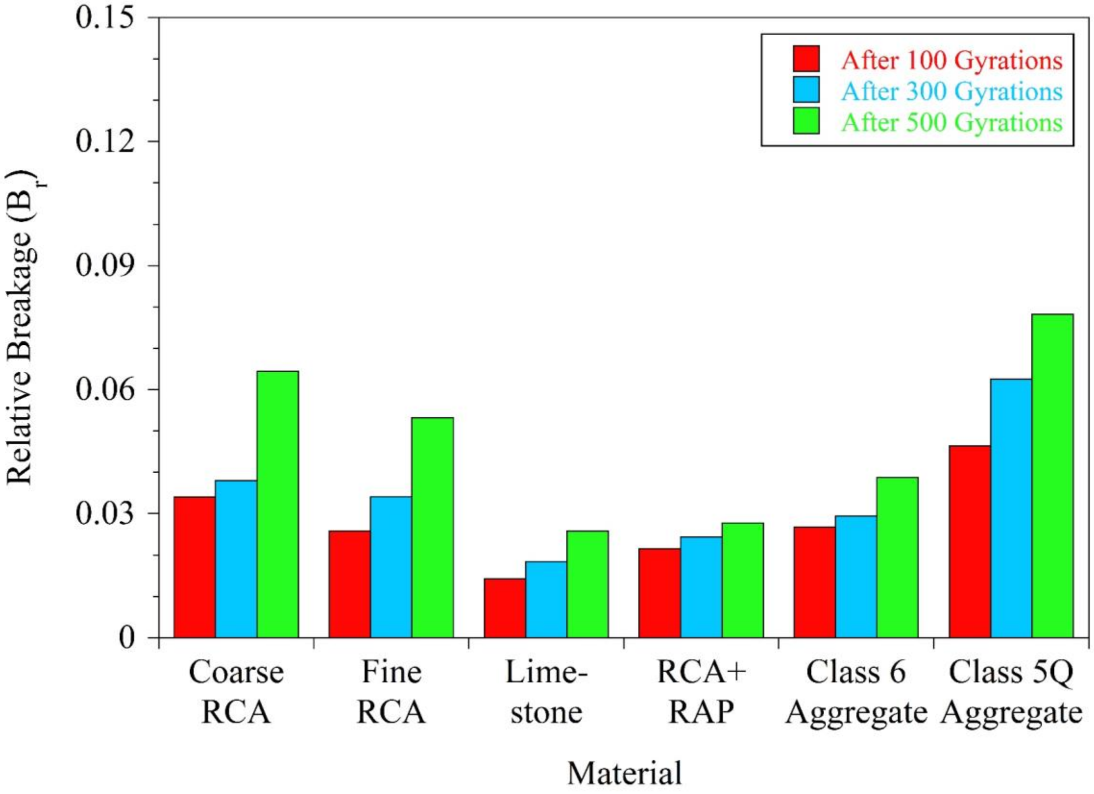
Gyratory Compaction

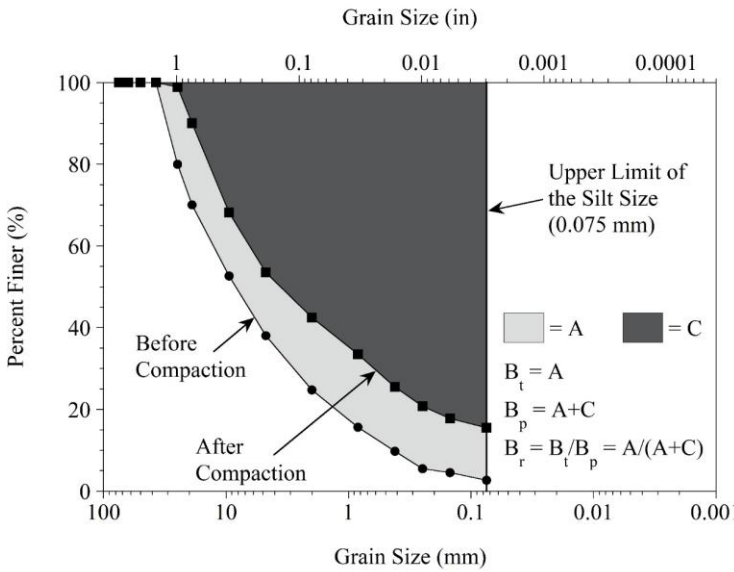




TASK 4

Gyratory Compaction





SUMMARY

- Deleterious materials < 0.1% by dry weight
- G_s
  - Fine RCA < coarse RCA < RCA+RAP & class 5Q aggregate < class 6 aggregate < limestone
- Absorption
  - Fine RCA > coarse RCA > class 5Q aggregate > RCA+RAP > class 6 aggregate > limestone
- MDD
  - Fine RCA < RCA+RAP < class 5Q aggregate < class 6 aggregate < coarse RCA < limestone
- OMC
  - Fine RCA > RCA+RAP > class 5Q aggregate > coarse RCA > class 6 aggregate > limestone

SUMMARY

- Class 6 & class 5Q aggregates → not natural
- Asphalt binder content
  - Ignition method > quantitative extraction
  - Class 6 aggregate > RCA+RAP > fine RCA > limestone > class 5Q aggregate > coarse RCA
- Constant head permeability
  - Insufficient compaction by light hammering in the membrane
  - Fine RCA > limestone, class 6 aggregate, & class 5Q aggregate > coarse RCA & RCA+RAP
- Falling head permeability
  - Better compaction in the compaction mold
  - Coarse RCA, fine RCA, & RCA+RAP > limestone

SUMMARY

- Falling head permeability – different DOC
  - DOC ↓ permeability ↑
  - Fine RCA > coarse RCA
- Hanging column test (for SWCC)
  - Lower suctions
  - Not suitable for RCA - cementation
- Pressure plate and activity meter test (for SWCC)
  - Higher suctions
  - DOC ↓ initial VWC ↑
- Stereophotography
  - Compatible with sieve analysis
  - Good for shape analysis

SUMMARY

- Gyratory compaction
  - Number of gyrations ↑ dry unit weight ↑
- Breakage potential (B_p)
  - Class 5Q aggregate > coarse RCA > limestone > fine RCA & RCA+RAP > class 6 aggregate
- Total breakage (B_t)
  - Number of gyrations ↑ B_t ↑
  - Class 5Q aggregate > coarse RCA > fine RCA > class 6 aggregate > RCA+RAP > limestone
- Relative breakage (B_r)
  - Similar to B_t

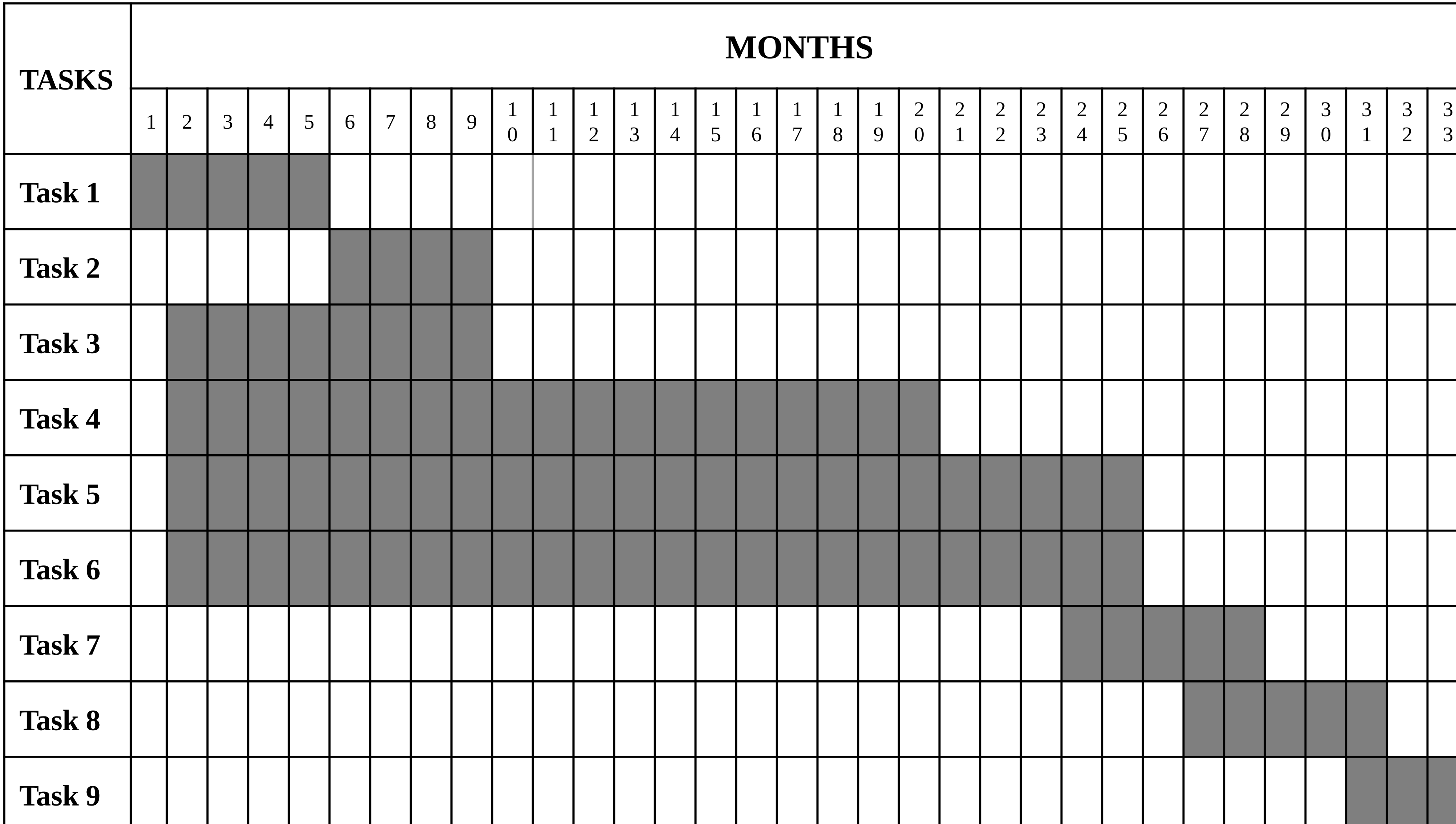
FUTURE STUDY

- Determination of the unhydrated cement contents
- Determination of the residual mortar contents
- Contact angle measurements
- Gradation of the materials used in permeability and SWCC tests
- Stereophotography for other materials
- Changes in morphology due to gyratory compaction

Thank You!

QUESTIONS??

SCHEDULE


TASKS
MONTHS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Task 1
Task 2
Task 3
Task 4
Task 5
Task 6
Task 7
Task 8
Task 9