Best Value Granular Material for Road Foundations

Mn/DOT FY09 H09PS07 Research Project TAP Meeting

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ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

MINNESOTA DEPARTMENT OF TRANSPORTATION

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Research Need Statements

- ✓ Aggregate base materials are becoming increasingly expensive in many parts of Minnesota
  - ✓ gravel mines & rock quarries are being lost to other land uses
- ✓ Aggregate specification, production & placement are based on testing techniques & design procedures that are several decades old
- ✓ **There is likely significant opportunity for better value to be achieved**
  - ✓ by implementing new mechanistic design procedures & testing techniques, road construction can better optimize material use & reduce waste
- ✓ Mechanistic pavement design and the field & lab tests required would be needed to implement
  - ✓ A granular material best value software tool to be added to MnPAVE to further encourage implementation of mechanistic design

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Research Objective

- ✓ *Demonstrate that locally available materials can be economically efficient in the implementation of the available mechanistic based design procedures in Minnesota through*

  MnPAVE Mechanistic-Empirical Pavement Design Method

- ✓ *Develop the components of a new granular material best value software module to be added to the MnPAVE program*

- ✓ *Provide pavement designers with index aggregate properties linked to modulus & strength characteristics and include example pavement designs*

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Expected Benefits

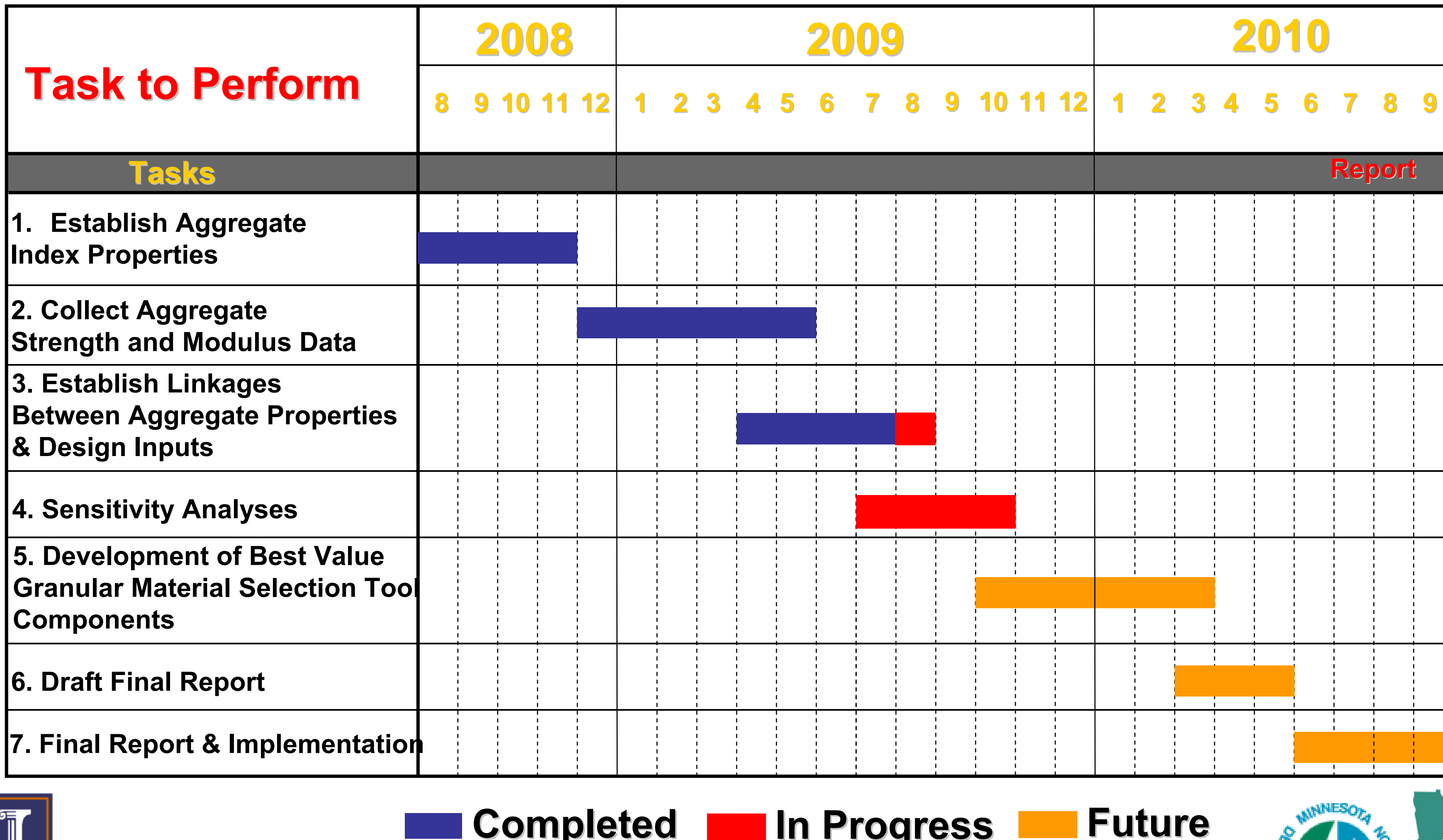
(i) Proper material **selection & utilization** according to aggregate properties

(ii) **Aggregate layer thickness optimizations** during the design process based on cost and mechanistic material properties related to performance, and as a result;

(iii) **More economical** use of the locally available aggregate materials in Minnesota

The ***benefits & costs*** *of implementing* ***new mechanistic design procedures & material testing techniques*** *would be demonstrated by these designs*

Project Schedule



Project Tasks

Task 1 - Overview:

Establish Index Properties of Minnesota Aggregates Used for Aggregate Base/Subbase Courses

Work with Mn/DOT engineers to identify & categorize the **types, sources, & properties** of locally available aggregates in Minnesota and obtain **typical costs**. This is an essential task for:

- Identifying types & qualities of aggregates to establish mechanistic strength & resilient modulus (M_R) properties
- Conducting a benefit/cost study to demonstrate life cycle benefits & costs of these aggregate materials typically used to construct road foundations throughout Minnesota

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Project Tasks

Task 1 – Data Sources:

Aggregate Source Information System (ASIS)

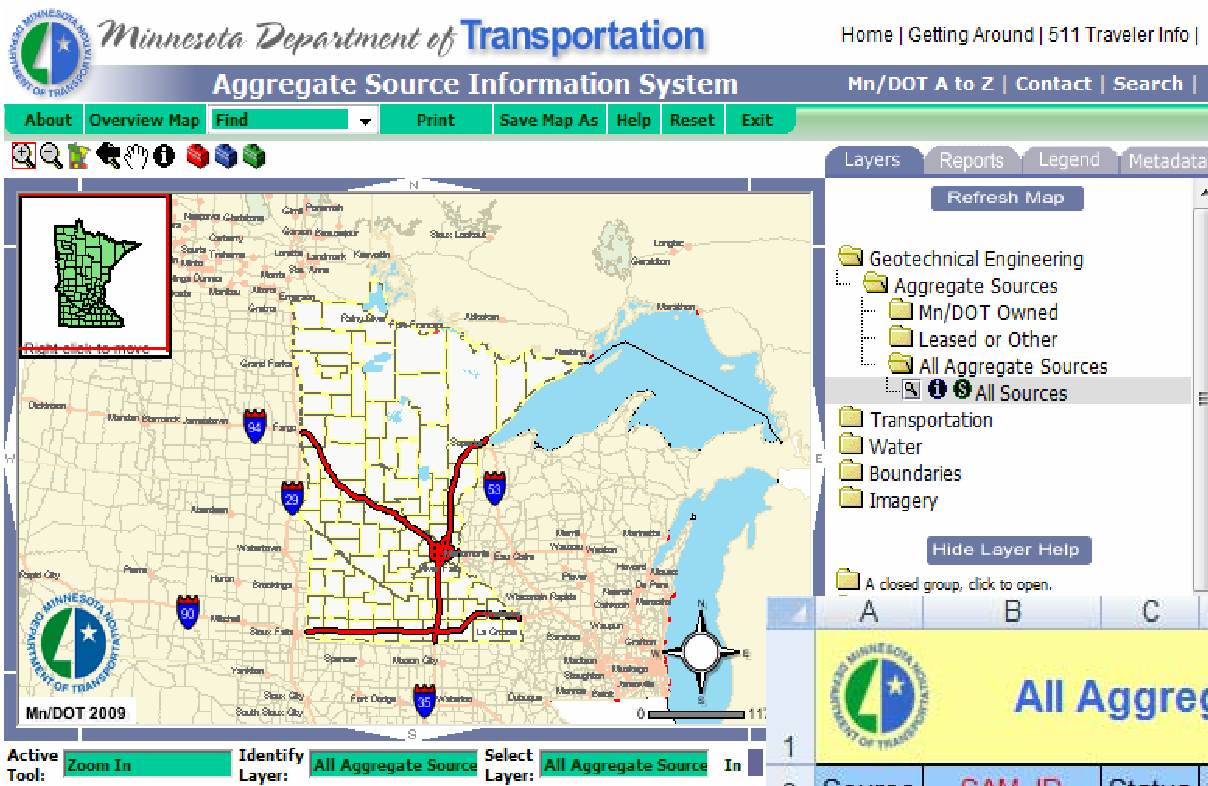
http://www.mrrapps.dot.state.mn.us/gisweb/viewer.htm?activelayer=8

Files received from Mn/DOT

Date	File Name	Description
Sep.-19-08	MNagg pits utmZone15N.xls ProspectLimsMNmap.pdf	UTM Coordinates for Prospect pits
Oct.-8-08	ProspectedPits_LimsRawResnames.xls	Designation explanation for Agg tests
Oct.-16-08	MnDOT agg pit_samid_gradations_ps_tname.xls all_pit_lims111408.xls	Agg gradation for all pits
Jan.-30-09	MnDOT MAP Agg pricesCL.pdf	Aggregate prices for MnDOT owned & leased Gravel pits

Project Tasks

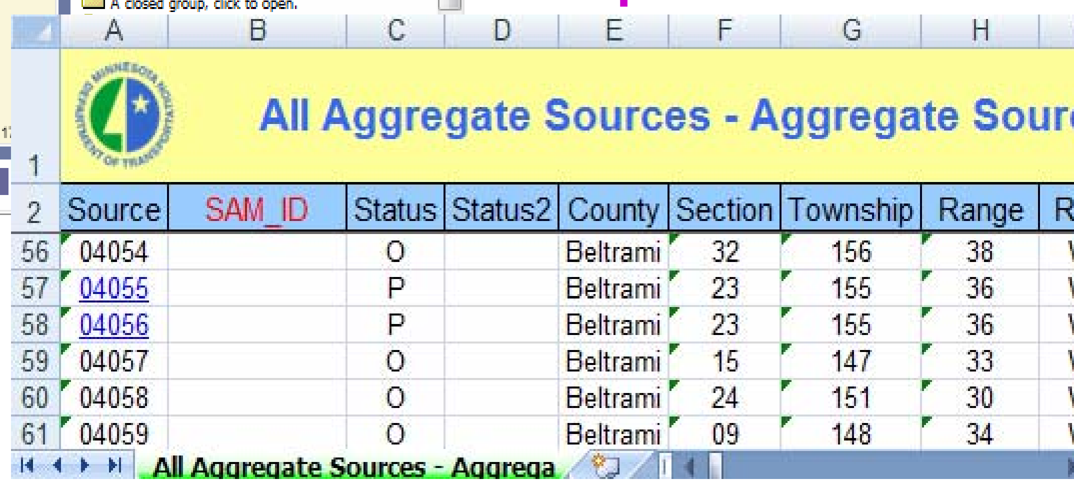
Task 1 – Data Sources (Cont'd):



ASIS Online Interface

- •Aggregate source data for MN counties
- • Limited agg properties
- • Merged with reliable data submitted

ASIS Database Spreadsheets



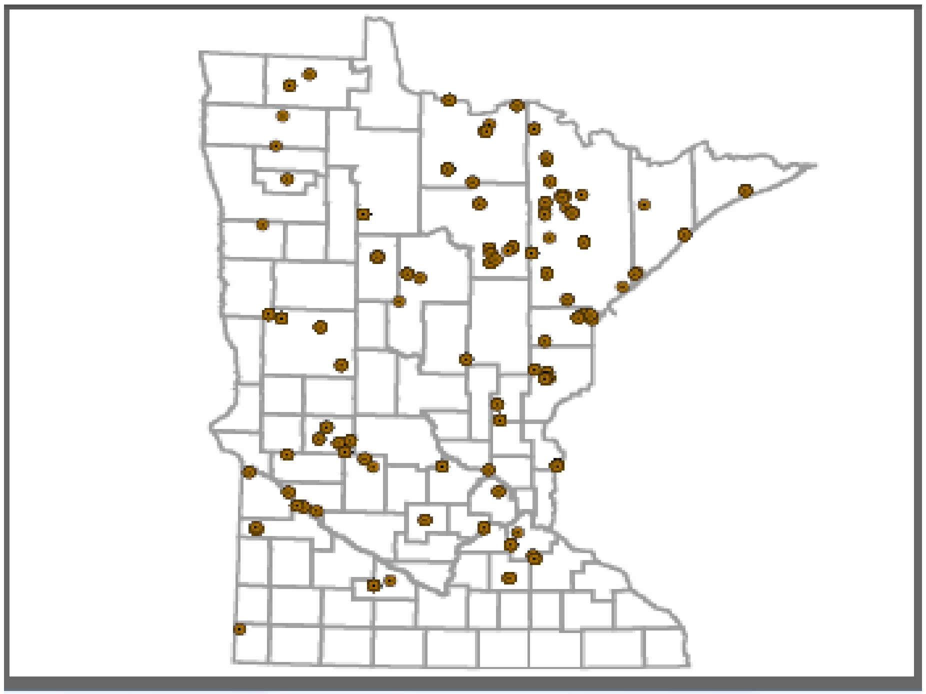
All Aggregate Sources - Aggregate Sourc

	Source	SAM_ID	Status	Status2	County	Section	Township	Range	Rd
56	04054		O		Beltrami	32	156	38	W
57	04055		P		Beltrami	23	155	36	W
58	04056		P		Beltrami	23	155	36	W
59	04057		O		Beltrami	15	147	33	W
60	04058		O		Beltrami	24	151	30	W
61	04059		O		Beltrami	09	148	34	W

All Aggregate Sources - Aggrega

Project Tasks

Task 1 – Data Sources (Cont'd):



	A	B	C	D
1	PITNUM	UTM_X	UTM_Y	County_Name
2	04090	341700	5273400	Beltrami
3	08014	366562	4904426	
4	08024	351343	4898899	Brown
5	08054	350770	4899511	
6	09041	510000	5145400	
7	09044	554084	5166993	
8	09048	546398	5172380	Carlton
9	09053	552421	5171747	
10	09068	540725	5168925	
11	11009	382198	5212846	

utmZone15Nxy

ProspectLimsMNmap.pdf
(Map of prospect pits)

MNagg pits utmZone15N.xls
(UTM Coordinates of prospect pits)

Project Tasks

Task 1 – Data Sources (Cont'd):

	A	B	C	D	E	F
1	INST_NAM	IN_NAM	WORKNAME	SH_DES	RES_NAME	
2		sam_res	COLR_PL	Color Pl.-Lab Tested	f_1022	
3	WTAVG	wtavg_i	CRUSH	% Pass #4	pgap4_75	
4	WTAVG	wtavg_i	CRUSH	% Pass 1/2"	pgap12_5	
5		sam_res	CYLINDER	Date Sampled	p_datsam	
6		sam_res	CYLINDER	Sample Comments	smpcmt	
7	GRDTIN	aggr1_i	FLD_GRAD	#200/1" Ratio	f_200_1r	
8	CSM202	aggr2_i	FLD_GRAD	Percent -#200 Field	gpct200f	
9	FDGRAD	f_aggr_i	FLD_GRAD	Field Pct Pass #10	f_pp_2mm	
10	FDGRAD	f_aggr_i	FLD_GRAD	Field Pct Pass #100	f_pp_150	
11	FDGRAD	f_aggr_i	FLD_GRAD	Field Pct Pass #16	f_pp1_18	

ProspectedPits_LimsRawResnames

ProspectedPits_LimsRawResnames.xls

(Designations of other aggregate tests

– only gradation and Proctor data were useful)

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Project Tasks

Task 1 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	
5	PITNUM	SAM_ID	Avg % Pass 3/8 in	Avg % Pass 1/2 in	Avg % Pass 5/8 in	Avg % Pass 3/4 in	Avg % Pass 1 in	Avg % Pa
6	04090	02-PS05-0026	86.	91.	95.	96.	99.	
7	04090	02-PS05-0027	67.	73.	80.	86.	94.	
8	04090	02-PS05-0028	81.	87.	95.	96.	100.	
9	04090	02-PS05-0029	86.	92.	95.	98.	100.	
10	04090	02-PS05-0030	98.	99.		99.	99.	
11	04090	02-PS05-0031	93.	95.	97.	99.	100.	
12	04090	02-PS05-0032	98.	99.		99.	100.	
13	04090	02-PS05-0033	100.	100.	100.			
14	04090	02-PS05-0034	98.	99.	99.	100.	100.	
15	04090	02-PS05-0035	93.	96.	98.	99.	100.	
16	04090	02-PS05-0036	90.	93.	95.	98.	100.	
17	04090	02-PS05-0037	84.	89.	93.	96.	99.	
18	04090	02-PS05-0038	82.	87.	91.	94.	97.	

MnDOT agg pit_samid_gradations_

MnDOT agg pit_samid_gradations_ps_tname.xls

(Gradation data for prospect pits)

(* 27 prospect pits out of 114 have no gradation data in this file)

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Project Tasks

Task 1 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	H	I	J	
1	PITNUM	SAM_ID	UTM_X	UTM_Y	Max Density PCF	Optimal Moistur	Avg % FAA	Pct Crushed	Pct Crushed 1/2 in -	Pct Crushed 1/2 in -#	Total %
2	01003	01-BA98-0066	480195	5116182							
3	01013	01-BA07-0052	473488	5164759							
4	01013	01-BA07-0053	473488	5164759							
5	01013	01-BA07-0054	473488	5164759							
6	01013	01-BR07-0015	473488	5164759							
7	01013	01-GS07-0050	473488	5164759							
8	01013	01-GS07-0055	473488	5164759							
9	01013	01-GS07-0179	473488	5164759							
10	01013	01-GS07-0180	473488	5164759							
11	01020	3A-BA07-0171	473486	5165160							
12	01020	3A-BA07-0181	473486	5165160							
13	01020	3A-BA07-0182	473486	5165160							
14	01020	3A-BA07-0183	473486	5165160							
15	01020	3A-BA07-0184	473486	5165160							
16	01020	3A-BR07-0023	473486	5165160							
17	01034	01-GS99-0072	481004	5205475							
18	01038	01-GS99-0047	455900	5203200							

all_pit_lims111408 | Sheet 2

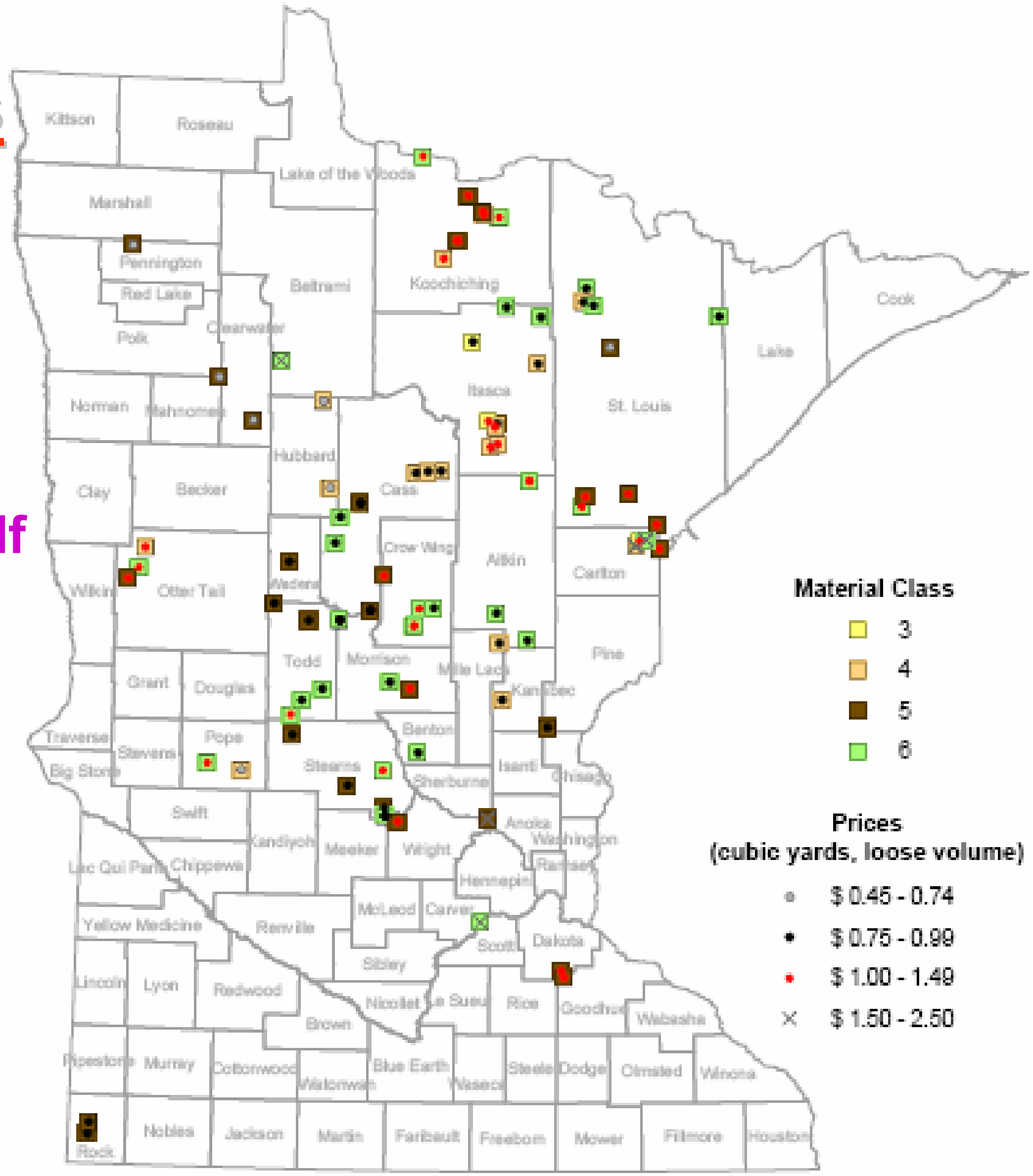
all pit lims111408.xls

(Mainly gradation data for samples from all pits)

Project Tasks

Task 1 – Data Sources (Cont'd):

Aggregate Prices
Mn/DOT Owned and Leased Gravel Pits
(2003 thru 2008)



MnDOT MAP Agg pricesCL.pdf

(Aggregate price reference and hauling cost information for cost estimation)

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Project Tasks

Task 1 – Methodology:

- ✓ *Considering the fact that prospect pits have the most reliable gradation, it was decided to use prospect pits to demonstrate the research methodology*

  MnDOT agg pit_samid_gradations_ps_tname.xls ***for Gradation***

  MNagg pits utmZone15N.xls ***for UTM Coordinates***

- ✓ *87 prospect pits from 34 counties were primarily considered*

- ✓ *Merged gradation data of prospect pits (reliable) & other pits with ASIS database spreadsheets, and included other aggregate index properties*

Project Tasks

Task 1 – Methodology (Cont'd):

- ✓ *Of those 87 prospect pits, 56 had no cost information recorded in ASIS database; default costs were thus estimated using the known costs of the closest pits*

  MnDOT MAP Agg pricesCL.pdf ***for default cost information***

- ✓ *Aggregate location, property and cost data for 87 prospect pits were all collected and built into a GIS based database for further analysis*

- ✓ *The typical functions of this GIS based database include* ***searching, storing, retrieving, and displaying data***

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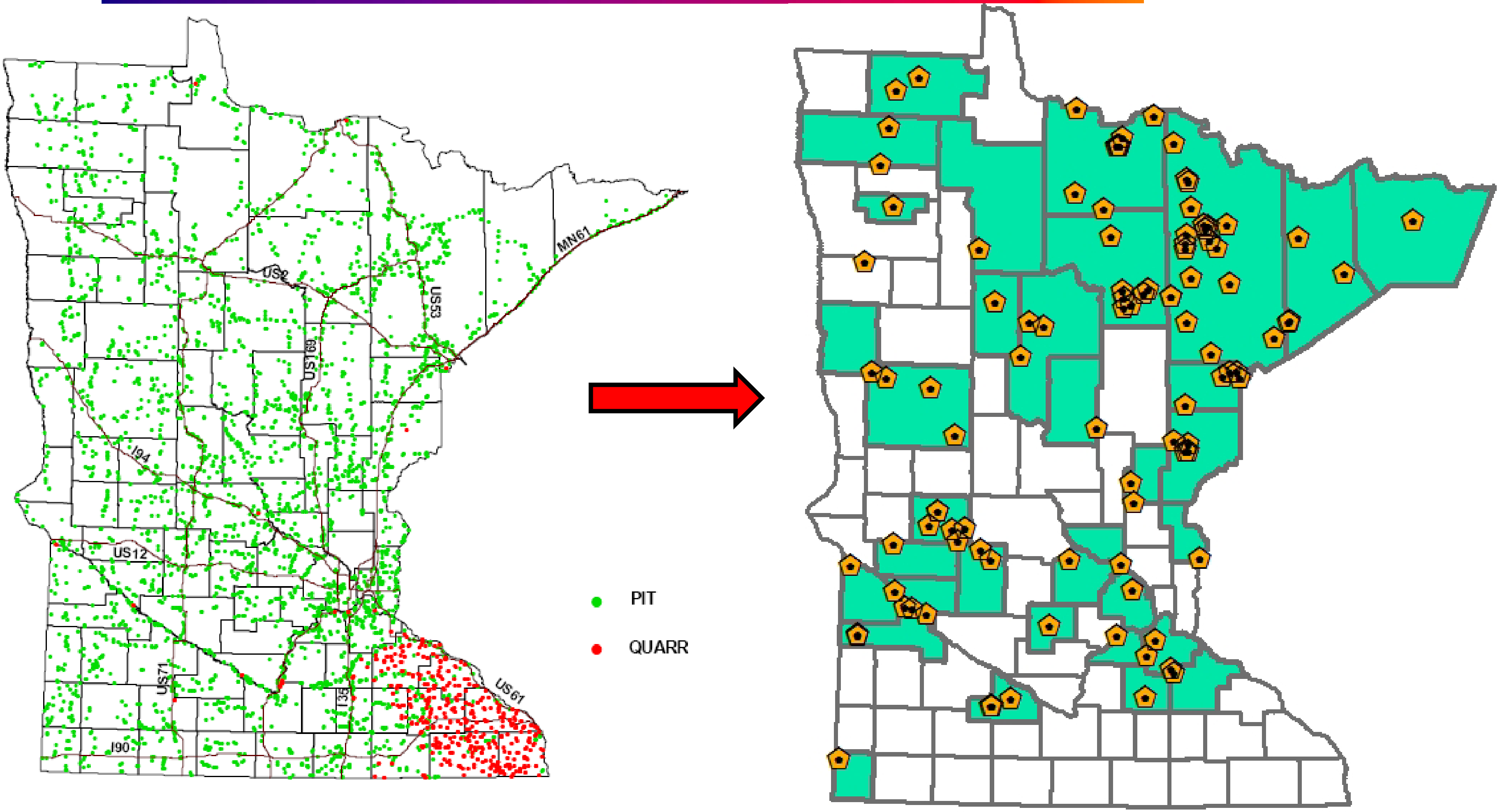
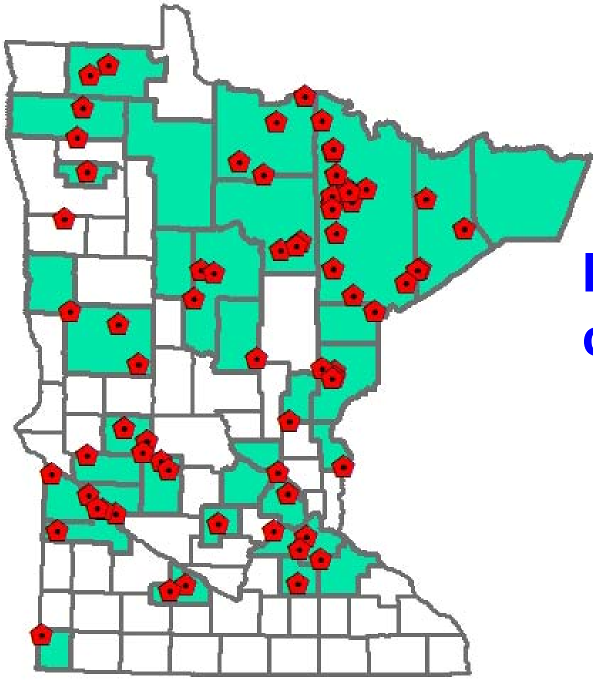
Task 1 – Selected Prospect Pits

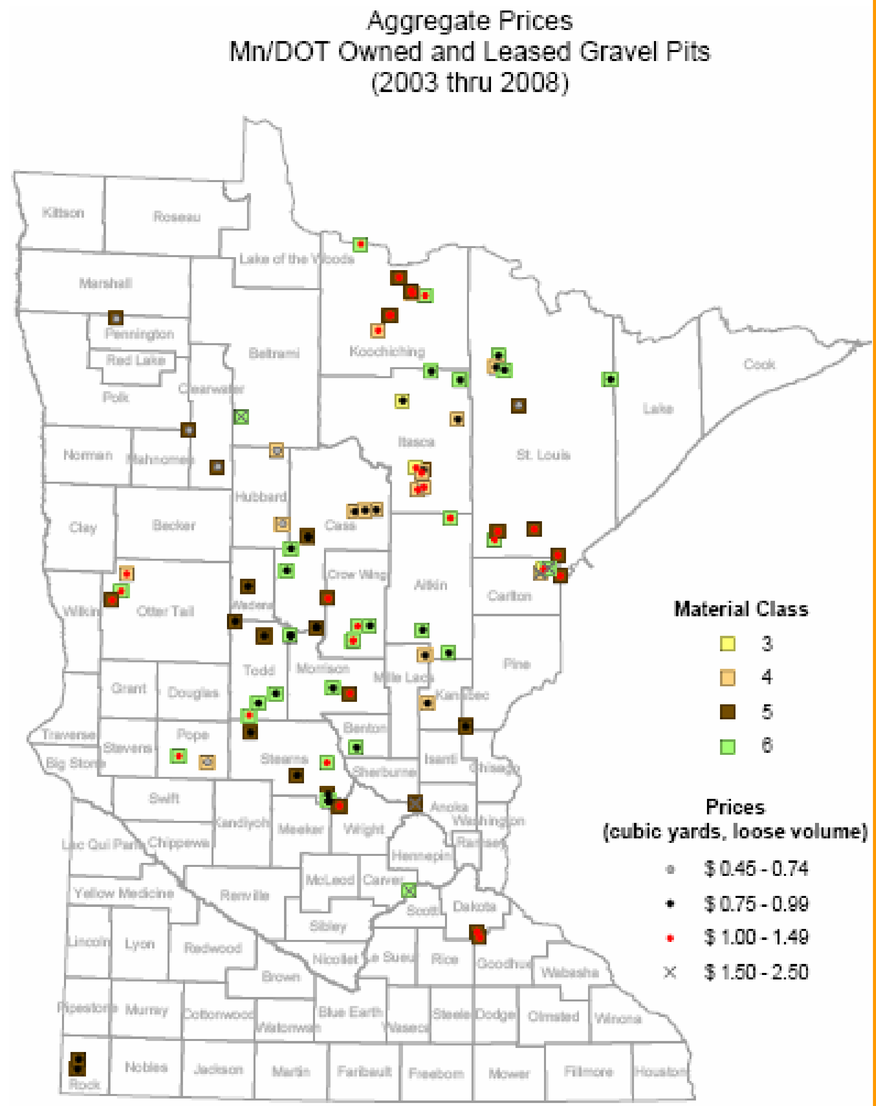


- **87 prospect pits with most reliable gradation selected for demonstrating the methodology**

Task 1 – Collected Cost Information



Identify default cost info



- Without Cost Information

Approach:

Estimate using the known costs of the closest pits

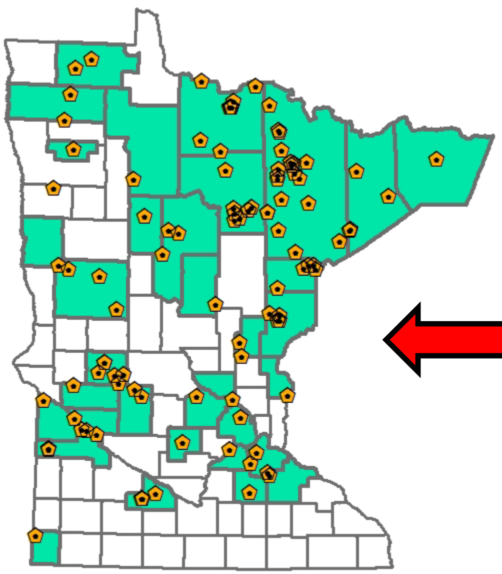
Task 1 – Collected Aggregate Data

- CLASS
- MCLASS1
- QUAN1
- COSTCYM1
- YRPRICECL1
- MCLASS2
- QUAN2
- COSTCYM2
- YRPRICECL2

From / to ASIS

UTM Coordinates

From MNagg pits utmZone15N.xls



From MnDOT agg pit_samid_gradations _ps_tname.xls

Reliable Gradations

From MnDOT MAP Agg pricesCL.pdf

Default Costs

Aggregate Location, Property & Cost Data

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Task 1 – Aggregate Database Illustration

ArcGIS based Database Management System (DBMS) was developed for storing, retrieving and displaying aggregate index properties

Attributes of Selected Prospect Pits

PITNUM	County	UTM_X	UTM_Y	Class	Mclass1	Quan1	Costcym1	Yrpricecl1	Avg % Pass 5/8 in	P
04090	Beltrami	341700	527340	C	6	35000	1.99	2006	<Null>	
08014	Brown	366562	490442	C	5	50300	<Null>	<Null>	<Null>	
08024	Brown	351343	489889	C	4	500000	<Null>	<Null>	<Null>	
08054	Brown	350770	489951	C	4	500000	1	<Null>	<Null>	
09041	Carlton	510000	514540	C	<Null>	97000	<Null>	<Null>	<Null>	
09044	Carlton	554084	516699	C	5	81250	1.25	2007	<Null>	
09048	Carlton	546398	517238	C	6	41800	2.5	2006	<Null>	<
09053	Carlton	552421	517174	C	<Null>	<Null>	<Null>	<Null>	<Null>	
09068	Carlton	540725	516892	C	4	800000	2.38	2005	<Null>	
11009	Cass	382198	521284	C	3	448000	<Null>	<Null>	<Null>	
11048	<Null>	394106	520926	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	
12006	Chippewa	297918	497442	C	6	5000	<Null>	<Null>	<Null>	
12017	Chippewa	272146	499307	C	5	64000	<Null>	<Null>	<Null>	
12050	Chippewa	286190	497821	C	6	142000	<Null>	<Null>	<Null>	
13023	Chisago	521528	501971	C	6	100000	<Null>	<Null>	<Null>	
14045	Clay	253851	517259	C	5	75000	<Null>	<Null>	<Null>	
16069	Cook	696363	529694	C	<Null>	<Null>	1	<Null>	<Null>	
18062	Crow Win	436923	512684	C	5	135000	<Null>	<Null>	<Null>	
19040	Dakota	478337	493995	C	5	160000	<Null>	<Null>	<Null>	
19048	<Null>	498826	492949	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<
25044	Goodhue	500631	492605	C	5	105000	1	2004	<Null>	<
27111	Hennepin	467197	499374	C	6	275000	<Null>	<Null>	<Null>	

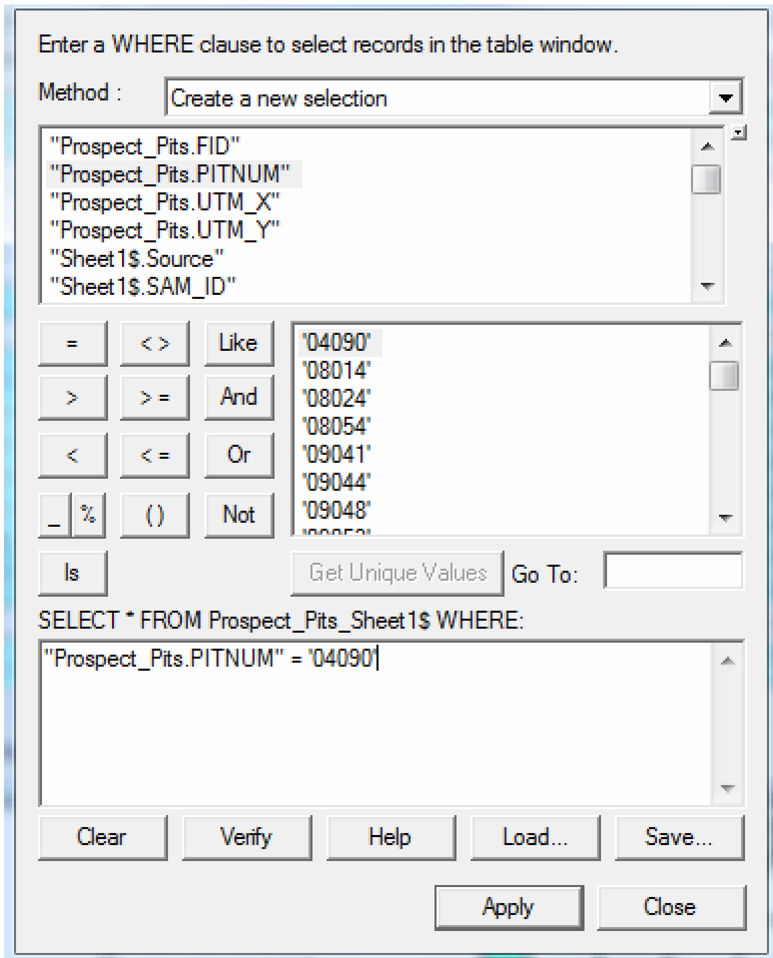
Record: 8 Show: All Selected Records (0 out of 99 Selected) Options

ArcGIS Functions:

- **Search**
- **Store**
- **Retrieve**
- **Display**

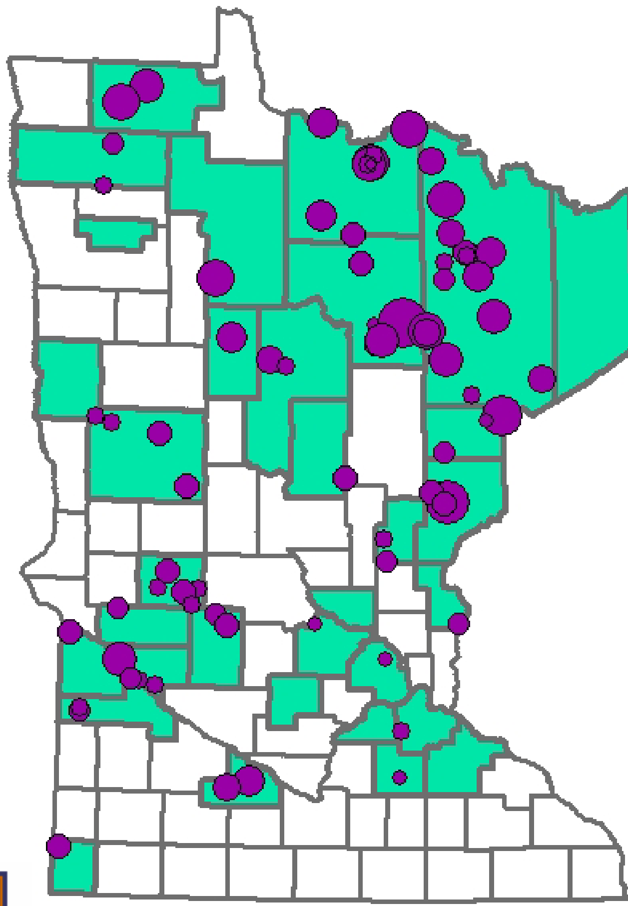
GIS based Aggregate Index Property Database

Task 1 – Aggregate Database Illustration (Cont'd)



- Search for features

Task 1 – Aggregate Database Illustration (Cont'd)



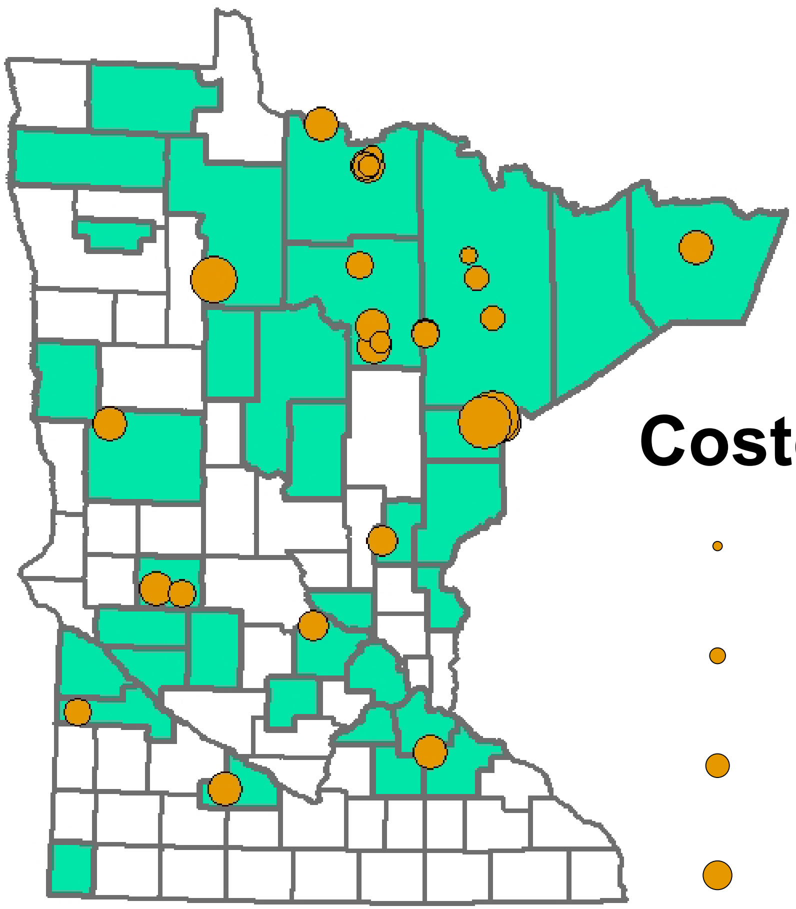
Passnum200

- 1
- 2.5
- 5
- 7.5
- 10

Graphical representation of Percent Passing #200 property distribution

- Example feature display

Task 1 – Aggregate Database Illustration (Cont'd)



Graphical representation of Cost per Cubic Yard property distribution

Costcym1

●	0.1
●	0.25
●	0.5
●	0.75
●	1

- Example feature display

Project Tasks

Task 1 - Summary:

Details of the techniques used to establish aggregate index property database will be given in final report

Deliverables that have been sent include:

- Spreadsheet & Map of 87 selected prospect pits
- ASIS database spreadsheets for 87 Minnesota Counties merged with reliable prospect pit gradations

Project Tasks

Task 2 - Overview:

Collect mechanistic pavement analysis & design inputs as the strength & M_R for unbound aggregate pavement base/subbase applications, together with corresponding aggregate index properties

LRBB Investigation 828 report (Chadbourn, 2007), Davich et al. (2004) study, Kim & Labuz (2007) report, other related research studies; a large database of previous M_R test results by the PI & data from the current Illinois DOT research project on three different types & qualities of aggregate materials

- This task does not include conducting new laboratory or field aggregate tests

Project Tasks

Task 2 – Data Sources:

Files received from Mn/DOT

Date	File Name	Description
Oct.-10-08	MnDOT MRR agg tests-10-10-2008.xls	Names & listings of Available aggregate tests
Nov.-21-08	MnDOT Mr Peaks last Cycles.xls MnDOT Mr k123.xls	Mr load-time history, and Mr model k1 k2 k3 data
Dec.-4-08	MnDOT Mr Agg Lab LIMS Column format.xls	Gradation & Proctor data of Mr test samples
Dec.-5-08	Resilient Modulus Equations.doc Statuscode.xls	Mr equations, and Mr test status codes
Dec.-19-08	Material Types 12-19-08_1.xls	Explanations of LIMS Material Types

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Project Tasks

Task 2 – Data Sources (Cont'd):

Design Guide Resilient Modulus Equation

$$Mr = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

Where P_a = atmospheric pressure (same units θ and τ_{oct})

Mr units are 1000 x the units for θ and τ_{oct}
(MPa or ksi) (kPa or psi)

P_a = 14.69595 psi

Other Database Resilient Modulus Equation

$$Mr = k_1 P_a \left(\frac{\sigma_3}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3}$$

$$\theta = \sigma_1 + 2\sigma_3$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$$

$$\sigma_d = \sigma_1 - \sigma_3$$

Representative Stress Levels for Pavement Layers (psi)

Design Type	Agg. Base		Subbase		Subgrade Soil	
	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
Mn/DOT	9.0	1.0	5.0	1.0	4.5	1.0
Low Volume	9.0	1.0			5.5	1.0

Based on MnPAVE default moduli and 18 kip dual-tire axle load on the following structures:

Mn/DOT

Material	Thickness (in.)
HMA: PG 58-34	6.0
AggBase: Cl. 6	6.0
Subbase: SelGr	18.0
EngSoil: CL	12.0

Low Volume

Material	Thickness (in.)
HMA: PG 58-34	5.0
AggBase: Cl. 5	8.0
EngSoil: CL	12.0

Resilient Modulus Equations.doc

	A	B	C	D	E
1	LIMS Material Types as of 12-19-08				
2					
3		AC	Asphalt		
4		AE	Asphalt Emulsion		
5		AR	Alkali-Silica Reaction		
6		AS	Asphalt		
7		BA	Bituminous Aggregate		
8		BC	Bituminous Core		
9		BK	Brick		
10		BM	Bituminous Mixture		
11		BP	Bearing Pad		

Material Types 12-19-08_1

Material Types 12-19-08_1.xls

(Material type explanations)

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Project Tasks

Task 2 – Data Sources (Cont'd):

STATUS	DESCRIPTION
0	OK
1	LVDT1 SNR < 3
2	LVDT2 SNR < 3
3	LVDT3 SNR < 3
4	2 OR MORE SNR < 3
5	TRXLOAD SNR < 5
6	ANGLE OF ROTATION >= 0.04°
7	MR SDEV >= 1000 PSI
8	EXT RATIO >= 1.3
9	QUARANTINE
11	DIV BY 0 LVDT1 SNR
12	DIV BY 0 LVDT2 SNR
13	DIV BY 0 LVDT3 SNR
15	DIV BY 0 TRXLOAD SNR
18	DIV BY 0 EXT RATIO

Squirrel SQL Export

Statuscode.xls

(Mr test status codes)

Project Tasks

Task 2 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	H	
1	FILE_NAME	SAM_ID	MNDOT_CLASS	OPT_MOIST	MAX_DENS_PCF	D10	D60	PP_75MM	PI
2	RRB24RM	CO-BA01-0189				20.957	36.31	100	
3	61CHHR1	CO-GS00-0277		8.2	133.4	0.075	7.058		
4	62CHHR1	CO-GS00-0280		9.7	138.7	0.075	6.201		
5	1001RM1A	CO-GS01-0015		11.5	124.2	0.189	1.277		
6	1001RM2A	CO-GS01-0015		11.5	124.2	0.189	1.277		
7	1001S4A	CO-GS01-0015		11.5	124.2	0.189	1.277		
8	1001S4B	CO-GS01-0015		11.5	124.2	0.189	1.277		
9	1001S8B	CO-GS01-0015		11.5	124.2	0.189	1.277		
10	0801RM2A	CO-GS01-0016		13.8	111.2	0.327	1.317		
11	0801S41A	CO-GS01-0016		11.5	124.2	0.327	1.317		
12	0901RM1A	CO-GS01-0017		12.8	116	0.178	0.841		
13	0901RM2A	CO-GS01-0017		12.8	116	0.178	0.841		

MnDOT Mr Agg Lab LIMS column

MnDOT Mr Agg Lab LIMS Column format.xls

(Gradation and Proctor data of Mr test samples)

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Project Tasks

Task 2 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	H	
1	FILE_NAME	SEQUENCE	CYCLE	CPRESSURE_PSI	PEAK_TRXLOAD_LBS	PEAK_EXVDFRM1_MIC	PEAK_EXVDFRM2_MIC	PEAK_INVDFRM1_MIC	PEA
2	0801RM2A	1	1	3.0684	84.96	-74137	-78543	-71699.3	
62	0901RM1A	1	1	3.0759	84.96	-82186	-87714	-88815.3	
122	0901RM2A	1	1	3.0768	85.94	-68163	-66824	-98391.3	
182	1001RM1A	1	1	3.7905	81.06	-64852	-64135	-99222	
242	1001RM2A	1	1	3.5752	85.94	-74629	-76746	-100302.7	
302	1101RM1A	1	1	3.2821	83.99	-88992	-84681	-105606.7	
362	1101RM2A	1	1	2.8116	82.03	-83872	-90392	-92710	
422	1415C5R1	1	1	3.0151	79.1	-45618	-40231	-94475.3	
483	1415R3	1	1	3.0413	83.99	-88878	-83918	-71328.3	
558	1415R4	1	1	2.9725	84.96	-79276	-78810	-80520.7	
633	16C6R1	1	1	3.1391	84.96	-91857	-86375	-84151	
707	3600RM1A	1	1	3.3439	84.96	-88317	-85223	-92650.3	
767	3600RM2A	1	1	3.1122	83.99	-94947	-89854	-82143	
827	3700RM1A	1	1	3.0772	83.99	-74343	-72966	-72252.7	
887	3700RM2A	1	1	3.1006	84.96	-74870	-77250	-72281.7	
947	371C62R	1	1	3.0292	84.96	-88656	-95927	-93021.7	
1015	371C63R	1	1	3.4614	82.03	-77002	-62792	-93805	
[illegible]	[illegible]	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

MnDOT Mr peaks last cycles

MnDOT Mr Peaks last Cycles.xls

(Load-time history data of last 4 or 5 cycles)

Project Tasks

Task 2 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	H	
1	FILE_NAME	K1	K2	K3	K123_R_SQ_PCT	MIN_BULKSTRESS_PSI	MAX_BULKSTRESS_PS	MIN_OCTASTRESS_PSI	MAX_OCT
2	C5ECR3	1.34605974	0.32531106	0.63472166	97.161	11.7388	95.8881	1.2914	
3	C5ECR4	2.10075562	0.60061175	-0.35408791	98.305	11.8097	95.9142	1.3217	
4	C5EJR1	3.12969137	0.60928742	-0.50559038	95.335	12.1064	95.8613	1.3264	
5	C5EJR2	2.12052022	0.16375626	0.6054002	94.089	14.5472	95.938	2.5598	
6	C5EJR3	2.60518838	0.56305914	-0.34006853	98.225	16.8625	95.9073	2.1642	
7	C5EKR1	2.93530183	0.74904293	-0.68829321	98.792	14.4179	95.9068	2.1702	
8	C5EKR2	2.27390398	0.7167304	-0.40233269	99.41	11.5598	95.9404	1.334	
9	C5ELR1	1.83274064	0.79247923	-0.24869917	99.336	11.7915	95.8214	1.2971	
10	C5FBR2	3.05876658	0.59380279	-0.79871531	97.341	14.4796	95.9617	2.1472	
11	C5FCR1	2.25439933	0.76736541	-0.62218183	99.455	11.8846	95.8988	1.3213	
12	C5FCR2	2.09955185	0.69877673	-0.50135784	99.111	11.9741	95.8992	1.3211	
13	C5FCR3	3.33132159	0.44472686	-0.35358552	91.28	12.0639	96.1288	1.3512	
14	C5FIR2	1.65739106	0.56868053	-0.25043967	98.886	11.8181	95.904	1.3065	
15	C5FIR3	1.08482969	0.21120367	0.77914422	86.417	11.739	95.9709	1.2783	
16	C5FIR4	1.09061228	0.01862906	1.29186952	95.877	11.6997	95.9712	1.2731	
17	C5FJR1	1.75759002	0.49319098	-0.20561244	98.261	11.7715	96.0635	1.3087	
18	C5FJR2	1.33164893	0.28055881	0.70906916	96.539	11.4929	95.9122	1.2923	

MnDOT Mr k123

MnDOT Mr k123.xls
(k values of Mr equations)

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MINNESOTA DEPARTMENT OF TRANSPORTATION

LRRB LOCAL ROAD RESEARCH BOARD

Project Tasks

Task 2 – Data Sources (Cont'd):

XLS_FILE_NAME	MOISTURE_PCT	DRY_DENSITY_PCF
0801RM2A	7.81	115.61
0901RM1A	9.77	117.42
0901RM2A	12.03	108.7
1001RM1A	8.54	126.89
1001RM2A	10.78	124.83
1101RM1A	9.05	116.68
1101RM2A	11.31	116.95
1415C5R1	9.75	126.93
1415R3	9.42	125.81
1415R4	9.28	125.2
16C6R1	7.14	127.7
3600RM1A	9.05	123.96
3600RM2A	9.86	123.91
3700RM1A	10.36	110.37
3700RM2A	8.3	112.26
371C62R	6.34	129.98

MnDOT_MRPeaksLastCycles01Aug09

Actual Moisture Content & Dry Density for Mr Samples

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Project Tasks

Task 2 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	H	I	J	K	L	M
1–2	Load Step	Stress				External Resilient Deformation		External Resilient Strain		Internal Resilient Deformation		Internal Resilient Strain	
3–4	Sequence	σ_d (kPa)	σ_b (kPa)	σ_c (kPa)	$\sigma_{d,dynamic}$ (kPa)	LVDT1 (mm)	LVDT2 (mm)	LVDT1	LVDT2	LVDT1 (mm)	LVDT2 (mm)	LVDT1	LVDT2
5	Test Step 1												
6	1	8.857102	95.25041	28.79777	2.262567	0.000677	0.002155	3.39E-06	1.08E-05	0.000514	0.000228	5.06E-06	2.24E-06
7	2	43.15051	208.7929	55.21412	29.10281	0.044734	0.039503	0.000224	0.000198	0.007527	0.014411	7.41E-05	0.000142
8	3	41.99704	207.8514	55.28479	28.1268	0.041684	0.034835	0.000208	0.000174	0.002395	0.007854	2.36E-05	7.73E-05
9	4	41.77522	206.5709	54.93189	27.86062	0.041684	0.035913	0.000208	0.00018	0.002224	0.007624	2.19E-05	7.5E-05
10	5	41.02104	206.2723	55.08377	27.32825	0.042362	0.036271	0.000212	0.000181	0.002395	0.007396	2.36E-05	7.28E-05
11	6	41.33159	207.2562	55.3082	27.59444	0.042362	0.036272	0.000212	0.000181	0.002052	0.007472	2.02E-05	7.35E-05
12	7	41.99704	208.198	55.40031	28.34862	0.043039	0.036271	0.000215	0.000181	0.002395	0.00732	2.36E-05	7.2E-05
13	8	42.57378	209.7691	55.73176	28.92536	0.042362	0.036271	0.000212	0.000181	0.002224	0.00732	2.19E-05	7.2E-05
14	9	41.46468	206.0904	54.87525	27.41698	0.042023	0.035913	0.00021	0.00018	0.002053	0.007319	2.02E-05	7.2E-05
15	10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

MnRd-98%-S50-R1 | MnRd-103%-S0-R1 | MnRd-103%-S22-R1 | MnRd-1

The template for reporting Mr load-time history data

Project Tasks

Task 2 – Data Sources (Cont'd):

	A	B	C	D	E	F	G	H	I	J	
1	Mr test Name	Spnum	Route	MnDOT lab ID	AASHTO	MnDOT	Material	Research	OPT Mositure	Max Dry Density	Actu
2					Classification	Classificatior	Type	Objective	Content	(PCF)	mois
3											
4	CR3_S_5.1_1_Feb7	5.1	CR 3 (Wright)(D	na	A-1-a	FDR	In-situ RAP with gravel	Effects of % RAP on	7.8	127	
5	CR3_S_5.1_2_Feb11	4.6	CR 3 (Wright)				In-situ RAP with gravel	Effects of % RAP on	7.8	127	
6	CR3_S_7.8_1_Dec31	7.4	CR 3 (Wright)				In-situ RAP with gravel	Effects of % RAP on	7.8	127	
7	CR3_S_7.8_2_Mar26	7.1	CR 3 (Wright)				In-situ RAP with gravel	Effects of % RAP on	7.8	127	
8	CR3_T_5.7_1_Feb22	6	CR 3 (Wright)	na	A-1-a	Class 5	gravel	Effects of % RAP on	8.8	127	
9	CR3_T_5.7_2_Feb28	5.8	CR 3 (Wright)				gravel	Effects of % RAP on	8.8	127	
10	CR3_T_8.8_1_Feb23	9.1	CR 3 (Wright)				gravel	Effects of % RAP on	8.8	127	
11	CR3_T_8.8_2_Mar24	8.3	CR 3 (Wright)				gravel	Effects of % RAP on	8.8	127	
12	CR3_U_5.7_1_Feb14	6.1	CR 3 (Wright)	na	A-1-a	Other	75% aggregate and 25	Effects of % RAP on	8.7	127	
13	CR3_U_5.7_2_Feb19	6	CR 3 (Wright)				75% aggregate and 25	Effects of % RAP on	8.7	127	
14	CR3_U_8.7_1_Feb15	8.3	CR 3 (Wright)				75% aggregate and 25	Effects of % RAP on	8.7	127	
15	CR3_U_8.7_2_Feb21	8.8	CR 3 (Wright)				75% aggregate and 25	Effects of % RAP on	8.7	127	
16	CR3_V_5.2_1_Mar15	4.9	CR 3 (Wright)	na	A-1-a	FDR	50% aggregate and 25	Effects of % RAP on	8.0	127	
17	CR3_V_5.2_2_Mar19	5.2	CR 3 (Wright)				50% aggregate and 25	Effects of % RAP on	8.0	127	
18	CR3_V_8_1_Mar16	7.5	CR 3 (Wright)				50% aggregate and 25	Effects of % RAP on	8.0	127	
19	CR3_V_8_2_Mar23	7.8	CR 3 (Wright)				50% aggregate and 25	Effects of % RAP on	8.0	127	

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The template for reporting index properties of Mr samples

Project Tasks

Task 2 – Mn/DOT Database Analysis:

- ✓ *Grouped index property data by Aggregate Maximum Sieve Size, Gradation Type (dense or gap), Percent Passing No. 200 sieve, Density, etc.*

- ✓ *Performed statistical analyses on M_R data with an aim to get typical M_R ranges for different index property groups*

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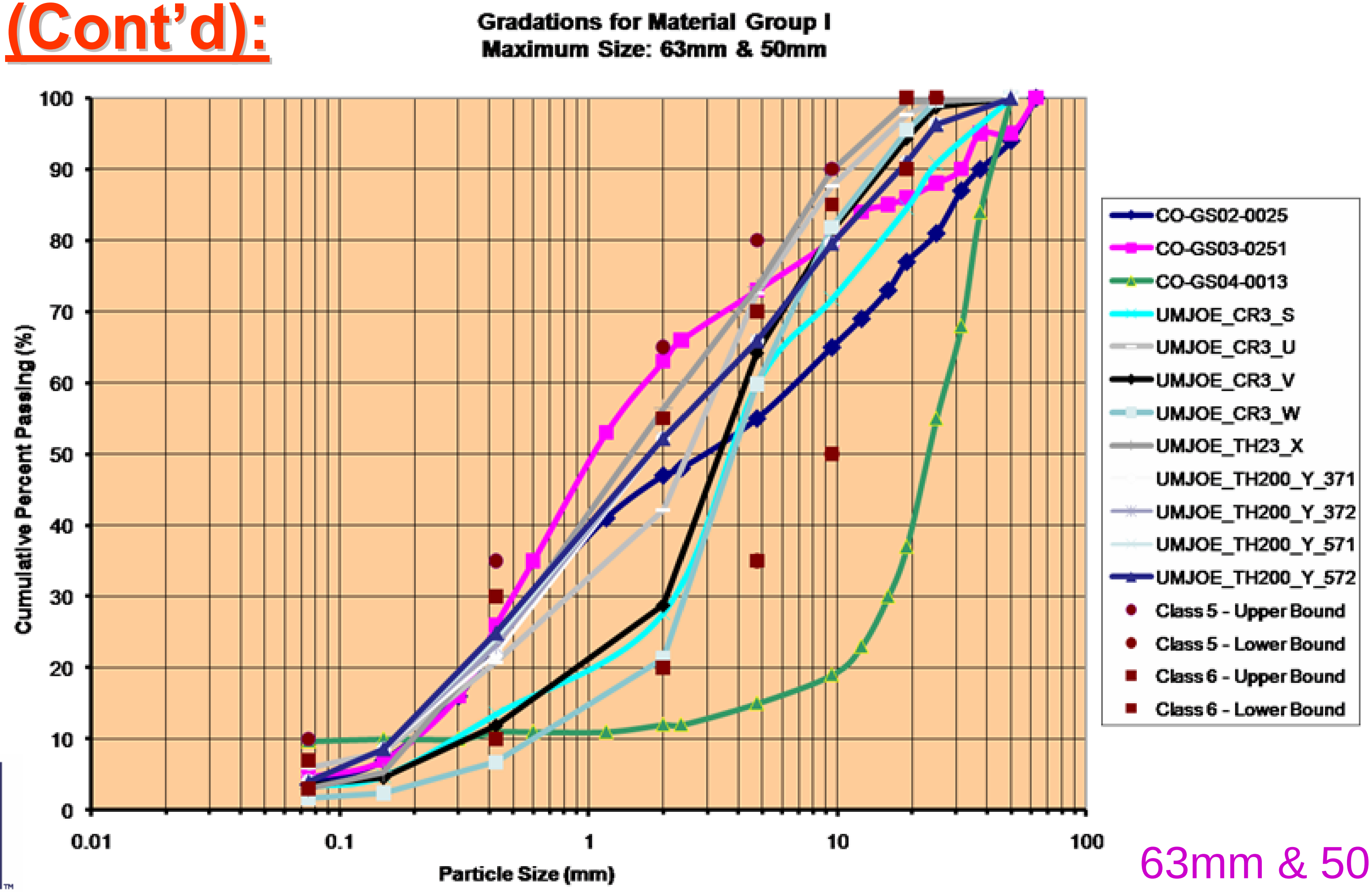
Project Tasks

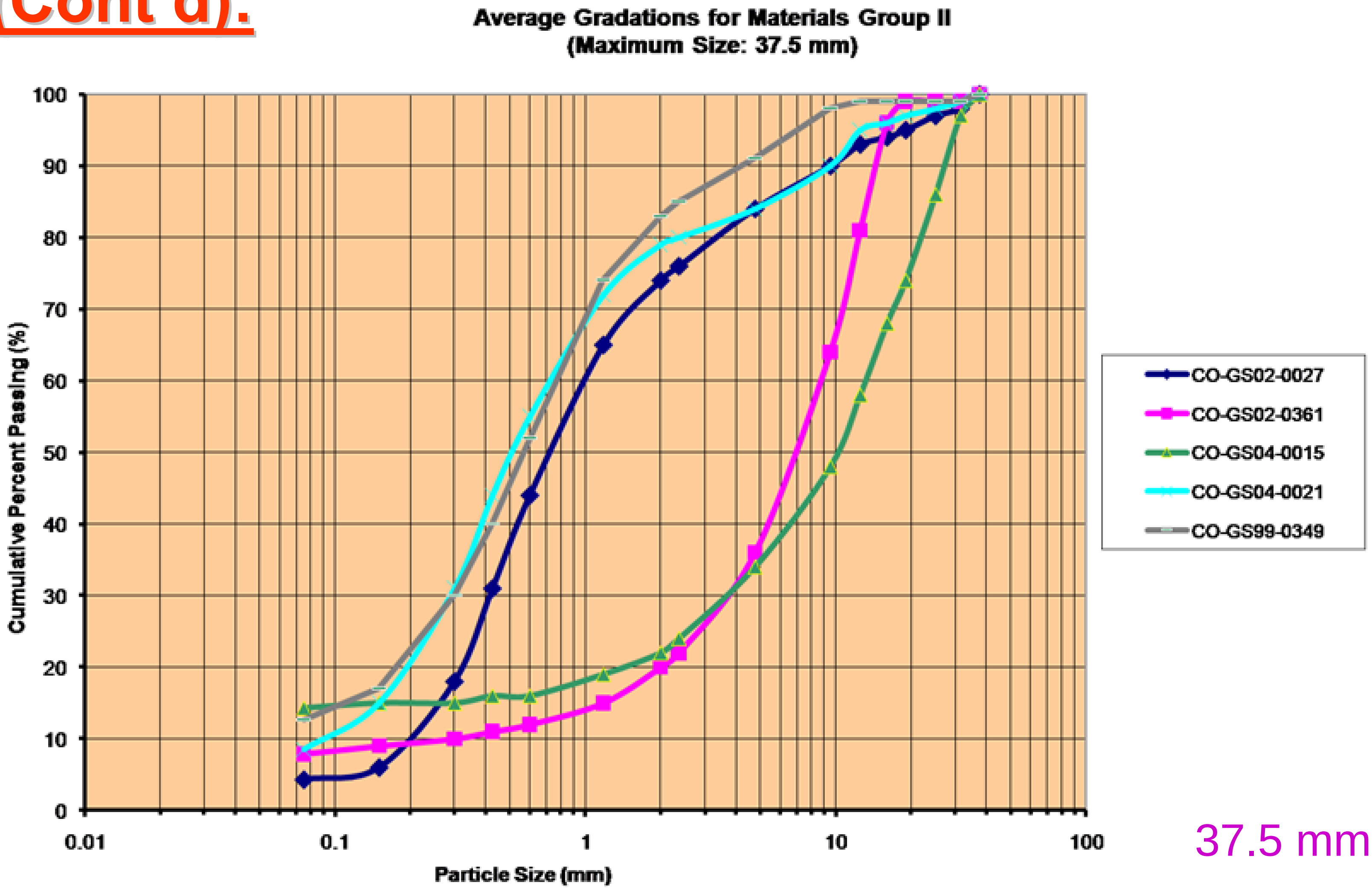
Task 2 – Mn/DOT Database Analysis (Cont'd):



63mm & 50mm

Project Tasks

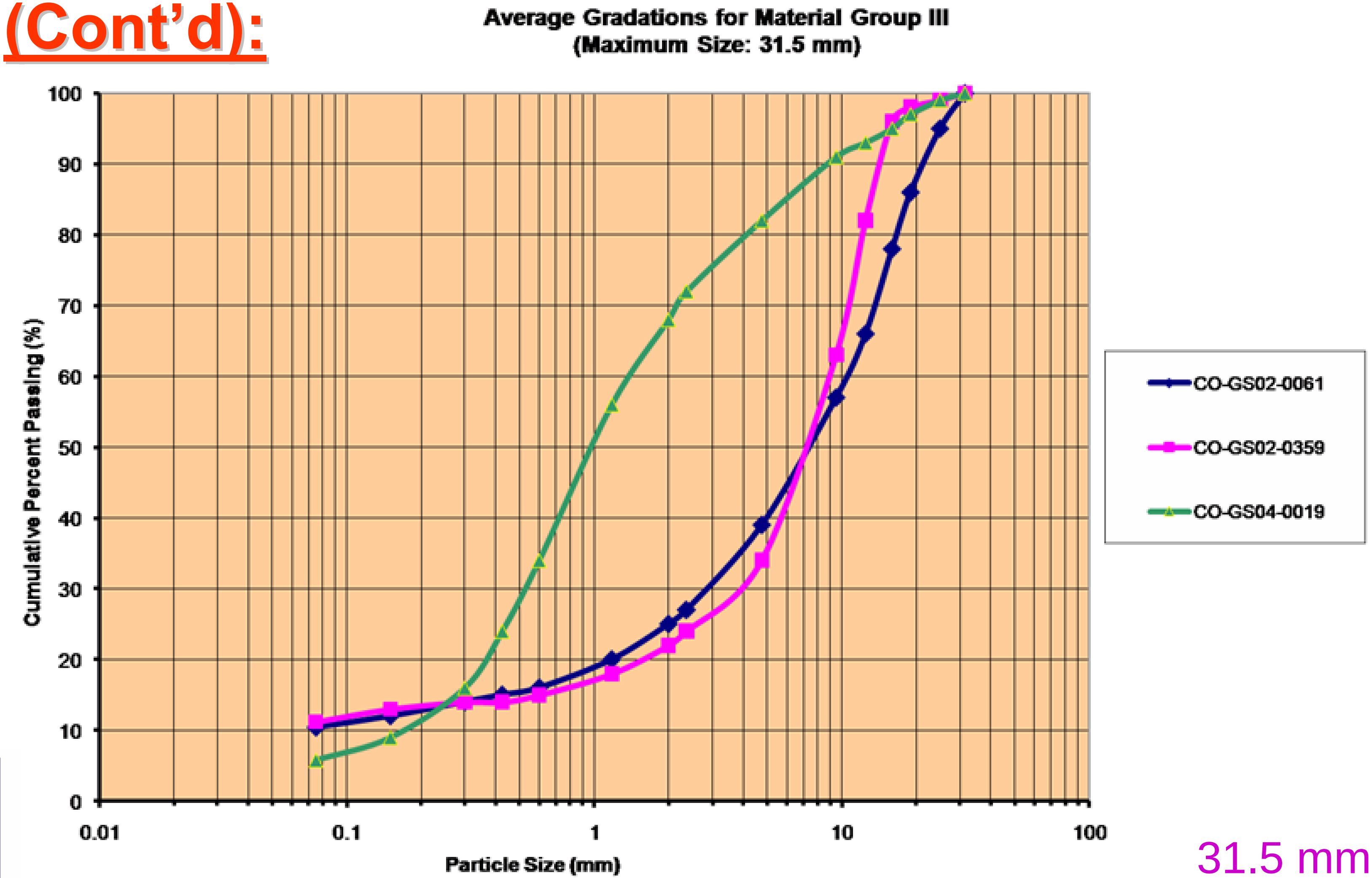
Task 2 – Mn/DOT Database Analysis (Cont'd):



37.5 mm

Project Tasks

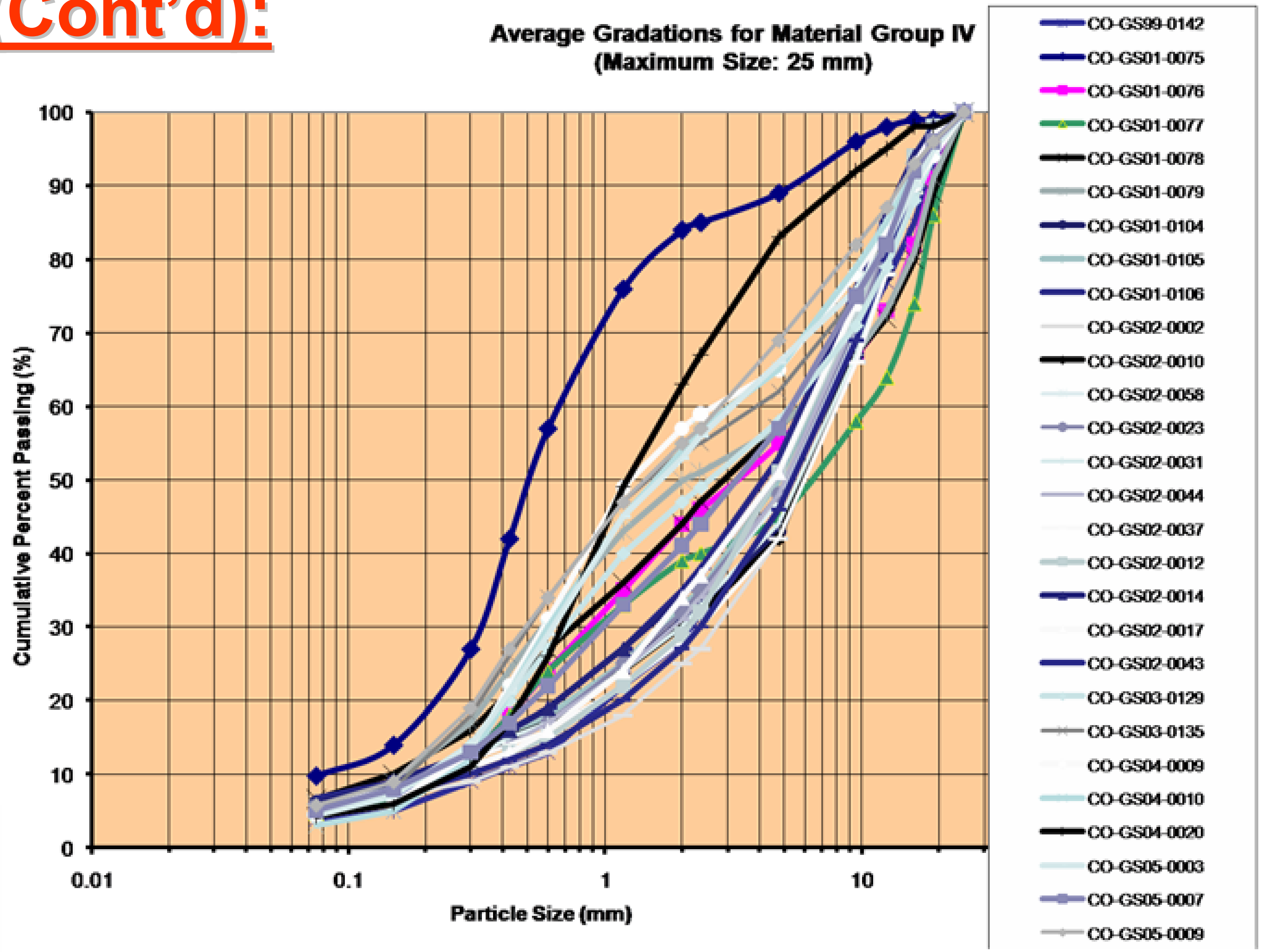
Task 2 – Mn/DOT Database Analysis (Cont'd):



31.5 mm

Project Tasks

Task 2 – Mn/DOT Database Analysis (Cont'd):



25 mm

Project Tasks

Task 2 – UI Database Brief Introduction:

Databases collected from U of I previous research studies

- Recently-completed ICT R27-1 Project:

Characterization of Illinois Aggregates for Subgrade Replacement and Subbase

- NCHRP 4-23 Project:

Performance Related Tests of Aggregates for Use in Unbound Pavement Layers

- FAA P209 & P154 Granular Base Materials Study

Investigation of the Behavior of the FAA NAPTF P209/P154 Base/Subbase Materials

- IDOT CA-6 & CA-11 Materials & Effect of Fines Content Studies

Characterization of Anisotropic Granular Layer Behavior in Flexible Pavements

Project Tasks

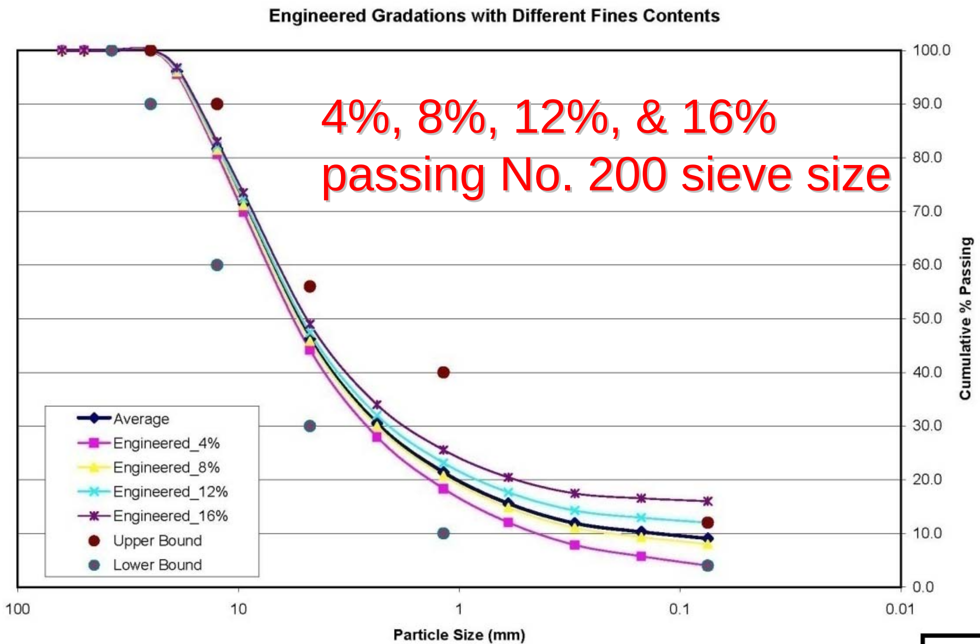
Task 2 – UI Database Brief Introduction:

ICT R27-1 Project

Studied a Laboratory Aggregate Test Matrix with typical midrange IDOT ***CA-6*** gradations for constructing aggregate layers as subgrade replacement & subbase

- Aggregate type: (1) dolomite, (2) limestone, (3) gravel
- Gradation: Midrange CA-6
- Fines content: 4%, 8%, 12%, & 16% passing No. 200 sieve size
- PI or plasticity of fines: 0% (non-plastic mineral filler) & 10% – **should be conducted on material passing the No. 40 sieve to be consistent with IDOT procedure**
- Moisture-density (compaction) condition: At optimum moisture content (OMC), 2% dry of OMC, and 2% wet of OMC

ICT R27-1 Project: Engineered Gradations



(1) dolomite

(2) limestone

(3) gravel

Particle Size (mm)		Average Cumulative Percent Passing				
(in / #)	(mm)	Original	4% Fines	8% Fines	12% Fines	16% Fines
2.5"	63	100.0	100.0	100.0	100.0	100.0
2"	50	100.0	100.0	100.0	100.0	100.0
1.5"	37.5	100.0	100.0	100.0	100.0	100.0
1"	25	100.0	100.0	100.0	100.0	100.0
3/4"	19	96.1	95.6	96.0	96.4	96.8
1/2"	12.5	81.6	80.6	81.4	82.2	83.0
3/8"	9.5	71.4	69.9	71.1	72.3	73.5
#4	4.75	46.2	44.2	45.8	47.4	49.0
#8	2.36	30.5	28.0	30.0	32.0	34.0
#16	1.18	21.4	18.3	20.7	23.1	25.5
#30	0.6	15.6	12.0	14.8	17.6	20.4
#50	0.3	11.9	7.8	11.0	14.2	17.4
#100	0.15	10.3	5.7	9.3	12.9	16.5
#200	0.075	9.1	4.0	8.0	12.0	16.0

Project Tasks

Task 2 - Summary:

Collecting M_R and strength data for establishing a comprehensive database will be continued in the subsequent tasks

Task 2 Deliverables include:

- Aggregate strength and modulus database spreadsheets
- Corresponding index property database spreadsheets

Project Tasks

Task 3 - Overview:

Establish linkages between collected field and laboratory aggregate strength and M_R data and aggregate physical properties for identifying mechanistic design moduli ranges

- gradation
- shape, texture and angularity
- fines content
- PI of fines, and
- moisture state in relation to optimum moisture (OMC) OR density achieved in relation to maximum Proctor density (MDD)

Project Tasks

Task 3 – Data Sources:

File received from Mn/DOT

Date	File Name	Description
Feb.-06-09	MnDOT samples image testing Illinois.xls	Explanation of Mn/DOT samples used for image analysis

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Project Tasks

Task 3 – Data Sources Received:

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	box 1						box 2						box 3
2	Label on Bag	TH 52 Taconite Tailings	TH 14/15 CL 5	Mnroad CL 5		CO RD 14 CL 5	Label on Bag	TH 23 CL 6m	TH 371 CL 6	TH 47 SGB		Olmsted CL 5	Label or
3													
4	Soils Lab #	CO-GS05-0004	CO-GS04-0034 CO-GS04-0035	CO-GS98-0142 CO-GS98-0143		CO-GS04-0130 CO-GS03-0142 CO-GS04-0131	Soils Lab #	CO-GS05-0003	CO-GS04-0010 CO-GS03-0129 CO-GS03-0135	CO-GS05-0005		CO-GS02-0380 CO-GS02-0363 CO-GS02-0347 CO-GS020350	Soils La
5													
6	Mr Filename	TTT053FORD043	C5T014CMRC173	M5EOR1	M5GOR3	C5C014HNRC010	Mr Filename	C6T023EORC018	C6T371FORC006	GBT047JKRD117		C5HCR4	Mr Filen
7		TTT053HNRD035	C5T014DMRC174	M5EOR2	M5GOS41	C5C014INRC003		C6T023EORC027	C6T371FORC107	GBT047JKRD118		C5FBR1	
8		TTT053HNRD044	C5T014DMRC207	M5EOR3	M5GOS42	C5C014INRC004		C6T023EPRC026	C6T371FORC108	GBT047JLRD122		C5GBR4	
9		TTT053HORD033	C5T014EMRC187	M5EOR3	M5GOS83			C6T023EPRC028	C6T371GORC112	GBT047JLRD129		C5GCR1	
10		TTT053HORD036	C5T014ENRC175	M5EOS41	M5GOS84			C6T023FMRC019	C6T371GORC113	GBT047JMRD130		C5GBR5	
11		TTT053HORD041	C5T014ENRC204	M5EOS42	M5GPR1			C6T023FORC024	C6T371HORC110	GBT047KKRD115		C5HBR1	
12		TTT053HPRD039	C5T014FNRC176	M5EOS81	M5GPR2			C6T023FORC025	C6T371HORC114	GBT047KKRD116		C5HCR3	
13		TTT053IMRD031	C5T014FNRC181	M5EOS82	M5GPR3			C6T023FPRC009		GBT047KLRD119		C5HBR2	
14		TTT053INRD011	C5T014FNRC186	M5EPR1	M5GPR4			C6T023FPRC023		GBT047KLRD121		C5HBR3	
15		TTT053INRD027	C5T014GNRC177	M5EPR2	M5GPR5					GBT047KLRD123		C5GAR1	

MnDOT samples image testing | Sheet2 | Sheet3

MnDOT samples image testing Illinois.xls

(Information about Mn/DOT samples for Image Analysis)

Project Tasks

Task 3 – Data Sources Used:

	A	B	C	D	E	F	G	H	I
1	FILE_NAME	SAM_ID	MNDOT_CLASS	OPT_MOIST	MAX_DENS_PCF	D10	D60	PP_75MM	PI
2	RRB24RM	CO-BA01-0189				20.957	36.31	100	
3	61CHHR1	CO-GS00-0277		8.2	133.4	0.075	7.058		
4	62CHHR1	CO-GS00-0280		9.7	138.7	0.075	6.201		
5	1001RM1A	CO-GS01-0015		11.5	124.2	0.189	1.277		
6	1001RM2A	CO-GS01-0015		11.5	124.2	0.189	1.277		
7	1001S4A	CO-GS01-0015		11.5	124.2	0.189	1.277		
8	1001S4B	CO-GS01-0015		11.5	124.2	0.189	1.277		
9	1001S8B	CO-GS01-0015		11.5	124.2	0.189	1.277		
10	0801RM2A	CO-GS01-0016		13.8	111.2	0.327	1.317		
11	0801S41A	CO-GS01-0016		11.5	124.2	0.327	1.317		
12	0901RM1A	CO-GS01-0017		12.8	116	0.178	0.841		
13	0901RM2A	CO-GS01-0017		12.8	116	0.178	0.841		

MnDOT Mr Agg Lab LIMS column

Gradation and Proctor data of Mr test samples
(Independent Variables)

Project Tasks

Task 3 – Data Sources Used (Cont'd):

	A	B	C	D
1	XLS_FILE_NAME	MOISTURE_PCT	DRY_DENSITY_PCF	
2	0801RM2A	7.81	115.61	
3	0901RM1A	9.77	117.42	
4	0901RM2A	12.03	108.7	
5	1001RM1A	8.54	126.89	
6	1001RM2A	10.78	124.83	
7	1101RM1A	9.05	116.68	
8	1101RM2A	11.31	116.95	
9	1415C5R1	9.75	126.93	
10	1415R3	9.42	125.81	
11	1415R4	9.28	125.2	
12	16C6R1	7.14	127.7	
13	3600RM1A	9.05	123.96	
14	3600RM2A	9.86	123.91	
15	3700RM1A	10.36	110.37	
16	3700RM2A	8.3	112.26	
17	371C62R	6.34	129.98	

MnDOT_MRPeaksLastCycles01Aug09

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Actual Moisture Content & Dry Density for Mr Samples
(Independent Variables)

Project Tasks

Task 3 – Data Sources Used (Cont'd):

	A	B	C	D	E	F	G	H	
1	FILE_NAME	K1	K2	K3	K123_R_SQ_PCT	MIN_BULKSTRESS_PSI	MAX_BULKSTRESS_PS	MIN_OCTASTRESS_PSI	MAX_OCT
2	C5ECR3	1.34605974	0.32531106	0.63472166	97.161	11.7388	95.8881	1.2914	
3	C5ECR4	2.10075562	0.60061175	-0.35408791	98.305	11.8097	95.9142	1.3217	
4	C5EJR1	3.12969137	0.60928742	-0.50559038	95.335	12.1064	95.8613	1.3264	
5	C5EJR2	2.12052022	0.16375626	0.6054002	94.089	14.5472	95.938	2.5598	
6	C5EJR3	2.60518838	0.56305914	-0.34006853	98.225	16.8625	95.9073	2.1642	
7	C5EKR1	2.93530183	0.74904293	-0.68829321	98.792	14.4179	95.9068	2.1702	
8	C5EKR2	2.27390398	0.7167304	-0.40233269	99.41	11.5598	95.9404	1.334	
9	C5ELR1	1.83274064	0.79247923	-0.24869917	99.336	11.7915	95.8214	1.2971	
10	C5FBR2	3.05876658	0.59380279	-0.79871531	97.341	14.4796	95.9617	2.1472	
11	C5FCR1	2.25439933	0.76736541	-0.62218183	99.455	11.8846	95.8988	1.3213	
12	C5FCR2	2.09955185	0.69877673	-0.50135784	99.111	11.9741	95.8992	1.3211	
13	C5FCR3	3.33132159	0.44472686	-0.35358552	91.28	12.0639	96.1288	1.3512	
14	C5FIR2	1.65739106	0.56868053	-0.25043967	98.886	11.8181	95.904	1.3065	
15	C5FIR3	1.08482969	0.21120367	0.77914422	86.417	11.739	95.9709	1.2783	
16	C5FIR4	1.09061228	0.01862906	1.29186952	95.877	11.6997	95.9712	1.2731	
17	C5FJR1	1.75759002	0.49319098	-0.20561244	98.261	11.7715	96.0635	1.3087	
18	C5FJR2	1.33164893	0.28055881	0.70906916	96.539	11.4929	95.9122	1.2923	
19	C5FKR1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

MnDOT Mr k123

k parameters of M_R modulus models

(Dependent Variables)

Project Tasks

Task 3 – Methodology:

- ✓ *Organized Mr data and aggregate property data*
  - *Mr tests without aggregate properties excluded*
  - *Multiple aggregate index properties averaged*

- ✓ *Related selected physical properties of M_R samples to k parameters of M_R models*
  - ***376 data sets*** *(80% for model development and 20% for validation)*

K_1, K_2 & K_3: $$Mr = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

K_4, K_5 & K_6: $$Mr = k_4 P_a \left(\frac{\sigma_3}{P_a}\right)^{k_5} \left(\frac{\sigma_d}{P_a}\right)^{k_6}$$

= f(index properties)

Project Tasks

Task 3 – Methodology (Cont'd):

- ✓ *Both stepwise regression analysis and Artificial Neural Network (ANN) modeling techniques were applied*

- ✓ *Results from both techniques were compared*

Project Tasks

Task 3 – Stepwise Regression:

Dependent Variable	Independent Variables	Note
K1	X1 - OMC	Optimum Moisture Content
K2	X2 - MDD	Maximum Dry Density
K3	X3 - C_u	Coefficient of uniformity
	X4 - C_c	Coefficient of curvature
	X5 – PP_3"	Percent passing 75mm sieve
	X6 – PP_2-1/2"	Percent passing 63mm sieve
	X7 – PP_2"	Percent passing 50mm sieve
	X8 – PP_1-1/2"	Percent passing 37.5mm sieve
	X9 – PP_1-1/4"	Percent passing 31.5mm sieve
	X10 – PP_1"	Percent passing 25mm sieve
	X11 – PP_3/4"	Percent passing 19mm sieve
	X12 – PP_5/8"	Percent passing 16mm sieve
	X13 – PP_1/2"	Percent passing 12.5mm sieve
	X14 – PP_3/8"	Percent passing 9.5mm sieve
	X15 – PP_#4	Percent passing 4.75mm sieve
	X16 – PP_#8	Percent passing 2.36mm sieve
	X17 – PP_#10	Percent passing 2mm sieve
	X18 – PP_#16	Percent passing 1.18mm sieve
	X19 – PP_#30	Percent passing 600um sieve
	X20 – PP_#40	Percent passing 425um sieve
	X21 – PP_#50	Percent passing 300um sieve
	X22 – PP_#100	Percent passing 150um sieve
	X23 – PP_#200	Percent passing 75um sieve

Selected Independent Variables

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Project Tasks

Task 3 – Stepwise Regression (Cont'd):

Dependent Variable	The Most Significant Variables							
K1	**X2**	**X13**	**X14**	**X15**	**X20**	**X23**		
K1=-2.2854+0.0260***X2**+0.1085***X13**-0.1550***X14**+0.0511***X15**+0.0128***X20**-0.0354***X23** **RMSE**=0.591538 R^2=0.152309 Adj R^2=0.133 **F**=8.05543; **p**=5.189e-008								
K2	**X2**	**X3**	**X8**	**X10**	**X18**			
K2= 9.7667-0.0180***X2**+0.0077***X3**-0.2059***X8**+0.126***X10**-0.0049***X18** **RMSE**=0.363049 R^2=0.374385 Adj R^2=0.363 **F**=32.315; p=0								
K3	**X2**	**X3**	**X7**	**X9**	**X11**	**X13**	**X15**	**X20**
K3= -10.8816+0.0133***X2**-0.0035***X3**+0.2253***X7**-0.141849***X9**+0.0424***X11**-0.0398***X13**+0.0131***X15**+0.0021***X20** **RMSE**=0.140868 R^2=0.326842 Adj R^2=0.307 **F**=16.2047; **p**=0								

Regression Results

Possible reasons for low R^2:

- **Different test setups**
- **Data inconsistency**
- **Colinearity between index properties**
- **Critical index properties not available**

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Project Tasks

Task 3 – Stepwise Regression vs. ANN:

ANN Models:

	27-10-3	27-14-15-3
K1	0.35	0.48
K2	0.43	0.46
K3	0.67	0.65

R^2

ANN Models (27 input Variables):

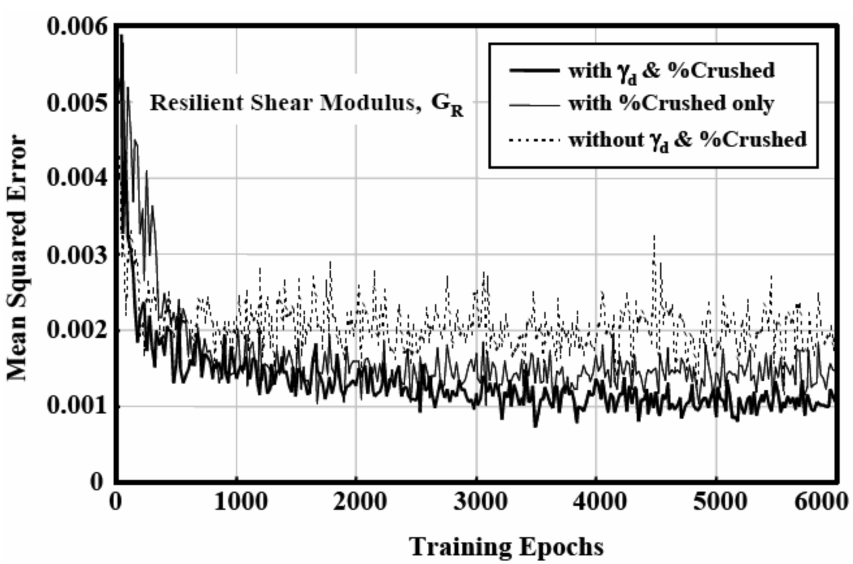
- Slightly better R^2 Values
- Different covariates identified

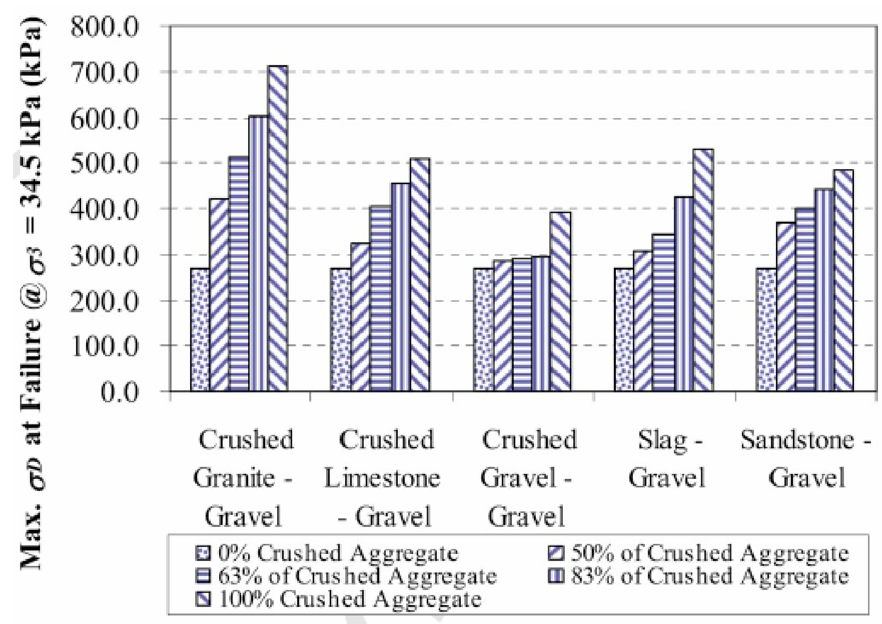
Dependent Variable	The Most Significant Variables														
K1	X1	X2	X3	X5	X7	X9	X10	X11	X12	X14	X16	X18	X24	X25	X26
K1=-12.5519+0.7116***X1**+0.1226***X2**-0.0049***X3**-1.6067***X5**-0.2152***X7**+26.4846***X9**-13.1223***X10**+0.6112***X11**-0.0186***X12**-0.2993***X14**+0.0905***X16**-0.1093***X18**+0.0496***X24**-0.0770***X25**+0.1913***X26** **RMSE**=0.533932 R^2=0.332 Adj R^2=0.294 **F**=8.63339; **p**=4.44089e-016															
K2	X2	X5	X13	X17											
K2= -0.9477+0.0141***X2**-0.2363***X5**+1.2853***X13**-0.0095***X17** **RMSE**=0.146541 R^2=0.260615 Adj R^2=0.2497 F=23.8802; p=1.11022e-016															
K3	X3	X4	X5	X6	X8	X11	X17	X18	x19	X21	X23				
K3= 0.4168+0.0005***X3**-0.0047***X4**+0.7884***X5**-0.0519***X6**-2.1530***X8**+0.1303***X11**-0.1126***X17**+0.1962***X18**-0.1297***X19**+0.0639***X21**-0.0152***X23** **RMSE**=0.302675 R^2=0.574822 Adj R^2=0.557 **F**=32.4469; **p**=0															

Project Tasks

Task 3 – Important Aggregate Physical Properties:

Previous research at UIUC indicated shape properties to have a significant impact on aggregate modulus & strength





γ_d & %Crushed

(Tutumluer, E. & Seyhan, U., 1998)

AI & ST

(Tutumluer, E. & Pan, T., 2007)

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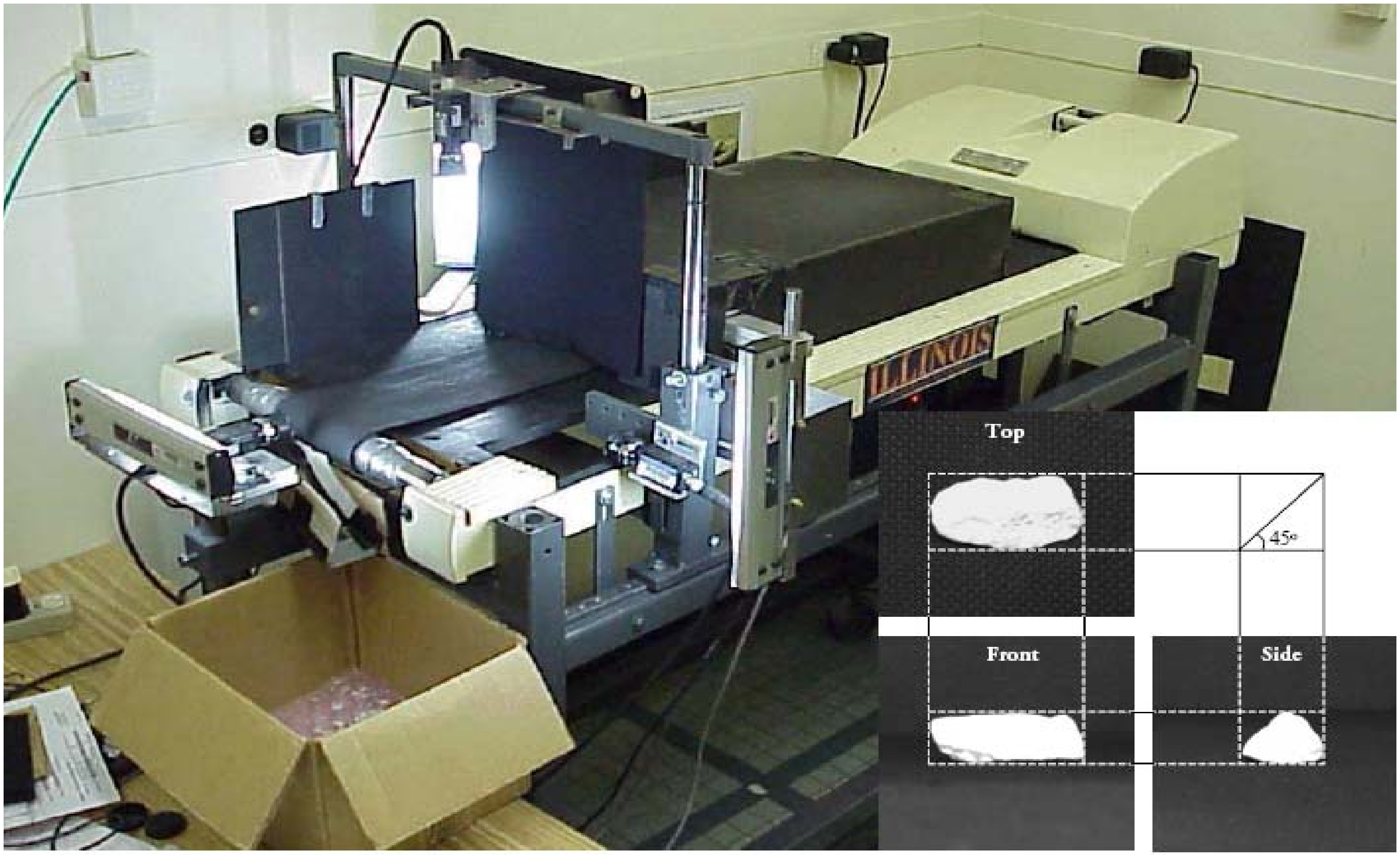
Project Tasks

Task 3 – Imaging based Shape Indices:



The University of Illinois Aggregate Image Analyzer (UIAIA) System

Project Tasks

Task 3 – Image based Shape Indices (Cont'd):

Aggregate Type	Angularity Index (AI)		Surface Texture (ST) Index	
	Range	Mean	Range	Mean
Uncrushed Gravel	250-350	300	0.5-1.20	0.90
Crushed Gravel	300-450	400	1.00-1.50	1.20
Crushed Limestone	400-550	475	1.20-1.80	1.60
Crushed Granite	500-650	550	1.80-2.90	2.20

Typical Ranges and Mean Values of AI and ST
(Pan and Tutumluer, 2005)

Project Tasks

Task 3 – Image based Shape Indices:

12 samples received from Mn/DOT for Image Analysis

All analyzed to develop imaging shape indices except for

Dark colored TH 52 Taconite Tailings

Very fine-graded (< 2mm) TH 47 SGB

Project Tasks

Task 3 – Image based Shape Indices (Cont'd):

Label on Sample's Bag	Average Values			
	F&E Ratio	Angularity Index (AI)	Surface Texture (ST)	Surface Area (SA, in^2)
TH 14/15 CL 5	2.717	306.7	0.898	1.3783
CO RD 14 CL 5	2.031	343.5	1.002	1.9765
TH 23 CL 6m	3.705	380.4	1.024	1.9866
TH 371 CL 6	10.605	464.3	0.808	40.9664
Olmsted CL 5	2.0535	414.0	1.640	3.1968
TH 16 CL 6	1.843	452.9	1.531	2.2317
Olmsted CL 5 M	2.024	430.5	1.638	2.7186
TH 52 SG	7.403	400.1	0.8211	13.5162

Image Analysis Results of Mn/DOT Samples Processed using UIAIA

Project Tasks

X24 – F&E Ratio	
X25 – AI	
X26 – ST	
X27 – SA	

Task 3 – Regression with Shape Indices:

Dependent Variable	Covariates	Goodness of Regression	
K1	X1, X2, X23	R^2 = 0.898368; Adj R^2 = 0.837389 (base line)	
	X1, X2, X23, X24	R^2 = 0.898443; Adj R^2 = 0.796887 (↓)	Add FE_Ratio
	X1, X2, X23, X25	R^2 = 0.935412; Adj R^2 = 0.870823 (↑)	Add AI
	X1, X2, X23, X26	R^2 = 0.983525; Adj R^2 = 0.967051 (↑)	Add ST
	X1, X2, X23, X24, X25, X26	R^2 = 0.989273; Adj R^2 = 0.957092 (↑)	Add all three
K2	X1, X2, X10, X23	R^2 = 0.910647; Adj R^2 = 0.821293 (base line)	
	X1, X2, X10, X23, X24	R^2 = 0.914783; Adj R^2 = 0.772754 (↓)	Add FE_Ratio
	X1, X2, X10, X23, X25	R^2 = 0.937404; Adj R^2 = 0.833077 (↑)	Add AI
	X1, X2, X10, X23, X26	R^2 = 0.913328; Adj R^2 = 0.768874 (↓)	Add ST
	X1, X2, X10, X23, X24, X25, X26	R^2 = 0.999937; Adj R^2 = 0.999498 (↑)	Add all three
K3	X10, X13, X20	R^2 = 0.745918; Adj R^2 = 0.593468 (base line)	
	X10, X13, X20, X24	R^2 = 0.749059; Adj R^2 = 0.498117 (↓)	Add FE_Ratio
	X10, X13, X20, X25	R^2 = 0.889244; Adj R^2 = 0.778487 (↑)	Add AI
	X10, X13, X20, X26	R^2 = 0.873318; Adj R^2 = 0.746635 (↑)	Add ST
	X10, X13, X20, X24, X25, X26	R^2 = 0.932507; Adj R^2 = 0.730028 (↑)	Add all three

- *ST is the most important for K_1; while AI is the most important for K_2 and K_3*

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Project Tasks

Task 3 – Methodology (Cont'd):

- ✓ *Stepwise regression equations for K_1 K_2 and K_3 without shape properties have low R^2 values*
- ✓ ***Predictive equations have high R^2 values only when shape properties are included***

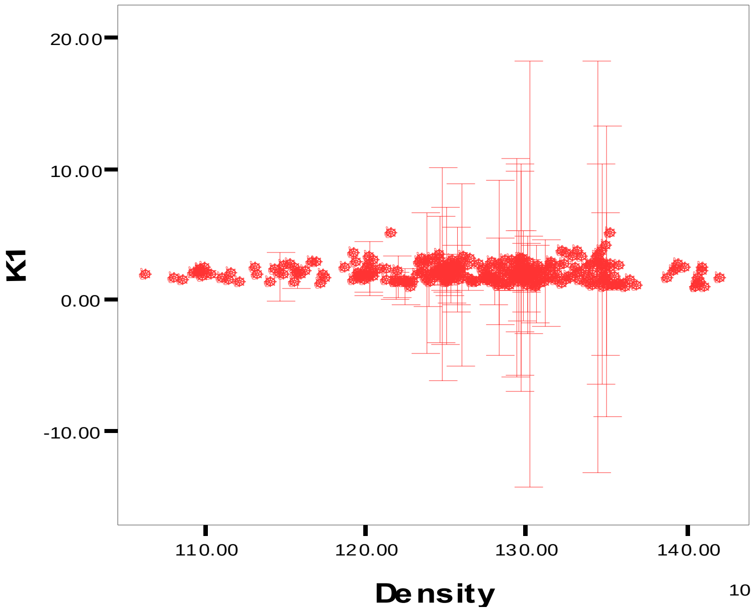
- ✓ *Typical trends in K values can be estimated for different group M_R data groups for the conditions:*
  - ❑ *Dense(Achieved density>=125 pcf)/ loose(Achieved density<125 pcf)*
  - ❑ *Crushed(Angularity Index AI>=400)/ uncrushed(AI<400)*
  - ❑ *Coarse(Max. size>=#4)/ fine(Max. size<#4)*
  - ❑ *Clean(Percent passing #200<8%)/ dirty(Percent passing #200>=8%)*

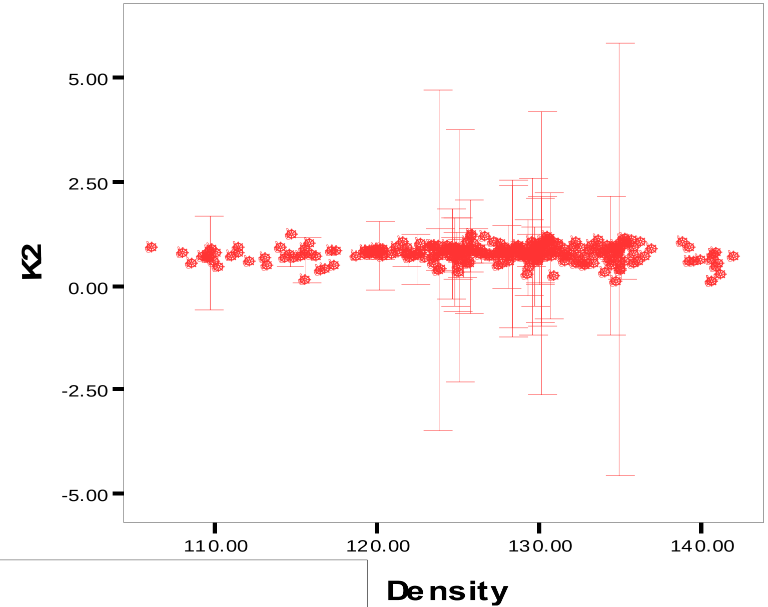
Project Tasks

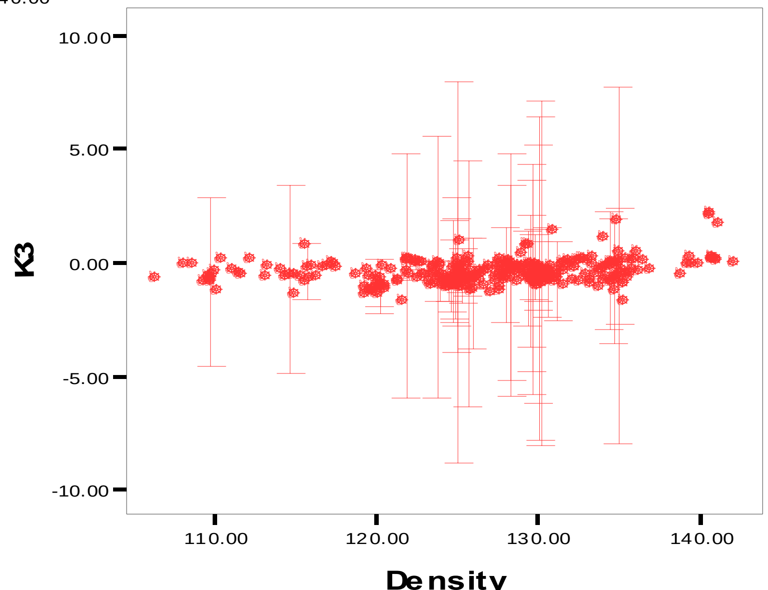
Task 3 – Grouping results (Cont'd):

Error Bars show 95.0% CI of Mean

Dot/Lines show Means







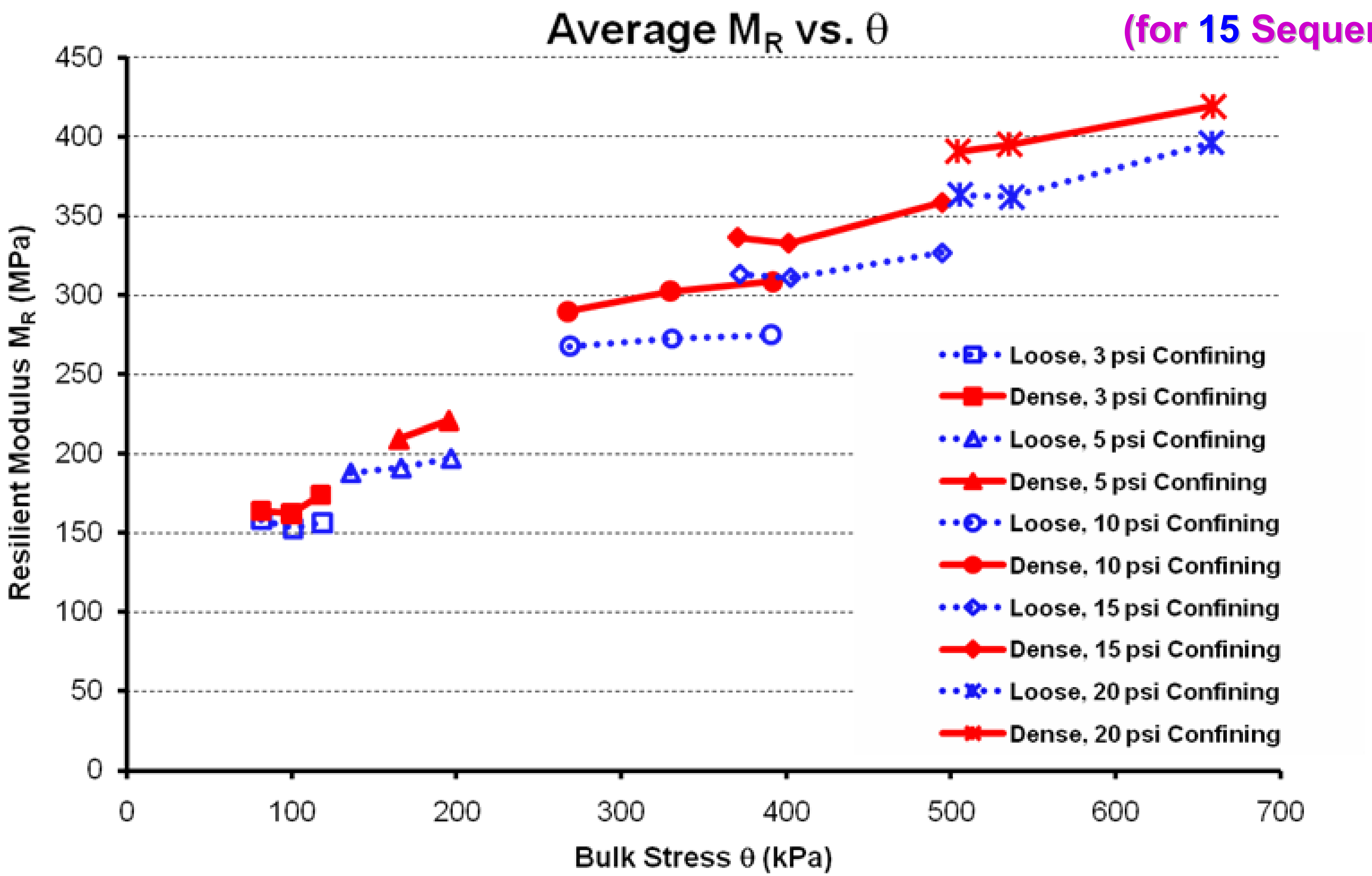
Select 125 pcf
as density threshold

Dense / Loose

Project Tasks

Task 3 – Grouping results (Cont'd):

N_{dense} = 136
N_{loose} = 55
Total = 191
(for 15 Sequences)



Dense / Loose

1 psi = 6.89 kPa

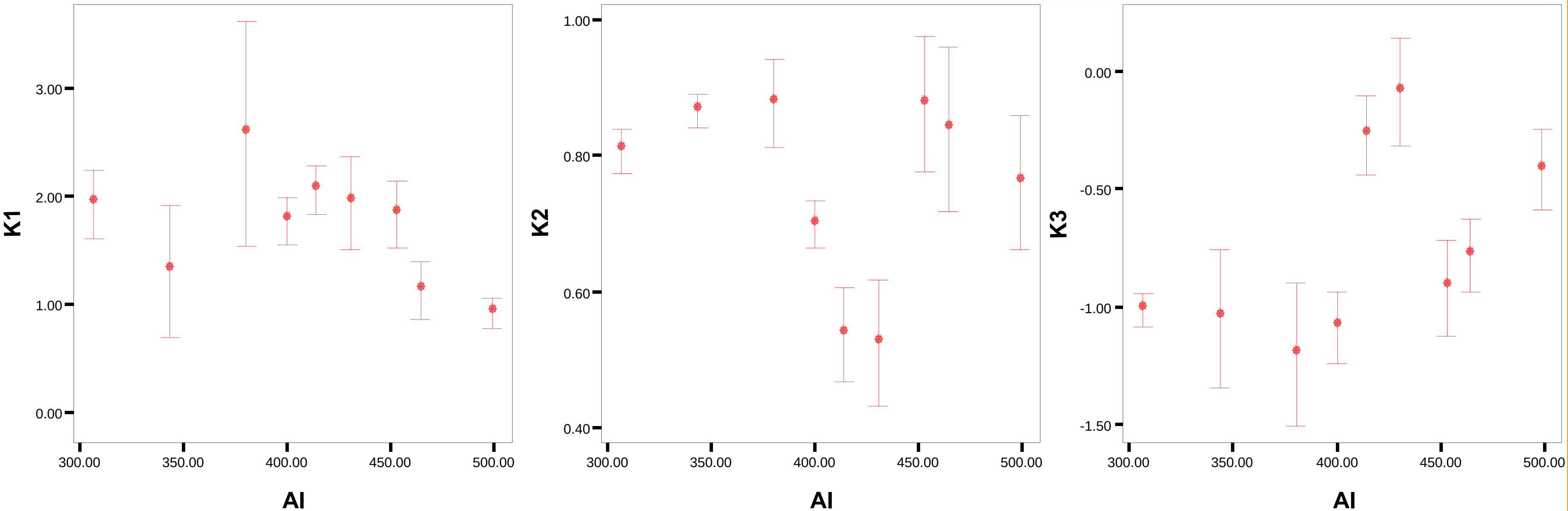
Project Tasks

Task 3 – Grouping results:

Error Bars show 95.0% CI of Mean

Crushed / Uncrushed

Dot/Lines show Means



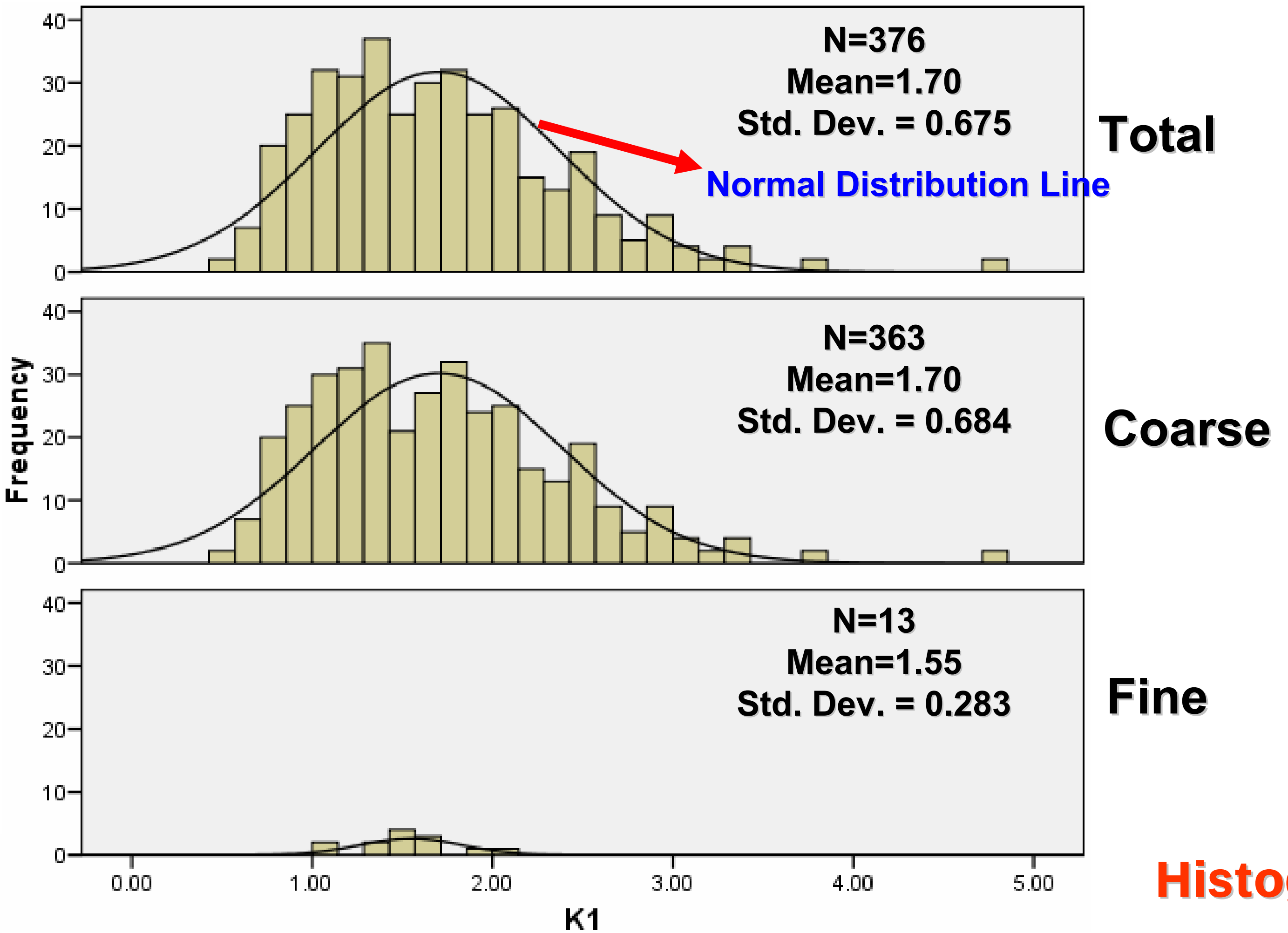
K1, k2, k3 vs. AI

(AI values from imaging of Mn/DOT samples)

- *43 Mr tests with AI < 400;*
- *72 Mr tests with AI >= 400;*
- *Total = 115*

Project Tasks

Task 3 – Grouping results (Cont'd):



Coarse / Fine

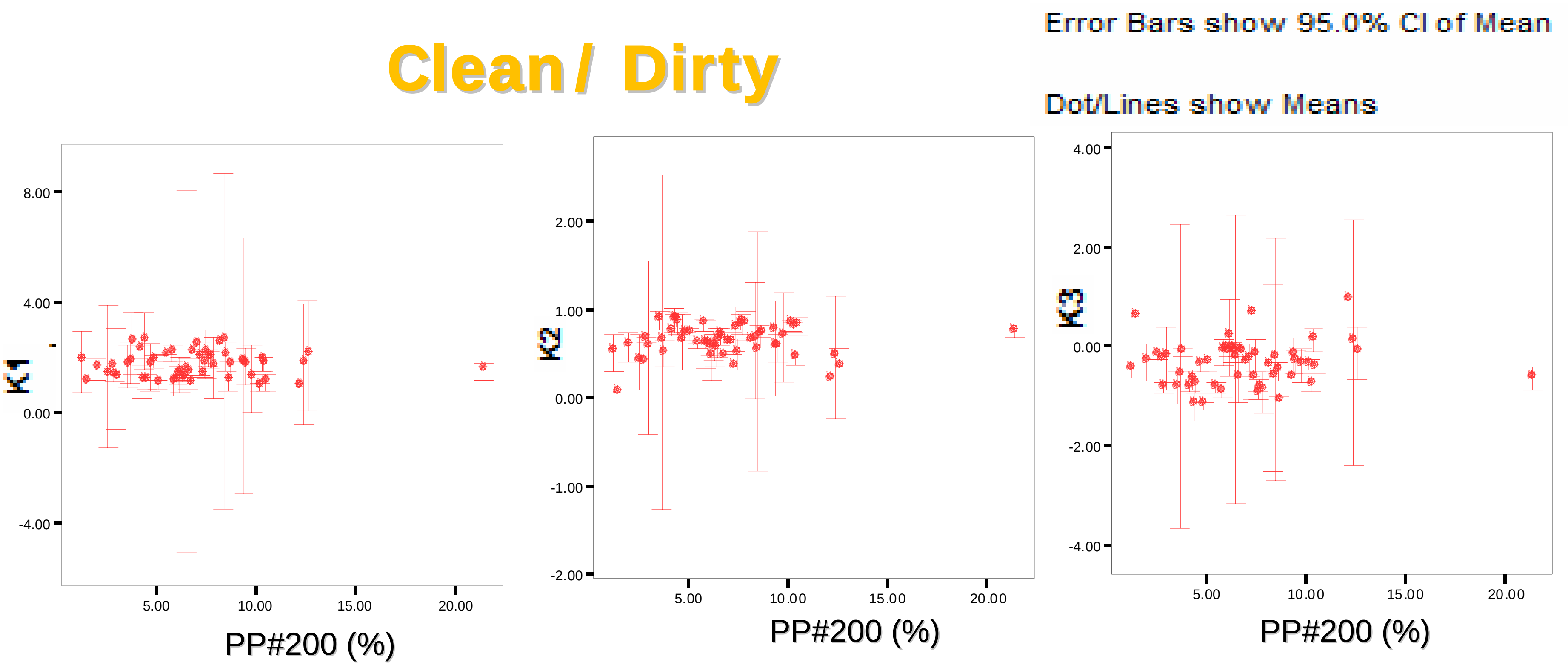
Histogram of K_1

K_2 and K_3 similar

Project Tasks

Task 3 – Grouping results (Cont’d):

Clean / Dirty



K1, K2, K3 vs. PP#200 (%)

- *257 Mr tests with PP#200 < 8%;*
- *119 Mr tests with PP#200 >= 8%;*
- *Total = 376*

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Task 3 – ICT R27-1 SAS^R ANOVA Results:

- ✓ *For ICT R27-1 project results, two primary procedures were conducted using SAS^R (Statistical Analysis Software) to develop the best models for predicting K-parameters:*
  - ✓ ***ANOVA (Analysis of Variance)***
  - ✓ ***Stepwise regression***

- ✓ *The ANOVA is a common method to study the effect of treatments or independent variables (aggregate properties in the test matrix herein) on some dependent variables (K_1, K_2, …, K_6 herein)*

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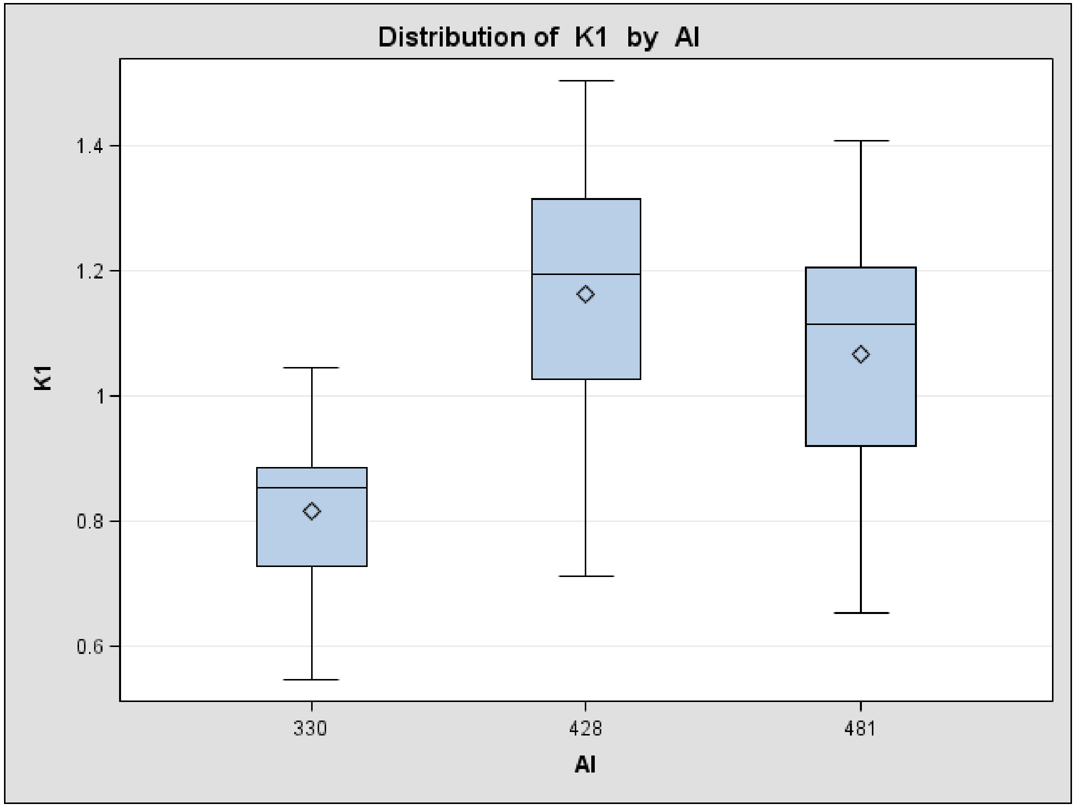
Task 3 – ICT R27-1 SAS[R] ANOVA Results:



From the plot, it can be seen that the mean K1 values are different for different AI values.

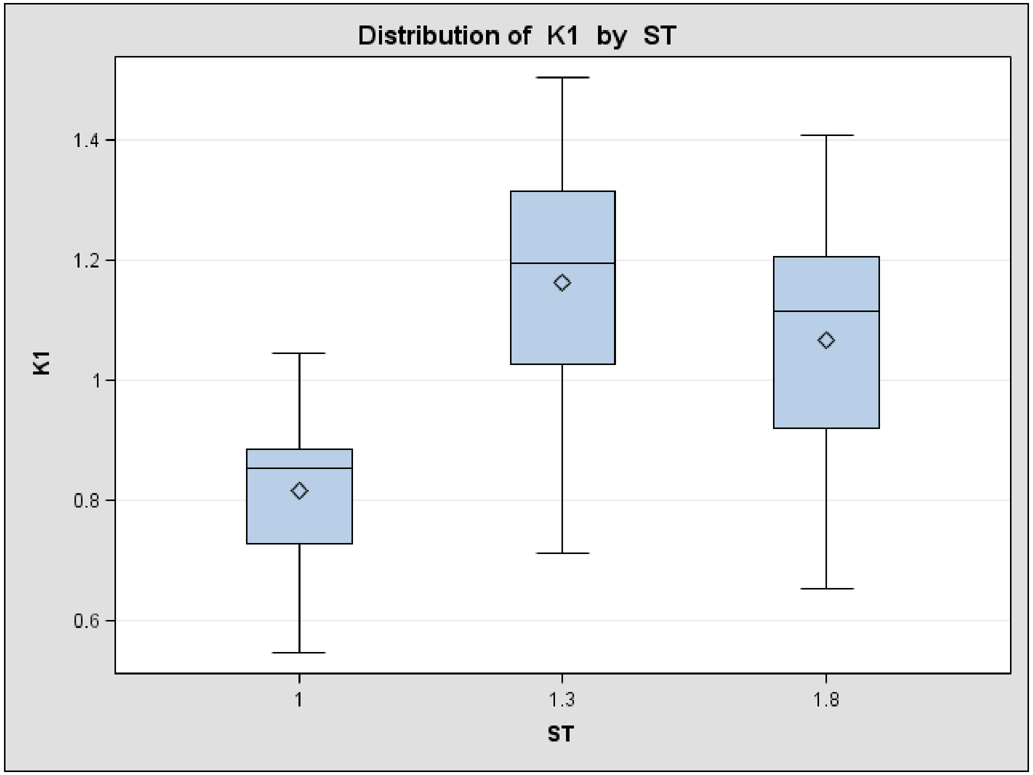
The p-value (<0.0001) from ANOVA is less than 0.05 (alpha level selected at this stage)

Therefore, AI value has a significant effect on K1

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AI	2	1.33095985	0.66547993	18.29	<.0001

α = 0.05 probability of Type –I error

Task 3 – ICT R27-1 SAS[R] ANOVA Results:



From the plot, it can be seen that the mean K1 values are different for different ST values.

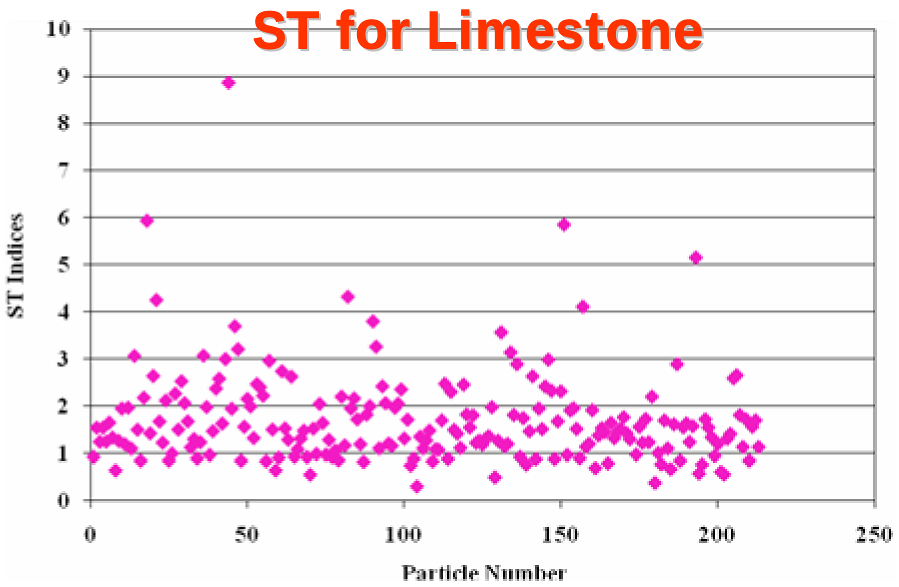
The p-value (<0.0001) from ANOVA is less than 0.05 (alpha level selected at this stage)

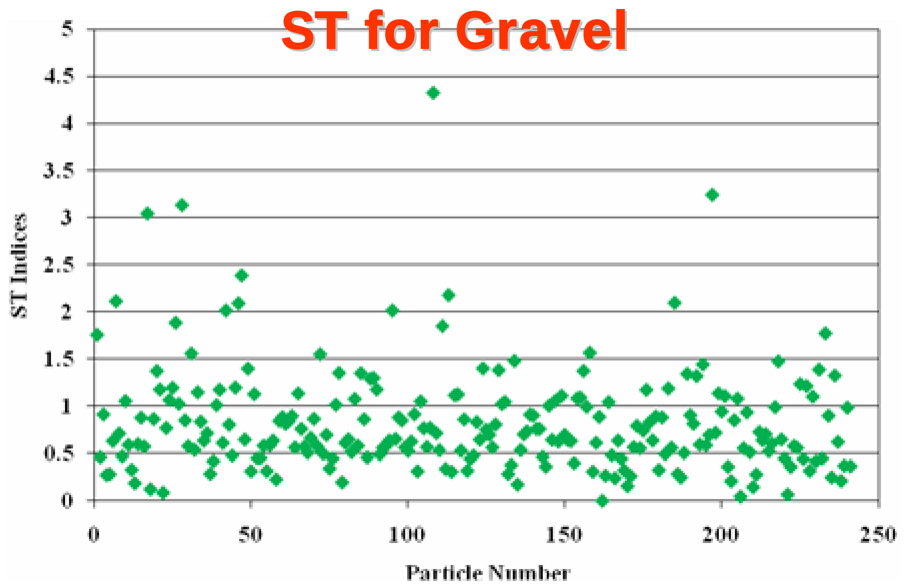
Therefore, ST value does have a significant effect on K_1

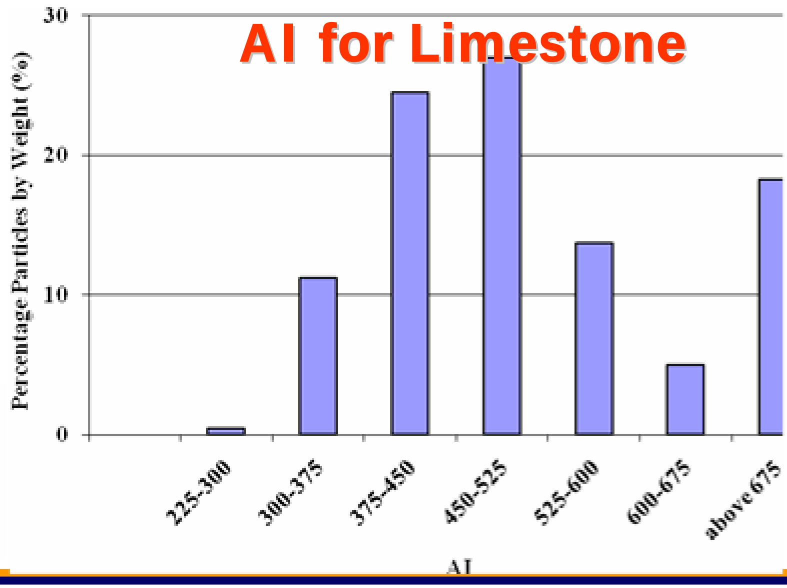
Source	DF	Type I SS	Mean Square	F Value	Pr > F
ST	2	1.33096	0.6654799	18.29	<.0001

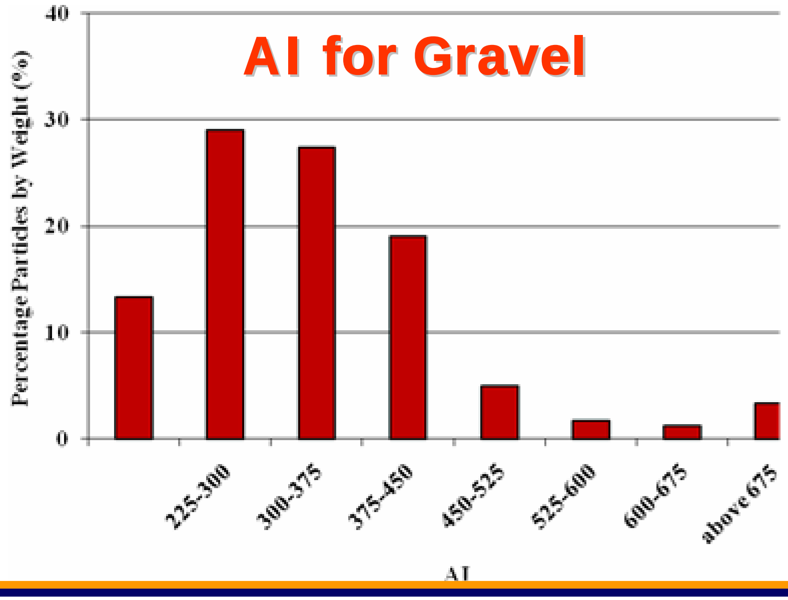
α = 0.05 probability of Type –I error

Task 3 – ICT R27-1 IDOT Project Results

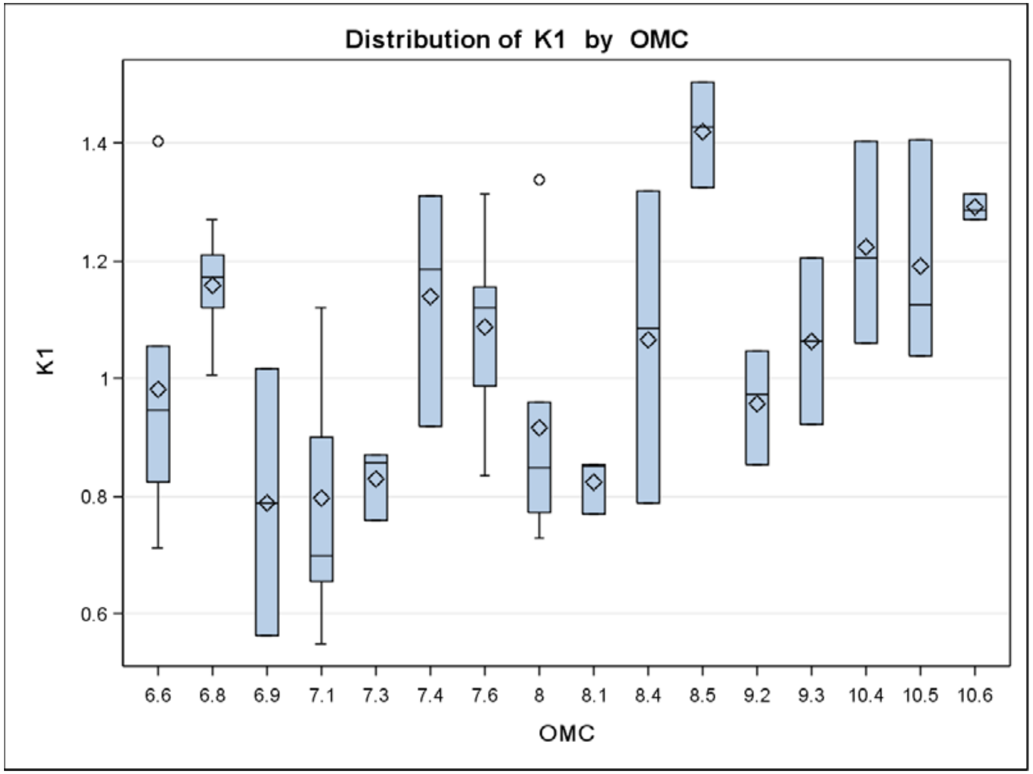








Task 3 – ICT R27-1 SAS[R] ANOVA Results:



Source	DF	Type I SS	Mean Square	F Value	Pr > F
OMC	15	1.970819	0.13138792	3.98	0.0001

From the plot, it can be seen that the mean K1 values corresponding to each optimum moisture content, demonstrate a roughly increasing pattern

The p-value (=0.0001) from ANOVA is less than 0.05 (alpha level selected at this stage)

Therefore, **Optimum Moisture Content (OMC) has a significant effect on K_1**

α = 0.05 probability of Type –I error

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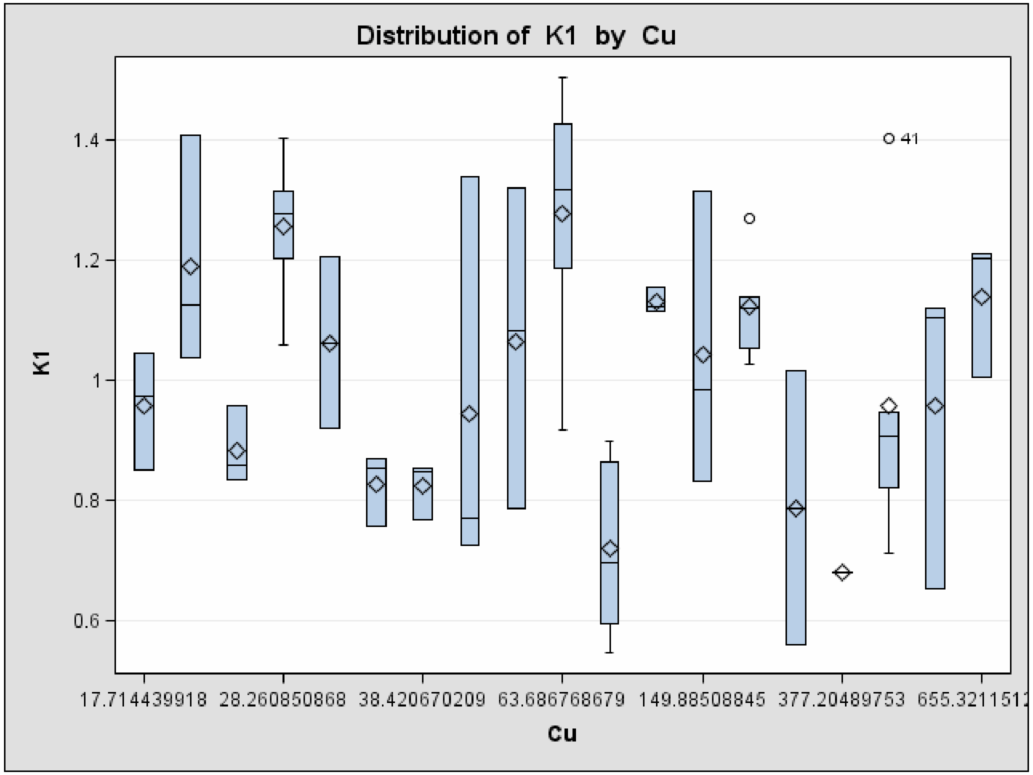
Task 3 – ICT R27-1 SAS[R] ANOVA Results:



From the plot, it can be seen that the mean K1 values corresponding to each C_u, demonstrate a roughly decreasing pattern

The p-value (=0.0009) from ANOVA is less than 0.05 (alpha level selected at this stage)

Therefore, **coefficient of uniformity (C_u) has a significant effect on K_1**

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Cu	18	1.97416	0.10968	3.13	0.0009

α = 0.05 probability of Type –I error

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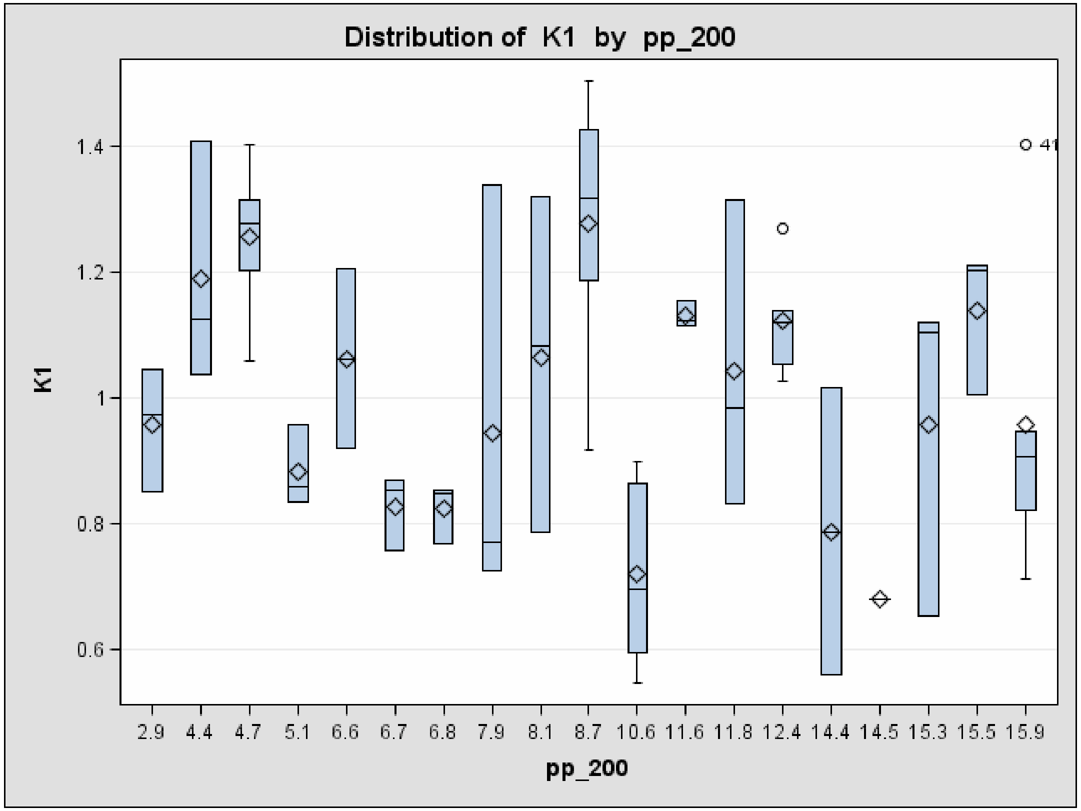
Task 3 – ICT R27-1 SAS[R] ANOVA Results:



From the plot, it can be seen that the mean K1 values corresponding to each fines content, demonstrate a roughly decreasing pattern

The p-value (=0.0009) from ANOVA is less than 0.05 (alpha level selected at this stage)

Therefore, **fines content (passing #200 sieve) has a significant effect on K_1**

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pp_200	18	1.9742	0.1097	3.13	0.0009

α = 0.05 probability of Type –I error

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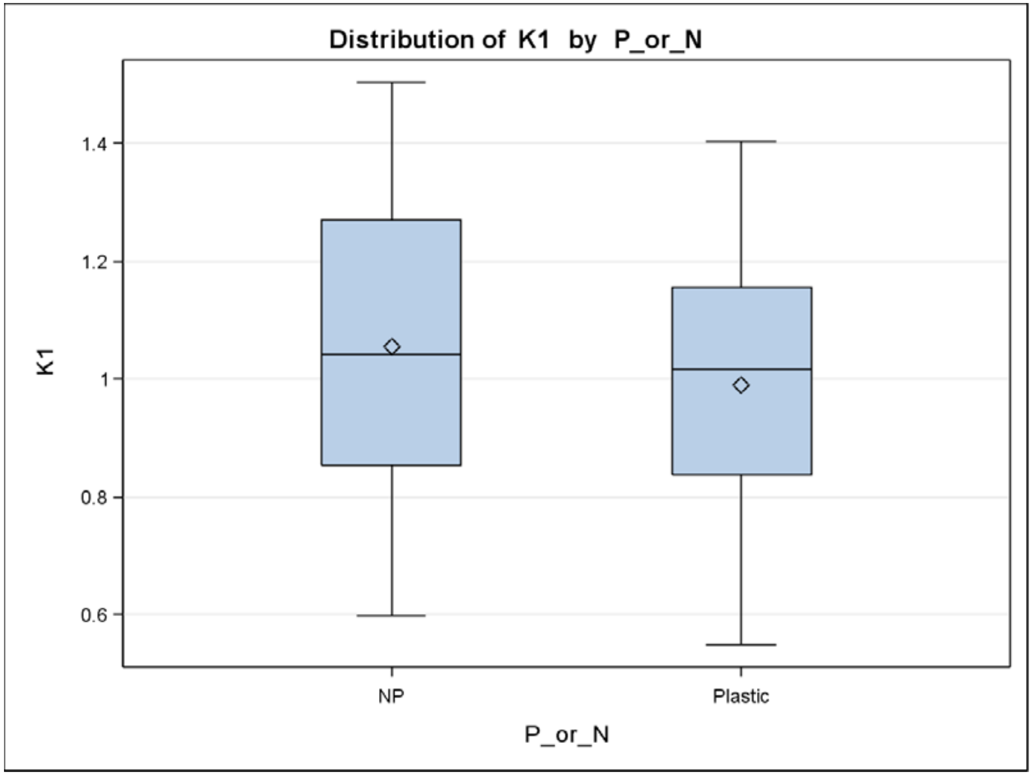
Task 3 – ICT R27-1 SAS[R] ANOVA Results:



From the plot, it can be seen that the mean K1 values corresponding to Plastic/Non-Plastic, do not demonstrate any particular pattern.

The p-value (=0.2773) from ANOVA is greater than 0.05

Therefore, **Plastic/Non-Plastic fines categories do not have a significant effect on the value of K_1**

Source	DF	Type I SS	Mean Square	F Value	Pr > F
P_or_N	1	0.067	0.067	1.20	0.2773

α = 0.05 probability of Type –I error

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Project Tasks

Task 3 - Summary:

Correlations developed between collected laboratory M_R data and aggregate index properties. Certain trends were verified with ICT R27-1 project findings.

Task 3 Deliverables include:

- Developed stepwise regression equations for predicting K model parameters from aggregate physical properties
- Image analysis results and improved correlations for 12 samples received from Mn/DOT
- Comparisons between stepwise regression equations and LTPP equations

Project Tasks

Task 4 - Overview:

Conduct sensitivity analyses for mechanistic design moduli inputs & seasonal pore suction resistance factors for different Mn/DOT aggregate classes using the MnPAVE program to generate pavement life expectancies

Relative importance of all pavement design input parameters will be better understood

- guidelines will be established to choose a range of design moduli for different Mn/DOT aggregate classes
- target values for strength, modulus & thickness will be recommended for different design scenarios involving various types & qualities of locally available aggregate materials

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Project Tasks

Task 4 - Methodology:

✓ Aggregate properties that may significantly affect M_R were identified from both Mn/DOT & ICT R27-1 data:

- AI &/ or ST
- Optimum moisture content (OMC)
- Maximum Dry Density (MDD)
- Coefficient of Uniformity (C_u)
- Percent Passing #200 (% fines)

✓ Different design scenarios considered for Mn/DOT:

- Dense & Loose (Achieved γ_d)
- AI/ ST or Crushed & Uncrushed (find $K_{1,2,3}$ trends)
- Clean & Dirty (PP#200)
- Coarse & Fine
- Dry, Opt. and Wet of OMC

Project Tasks

Task 4 – Methodology (Cont'd):

- ✓ For those cases developed, effects of changing aggregate properties on K_1, K_2 , K_3 and hence M_R mechanistic design inputs will be investigated
- ✓ Default values of K_1, K_2 , and K_3 will be recommended; M_R values at typical stress states suggested by NCHRP 1-28A will be predicted
- ✓ Comprehensive matrix of design moduli and seasonal pore suction resistance factors will be used to conduct MnPAVE analyses and identify the sensitivity of the design inputs to pavement life expectancies

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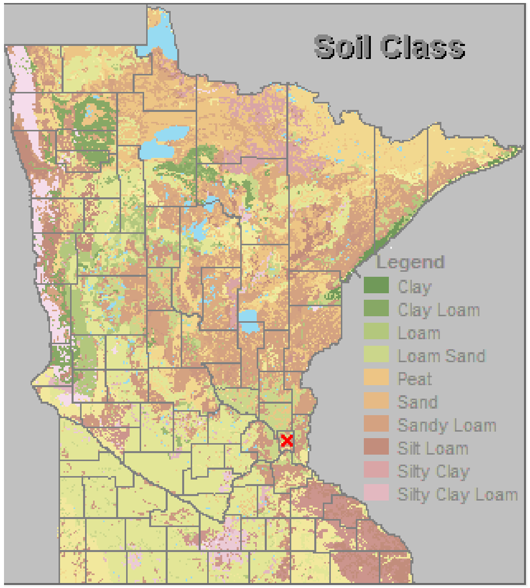
Project Tasks

Task 5 - Overview:

Develop a best value software tool to incorporate into the MnPAVE program and implement mechanistic pavement design concepts in aggregate selection/utilization



Aggregate Material Resource Map similar to Soil Class Map

- source
- type
- quality
- impact on M-E design

Project Deliverables

- ✓ A **Final Report** will be prepared at the end of the 2-year study to include all research findings

- ✓ **Revised MnPAVE Manual** pages will be prepared for **The Best Value Software Tool** by giving examples on how to use the developed correlations and mechanistic design moduli inputs

The ultimate benefit: *More economical use of the locally available aggregate materials in Minnesota*

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Thank you!..