15th Annual TERRA Pavement Conference
February 10, 2011

Granular Material Selection for Best Value Pavement Performance

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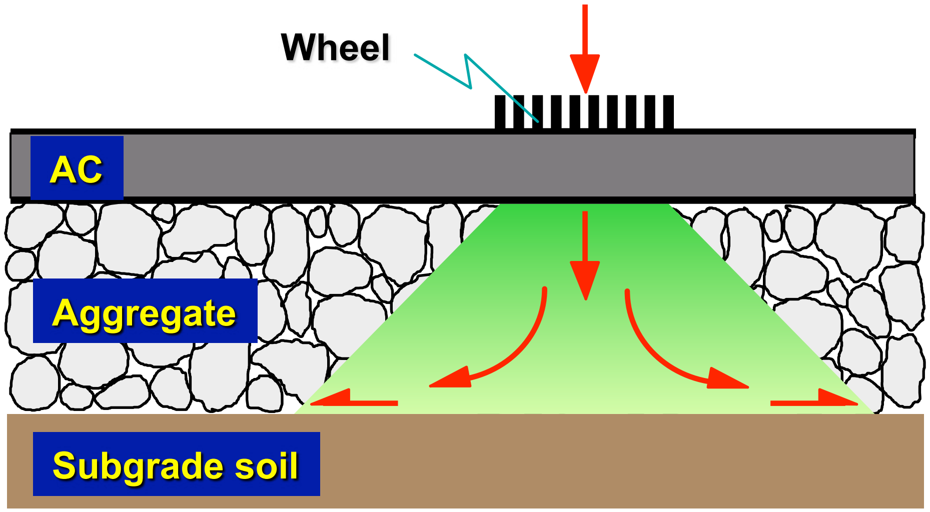
LRRB LOCAL ROAD RESEARCH BOARD

Introduction

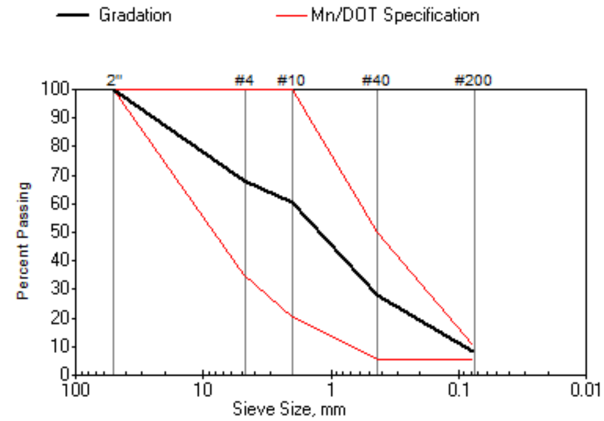
- **Unbound aggregate base/subbase** layers serve the primary purpose of **load distribution** in flexible pavements
- **Type and quality** of aggregate materials are directly linked to their engineering properties & **impact field performances**
- **Economical use** of locally available unbound aggregates in pavement layers require **mechanistic design inputs of modulus & strength characteristics** related to response & performance



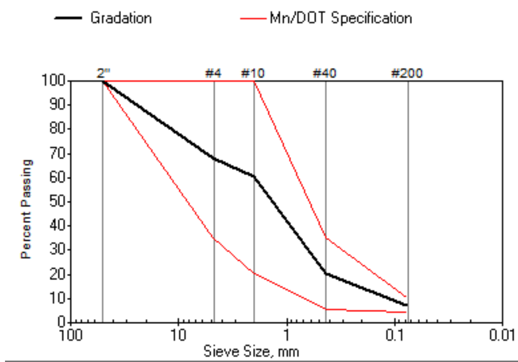
Mn/DOT Aggregate Classes

Aggregate Subbase

- Class 3
- Class 4
- Select Granular
- Granular



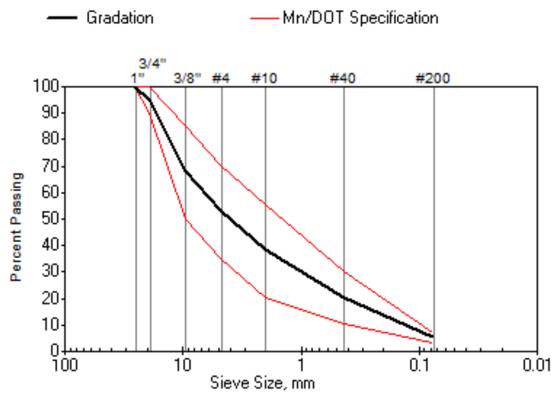
Class 3



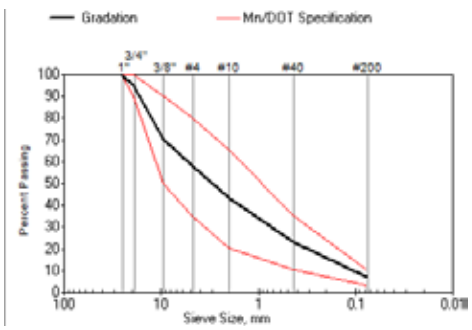
Class 4

Aggregate Base

- Class 5
- Class 6
- Class 7



Class 5



Class 6

Mn/DOT Research Background

- ü **Lukanen (1980)** found certain **Mn/DOT Class 3 aggregates** were **even stronger** than **Class 6 aggregates** when placed in pavement granular layers ***("Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota")***

- ü During **Mn/ROAD study**, similar contradictory trends were also observed in **backcalculated base layer moduli** from **FWD testing** of flexible pavements:

  *For both **thin** **(<15 cm)** and **thick** **(>15 cm)** asphalt concrete surfacing, the backcalculated base moduli of **Class 3sp materials** were often found **greater than** those of **higher classes, i.e., 4sp, 5sp, and 6sp***

- ü These **surprising field evaluation findings** indicate it may be challenging how to best utilize different qualities of locally available aggregate materials in road bases/subbases

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Research Project Objective

ü ***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

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

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

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Established Index Properties of Minnesota Aggregates Used for Aggregate Base/Subbase

Identified & categorized **types, sources, & properties** of locally available aggregates in Minnesota and obtained **typical costs**

ASIS Online Web Interface

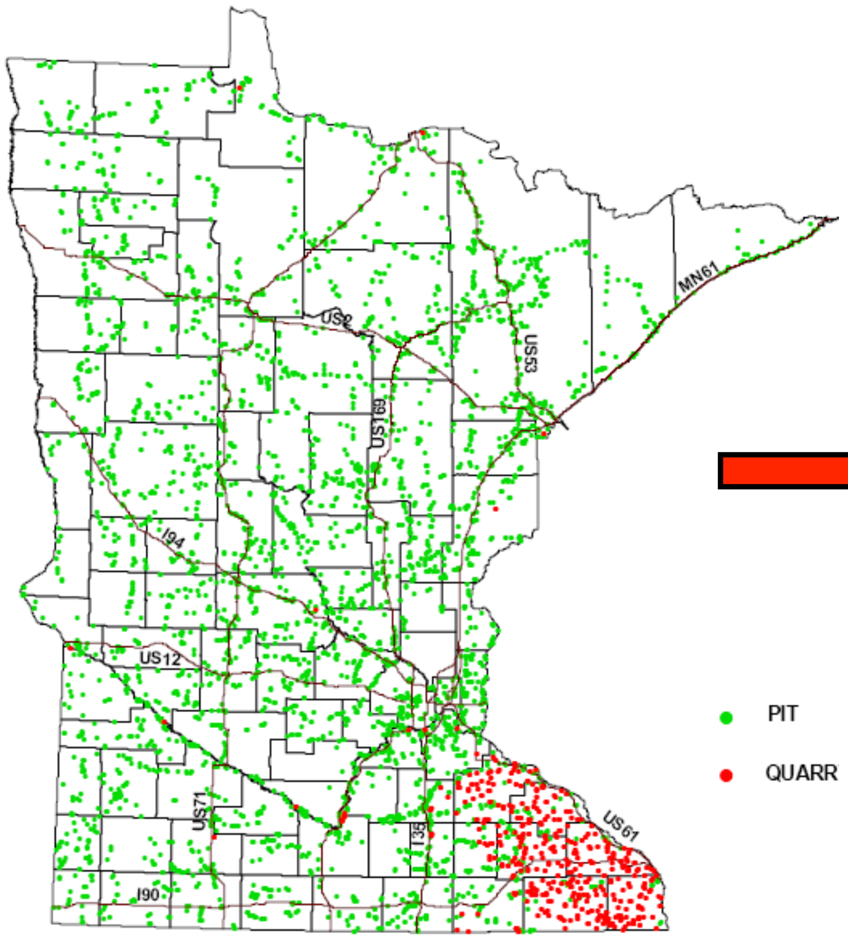
Database Spreadsheets

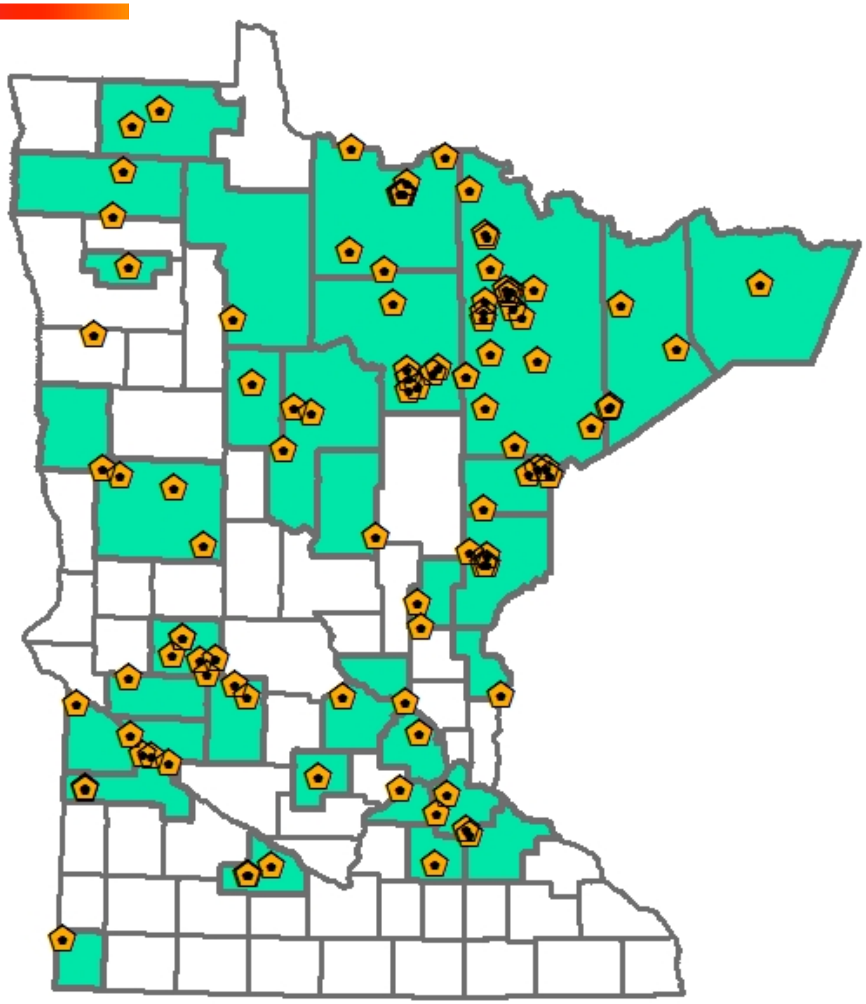
All Aggregate Sources - Aggregate Sourc

	A	B	C	D	E	F	G	H	I
2	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

Selected Prospect Pits





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

Established Aggregate Database

ArcGIS based Database Management System (DBMS) was developed for storing, retrieving and displaying aggregate index properties (87 counties)

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>	

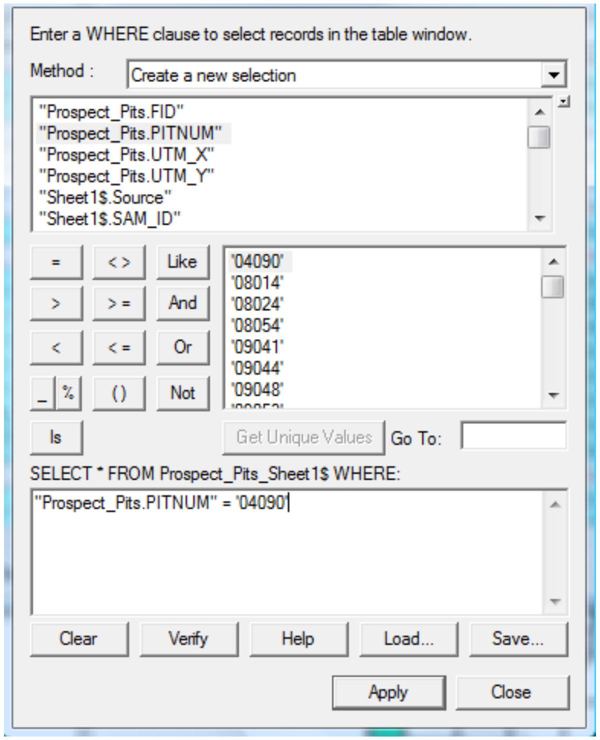
Record: 8 Show: All Selected Records (0 out of 99 Selected) Options

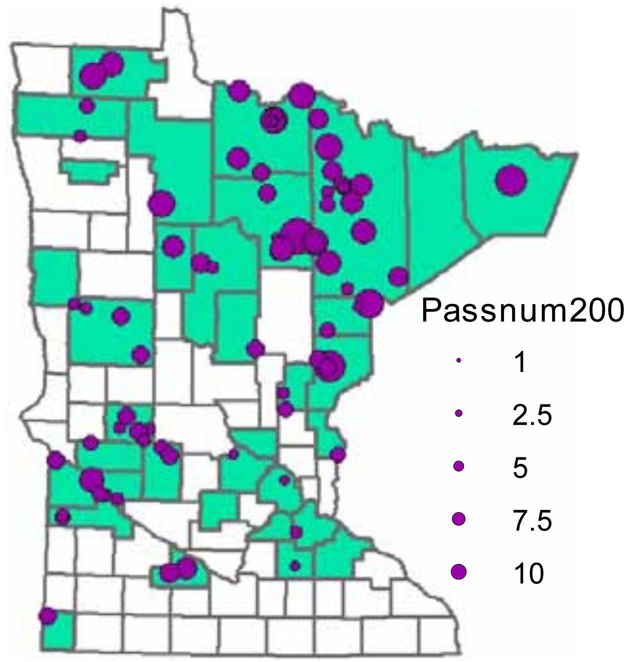
GIS based Aggregate Index Property Database

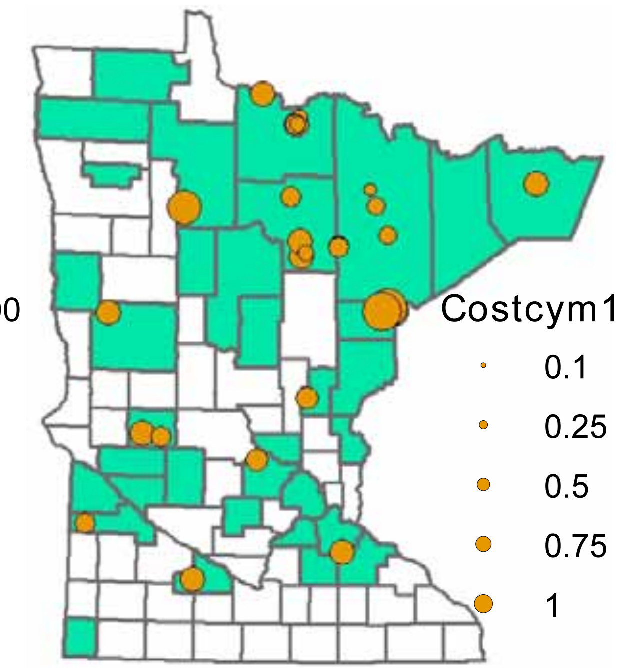
DBMS Functions:

- Search
- Store
- Retrieve
- Display

Aggregate Database Example







- **Search for features**
- **Retrieve and graphically display features**

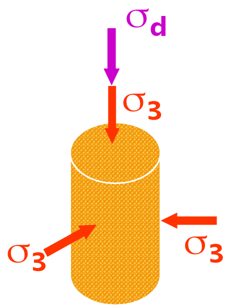
- Spreadsheets & Maps of 87 selected prospect pits
- ASIS database spreadsheets for 87 Minnesota Counties merged with reliable prospect pit gradations

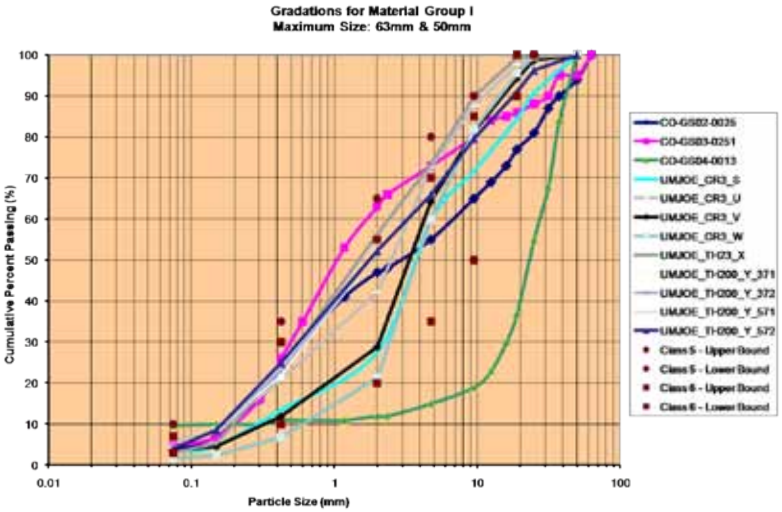
Collected Aggregate Characterization Inputs

Mechanistic pavement analysis & design inputs resilient modulus (M_R) & strength properties, for unbound aggregate base/subbase applications, together w/ corresponding aggregate index properties

- Databases collected from relevant Mn/DOT, University of Minnesota and University of Illinois research studies

$$M_R = \frac{\sigma_d}{\varepsilon_r}$$





Linked Modulus to Aggregate Properties

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

- gradation
- fines content
- Plasticity Index (PI) of fines
- moisture state in relation to optimum moisture content (OMC) **or** density achieved in relation to maximum Proctor density (MDD)
- **Shape properties (flat & elongated ratio, texture and angularity)**

Regression Models Developed for Predicting Modulus from Aggregate Source Properties

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

$$k_1 = 10^{\left(1.37862 - 0.04124\,\omega_{opt} - 0.00478\,\gamma_{dry} - 0.29437\frac{\omega}{\omega_{opt}} + 0.00119\,SAND\right)}$$

$$\left(R^2 = 0.1399;\ Adj.\ R^2 = 0.1307;\ p < 0.0001;\ MSE = 0.06216\right)$$

$$k_2 = 1.60611 - 0.01197\,\omega + 0.00569\,\gamma_d - 0.00015125\frac{\gamma_{max}^2}{P_{40}} - 0.0387\,C_u - 0.42692\,C_c - 0.01106\,P_{3/4''} \quad \text{(Eq. 1)}$$

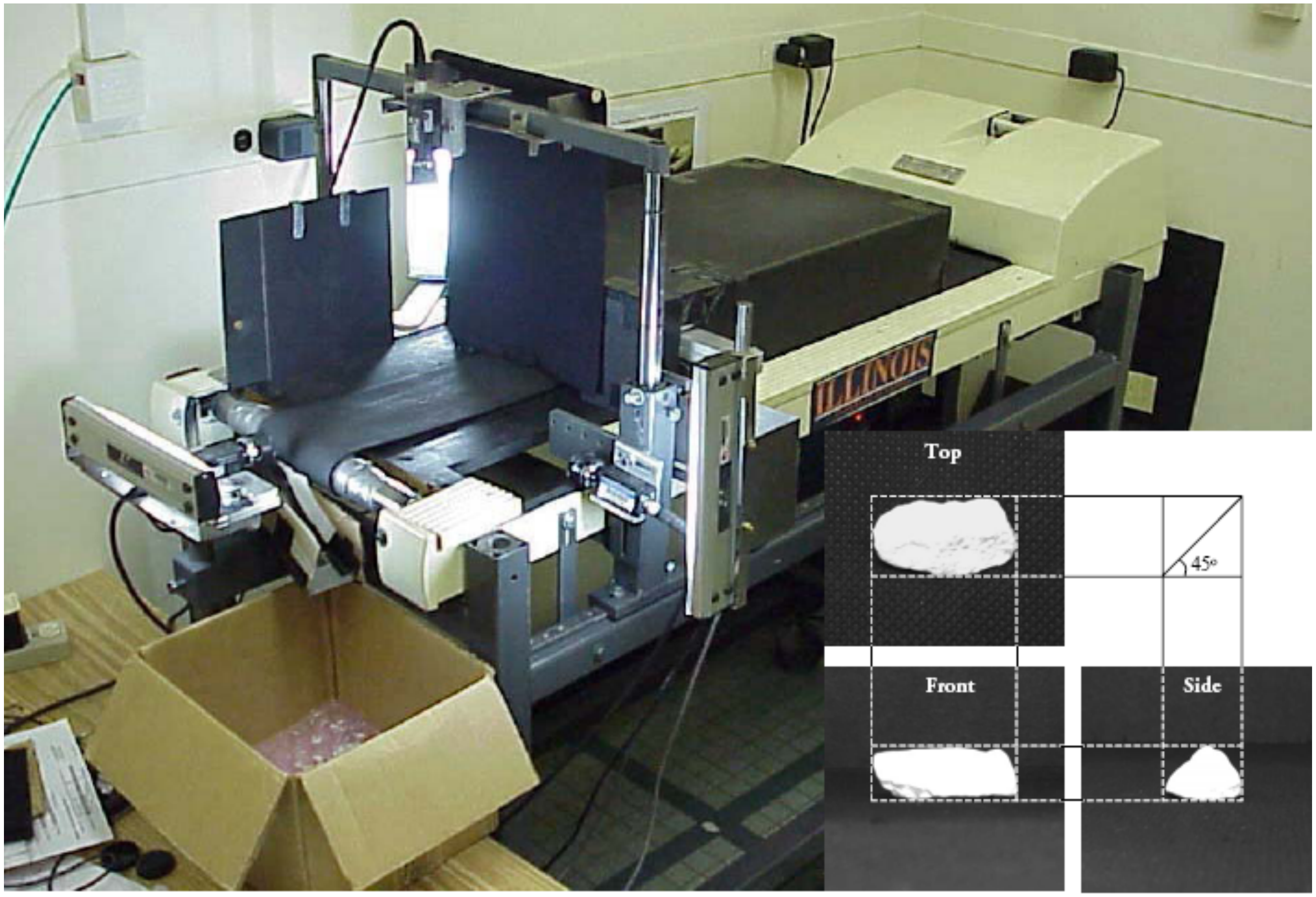
$$\left(R^2 = 0.3177;\ Adj.\ R^2 = 0.3066;\ p < 0.0001;\ MSE = 0.0292\right)$$

$$k_3 = -9.86685 + 0.00065186\frac{\gamma_{max}^2}{P_{40}} + 0.00734\,C_u + 0.06729\,P_{2''} + 0.01505\,P_{3/4''} + 0.0894\,P_{40}$$

$$\left(R^2 = 0.3940;\ Adj.\ R^2 = 0.3858;\ p < 0.0001;\ MSE = 0.1740\right)$$

Poor Correlations! – No Aggregate Shape Properties

Imaging Based Aggregate Shape Indices



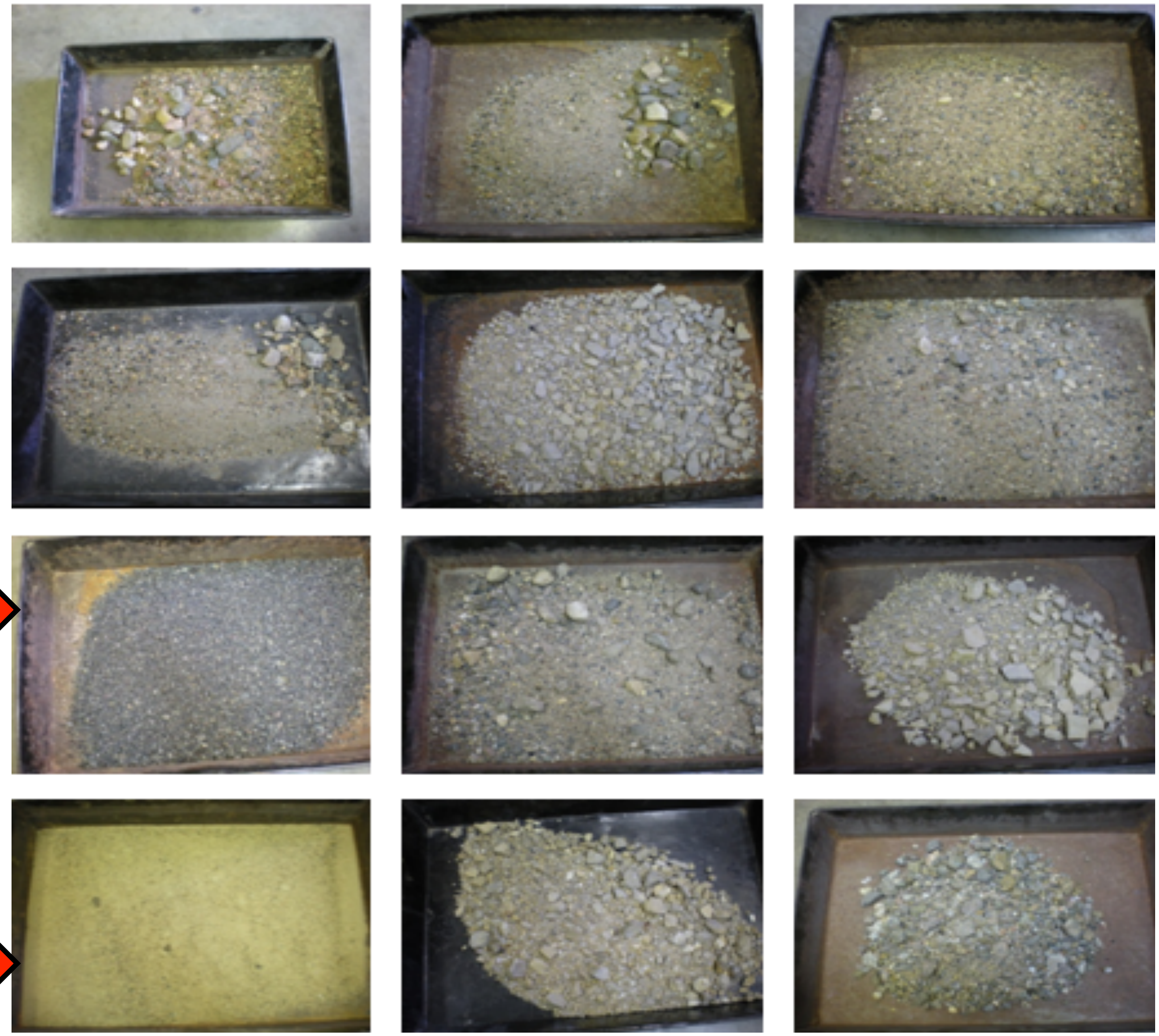
The University of Illinois Aggregate Image Analyzer (UIAIA) System

Image Analyses of Mn/DOT Agg. Samples

12 representative samples received from Mn/DOT for UIAIA Image Analyses

Dark colored
TH 52 Taconite Tailings

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



Imaging Results of Mn/DOT Agg. Samples

Bag Sample	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

Regression Models Developed for Predicting Modulus from Aggregate Source Properties

$$
\begin{cases}
M_R = k_1 P_a \left(\dfrac{\theta}{P_a}\right)^{k_2} \left(\dfrac{\tau_{oct}}{P_a} + 1\right)^{k_3} \\
k_1 = 10^{\left(0.132 - 0.016 FE\_Ratio - 0.055 ST - 0.026 \omega_{opt} - 0.628 \frac{\omega}{\omega_{opt}} + 0.0004 \frac{\gamma_{max}^2}{P_{40}} + 1.197 \epsilon\right)} \\
\left(R^2 = 0.5523;\ Adj.\ R^2 = 0.5313;\ p < 0.0001;\ MSE = 0.0178\right) \\
k_2 = 1.573 + 0.007 \gamma_d - 0.0009 \dfrac{\gamma_{max}^2}{P_{40}} - 0.013 P_{10} - 0.046 P_{200} \\
\left(R^2 = 0.5062;\ Adj.\ R^2 = 0.4910;\ p < 0.0001;\ MSE = 0.0143\right) \\
k_3 = -15.914 + 0.041 FE\_Ratio + 0.004 AI + 0.015 \gamma_d + 0.488 \dfrac{\omega}{\omega_{opt}} - 0.0008 \dfrac{\gamma_{max}^2}{P_{40}} \\
\quad + 0.246 \dfrac{P_{200}}{\log C_u} + 0.145 P_{2''} - 0.057 P_{1''} \\
\left(R^2 = 0.6633;\ Adj.\ R^2 = 0.6419;\ p < 0.0001;\ MSE = 0.0328\right)
\end{cases}
\quad \text{(Eq. 2)}
$$

Improved Correlations with Imaging based Aggregate Shape Properties

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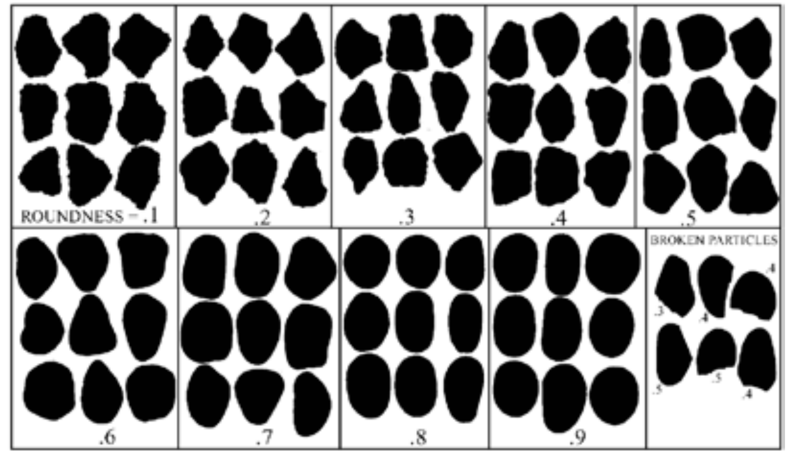
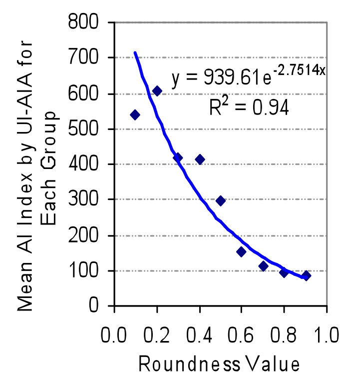
Aggregate Shape Indices Needed for Predicting Base/Subbase M_R Behavior

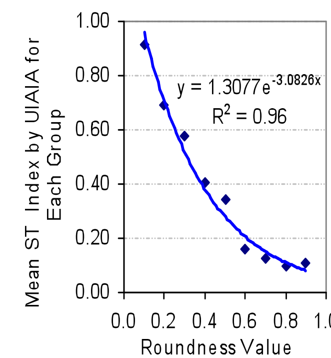
Approaches

1. *Guidelines can be developed using current data for entering some visual shape categories and linking them to the imaging based quantifiable shape index variables (FE_Ratio, AI, & ST)*

2. *Determination of aggregate shape indices from field high-resolution images using **fragmentation/segmentation technique** can be implemented*







Pan & Tutumluer, 2006

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MnPAVE Pavement Designs for Performance

ü *Established a comprehensive matrix of **design moduli** for various aggregate types and properties used for typical flexible pavement sections throughout Minnesota*

ü *Identified **sensitivity of the design inputs** (mainly design moduli) to pavement life expectancies*

MnPAVE Mechanistic-Empirical Pavement Design Method

MnPAVE Mechanistic Design Objectives

- *Instead of using unbound aggregates of higher quality, exploit the potential of cost-effectively maintaining satisfactory pavement performance with* ***the use of readily available marginal materials***

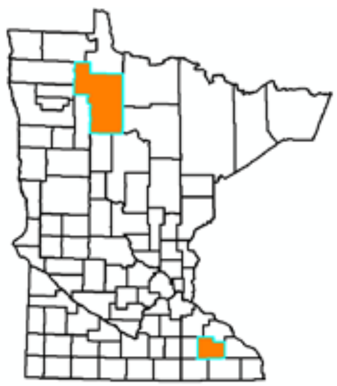
- *Investigate* ***where in pavements to place*** *locally available materials of marginal quality*

- *Determine* ***the optimum combination of high and marginal quality aggregate uses with design features and site factors taken into account***

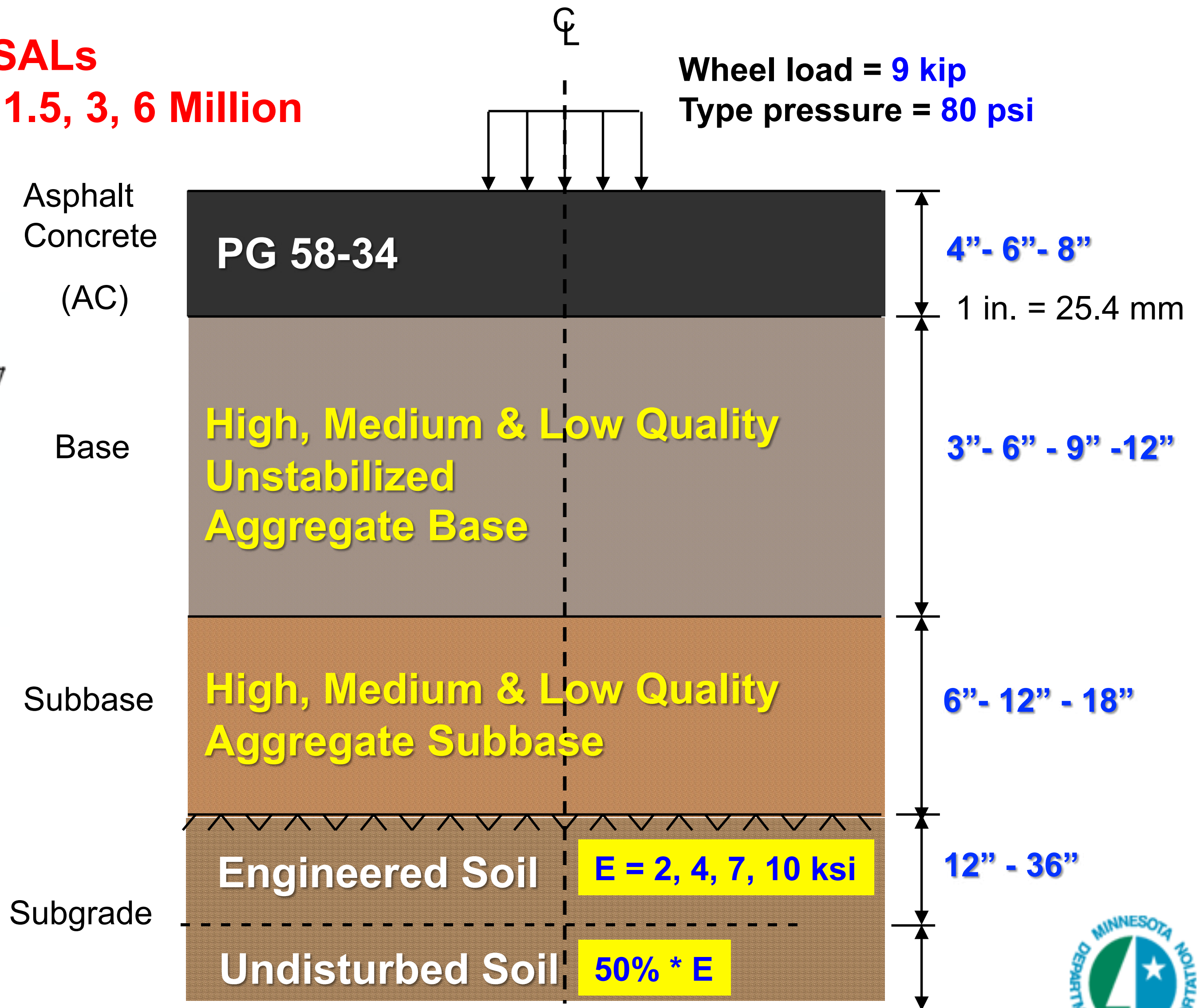
MnPAVE Sensitivity Analysis Matrix

20-year ESALs
= 0.2, 0.6, 1.5, 3, 6 Million

Climate

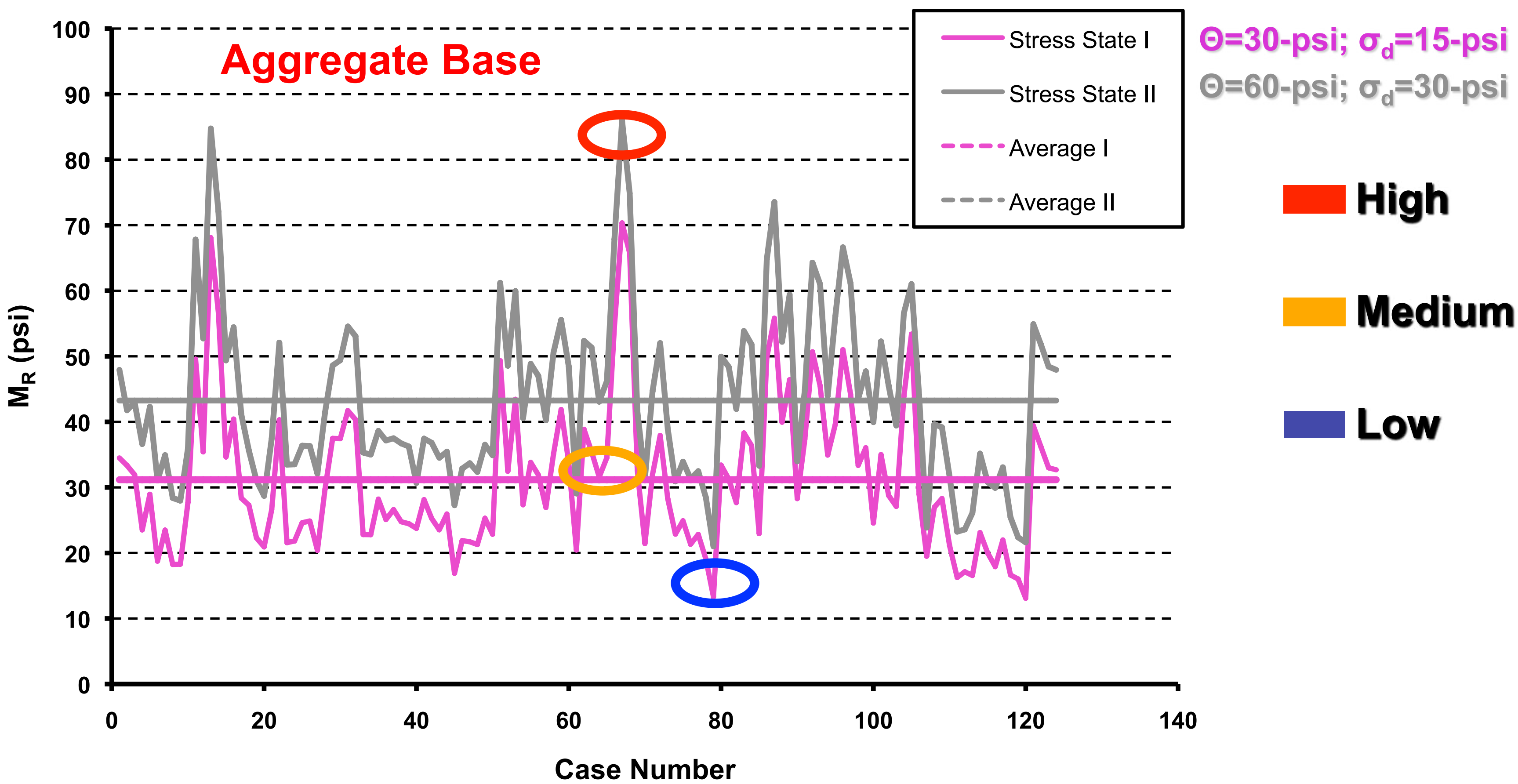


Beltrami
&
Olmsted



2592 Pavement Sections; 51,840 MnPAVE Analyses

Representative Moduli for Base Layer



(MEPDG Model)

Quality Level	K_1	K_2	K_3
Low	0.6201	1.0224	-0.8945
Intermediate	1.8169	0.9243	-0.9592
High	4.7156	1.0418	-1.8549

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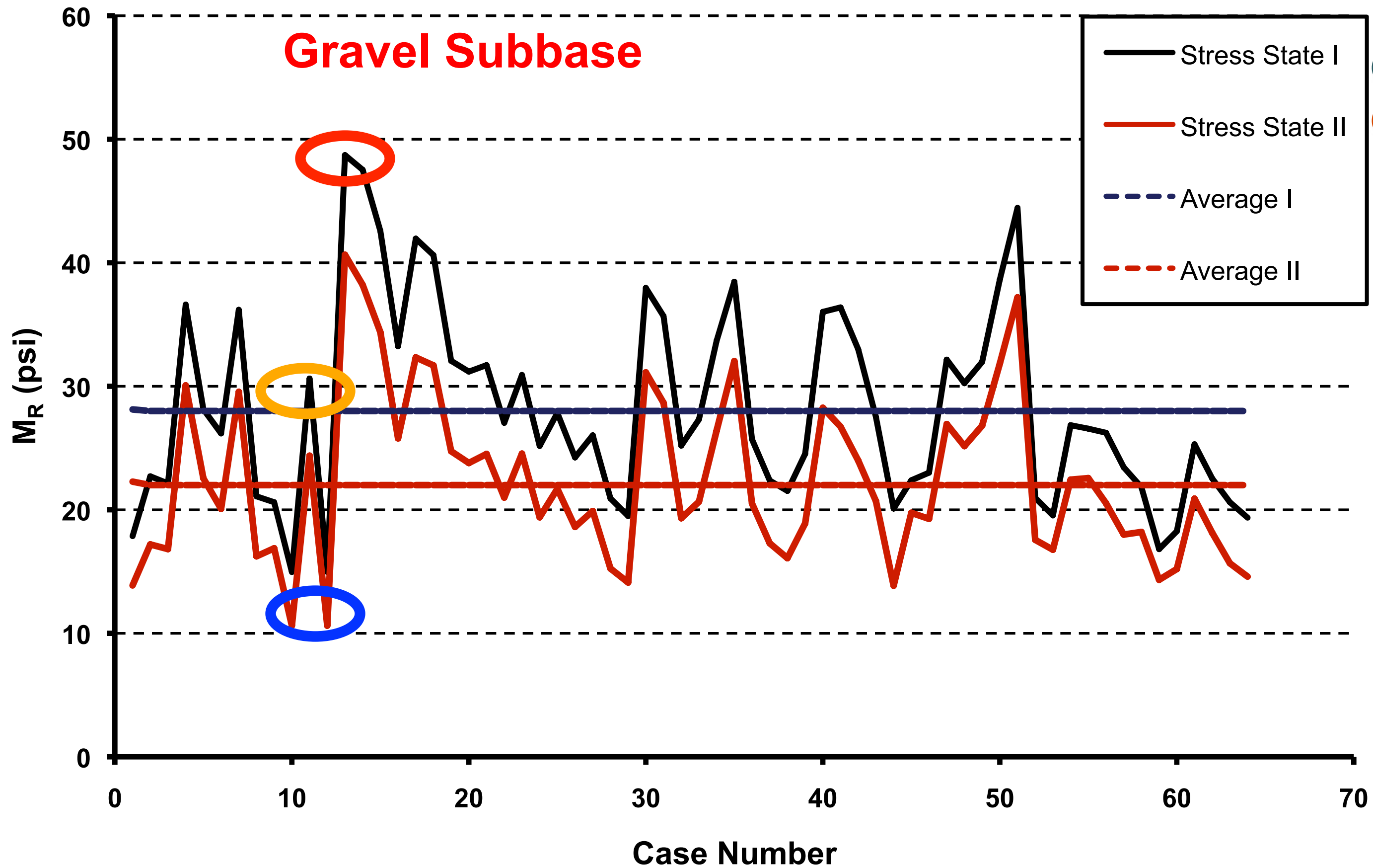
Representative Moduli for Subbase Layer



Θ=25-psi; σ_d=10-psi

Θ=15.5-psi; σ_d=5-psi

High

Medium

Low

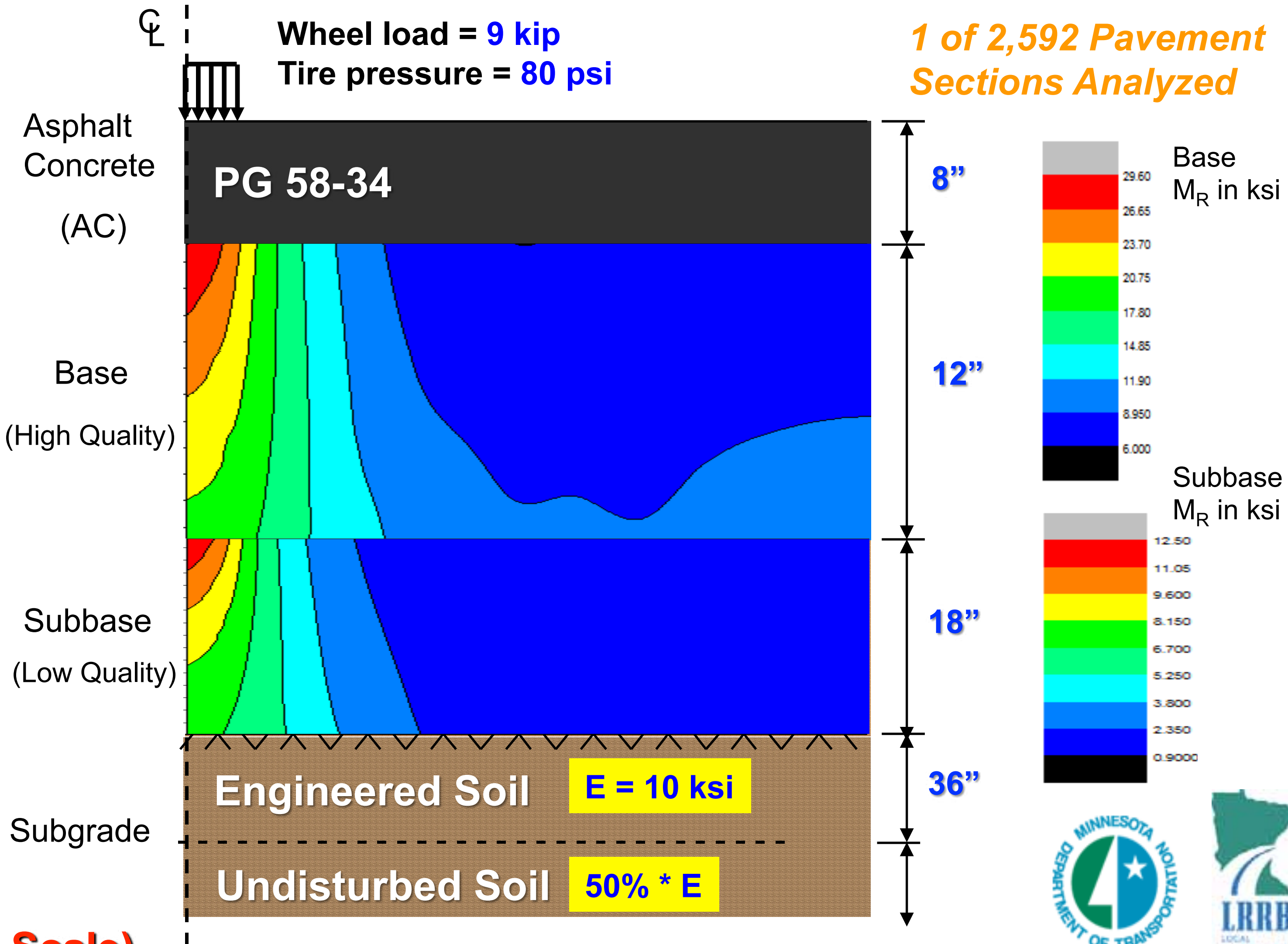
(MEPDG Model)

Quality Level	K_1	K_2	K_3
Low	0.7235	0.7947	-0.2890
Intermediate	1.6209	0.6238	-0.5932
High	3.1953	0.7107	-1.2255

Typical Nonlinear M_R Distributions Predicted In Base/Subbase Layers

GT-PAVE Finite Element Analyses

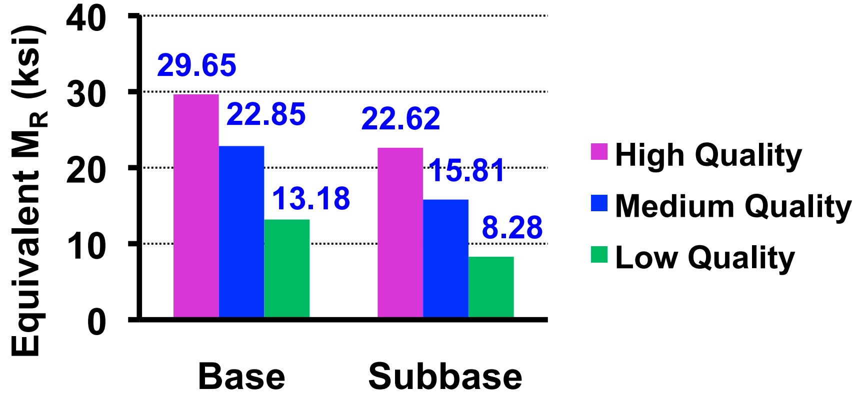
1 of 2,592 Pavement Sections Analyzed



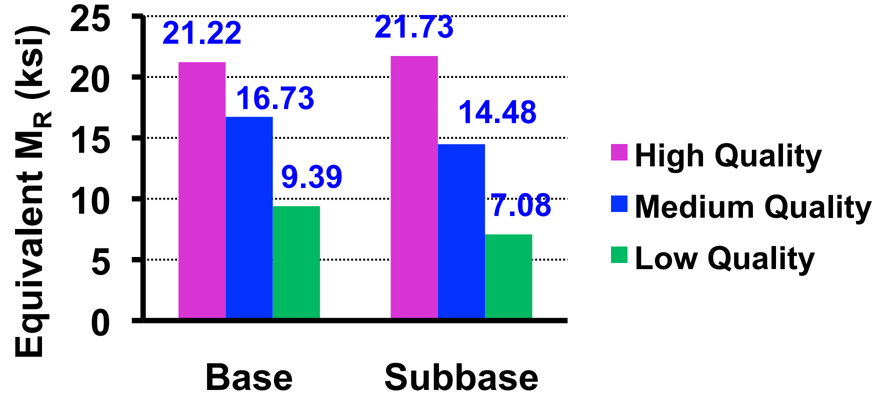
(NOT to Scale)

Equivalent Avg M_R Values Linked to Quality

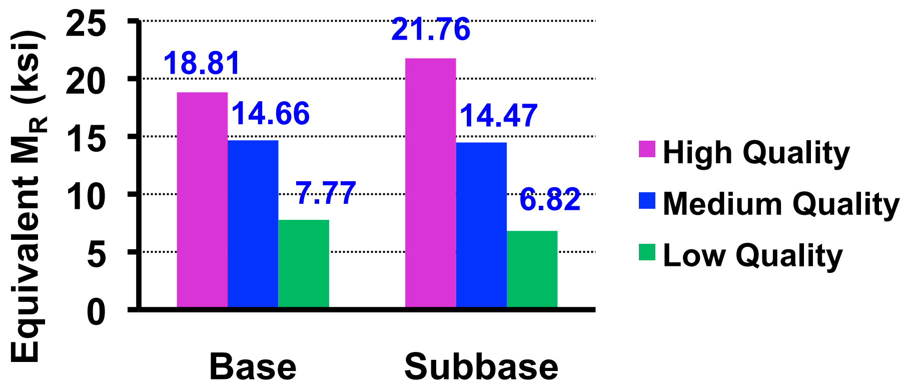
4-in. AC

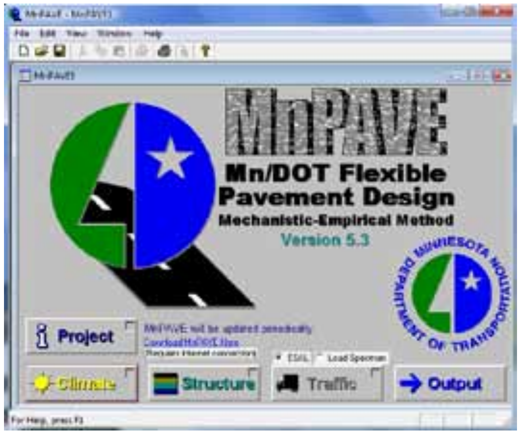


6-in. AC



8-in. AC



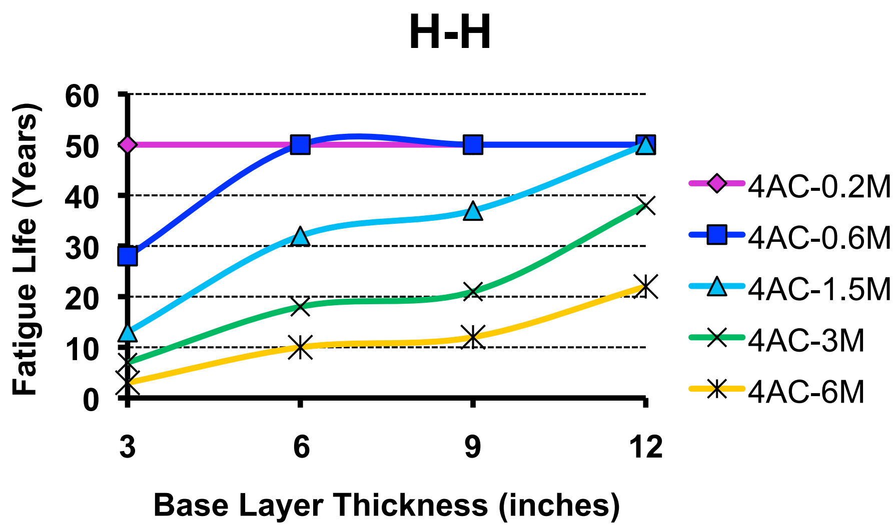


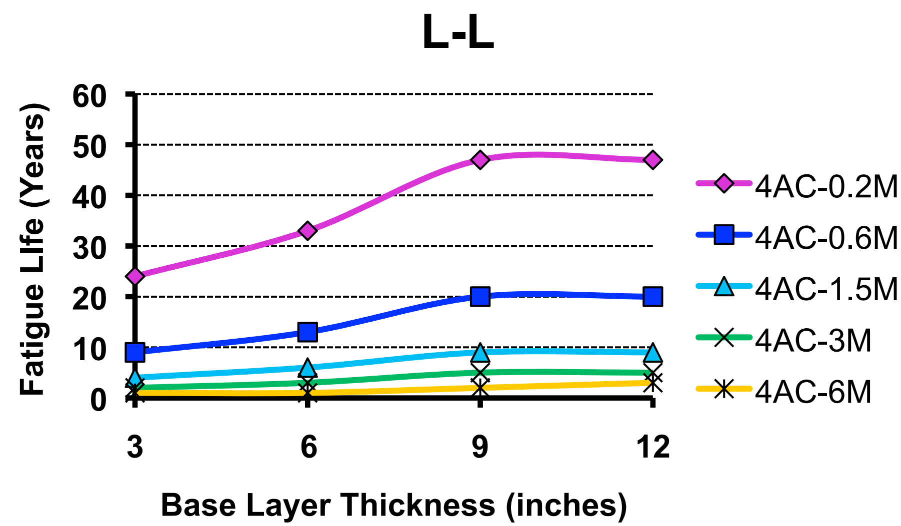
Note that in some cases, the granular subbase materials had higher moduli than the aggregate base materials

Pavement Performance:

(Full-season Fatigue Life)

Beltrami



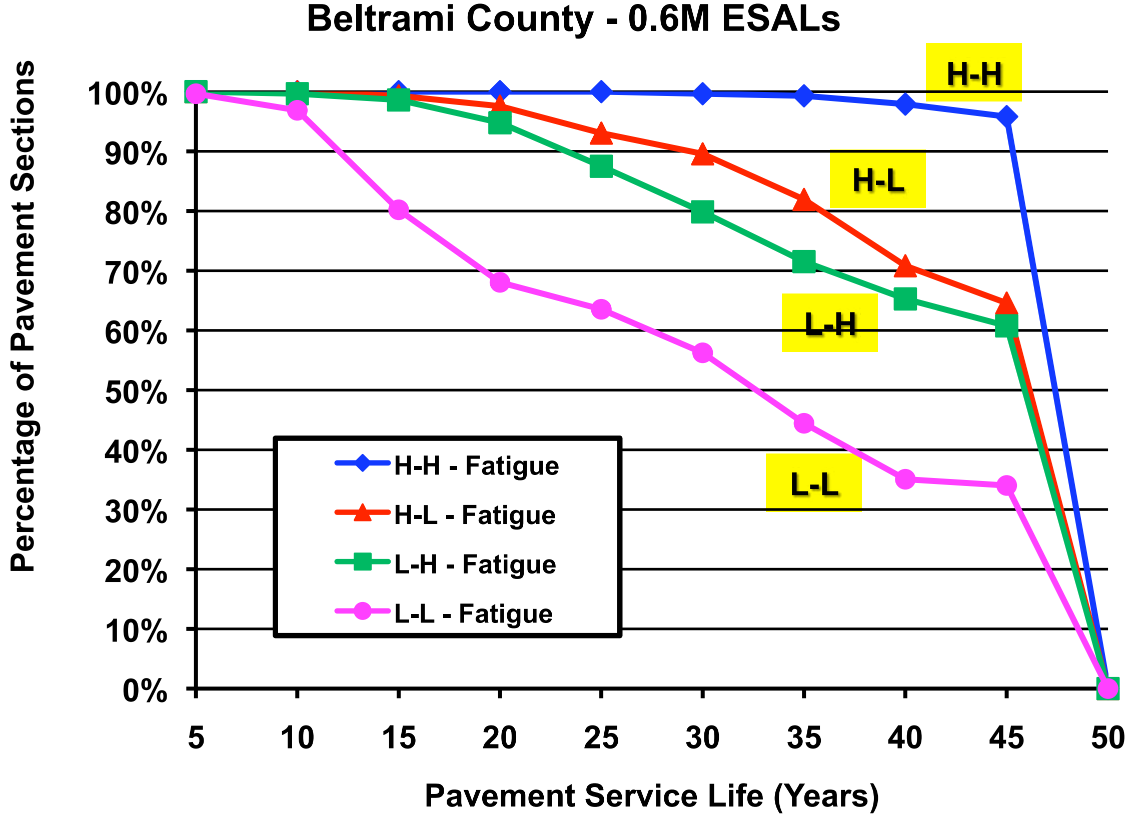


1) **For the same thicknesses, pavements with high quality base/subbase materials can last for many more ESALs (horizontal line)**
2) **With low quality base materials, increasing base layer thickness does not seem to help much (not enough support under AC)**

For low-volume roads, using locally available materials may be more cost-effective

H-H: high M_R levels for both base and subbase
L-L: low M_R levels for both base and subbase

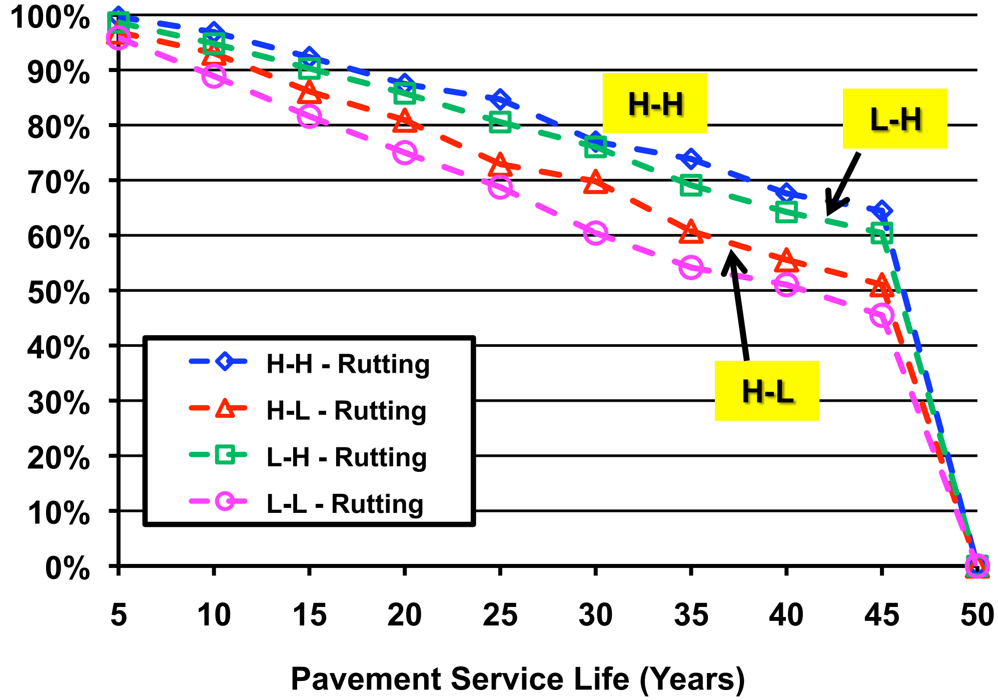
Effect of Aggregate Quality on Fatigue



- Decreased aggregate base/subbase quality significantly reduces long-term fatigue performance; high and low quality combinations for base and subbase (H-L and L-H) fall in between (solid lines)

Beltrami – 0.6M to 1.5 M ESALs

Effect of Aggregate Quality on Rutting



- If high quality subbase materials are used, the quality of base materials seems to have trivial effect on rutting performance
- For low-volume roads, locally available materials may be used in base layer while better quality materials are used for subbase to tradeoff the rutting and fatigue performances – Inverted Pavements ???

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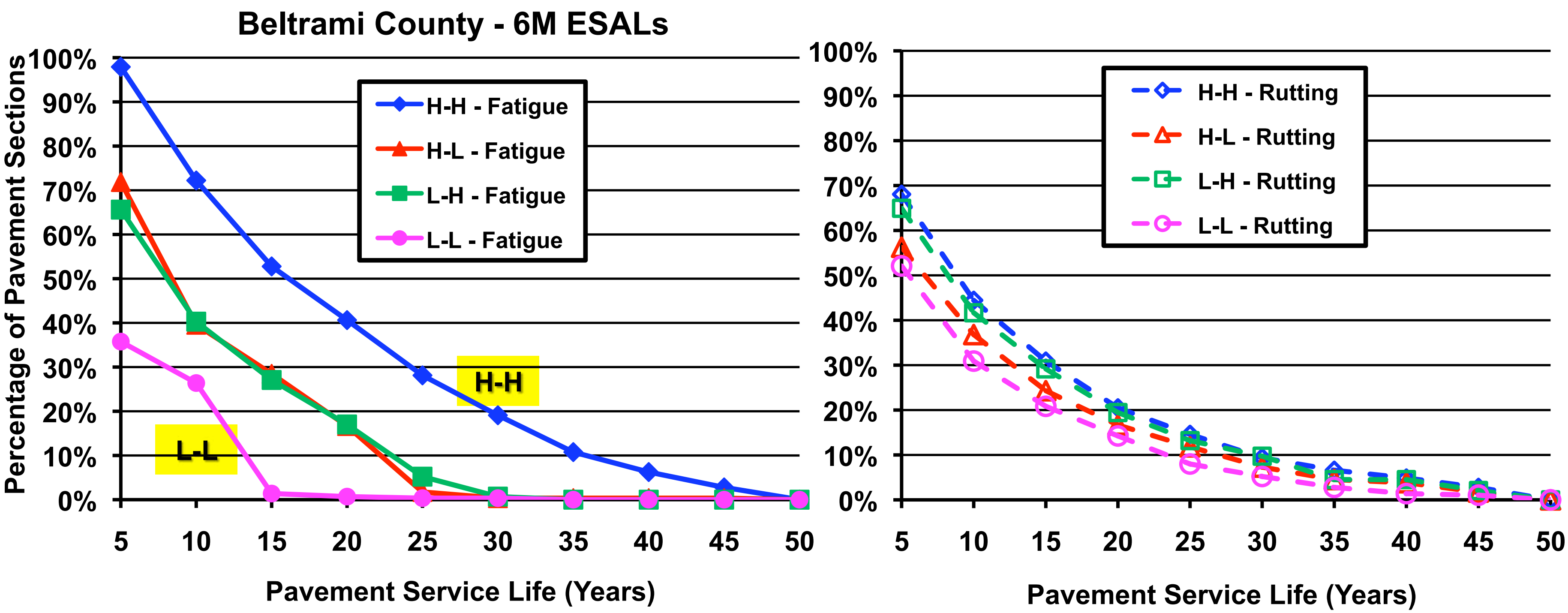
Beltrami – 0.6M to 1.5 M ESALs

Effect of Aggregate Quality – High Traffic



- For high traffic volume – 6M ESALs, rutting performance seems to be insensitive to unbound aggregate material quality (dotted lines) due to thicker HMA; but fatigue performance is very sensitive (solid lines)

Beltrami – 6 Million ESALs

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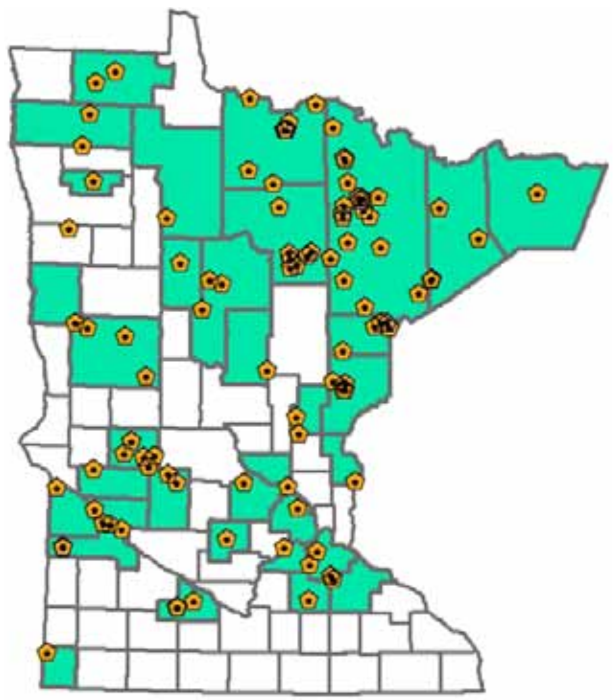
Validation of MnPAVE Findings for Strength

Collect additional **aggregate strength data** from the available M_R tests and other existing Mn/DOT laboratory and field (*MnROAD*) studies to evaluate established trends in the M_R database. This is an essential task for:

- **Verifying and accurately interpreting the sensitivity analysis results (primarily assumed different M_R modulus levels could be linked to high, medium, and low material quality standards, in relation to strength properties)**
- **Ensuring performance through the established M_R-strength relationships for different Mn/DOT aggregate classes from field FWD-backcalculation and strength data**

Best Value Granular Material Selection

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



Aggregate Material Resource Map

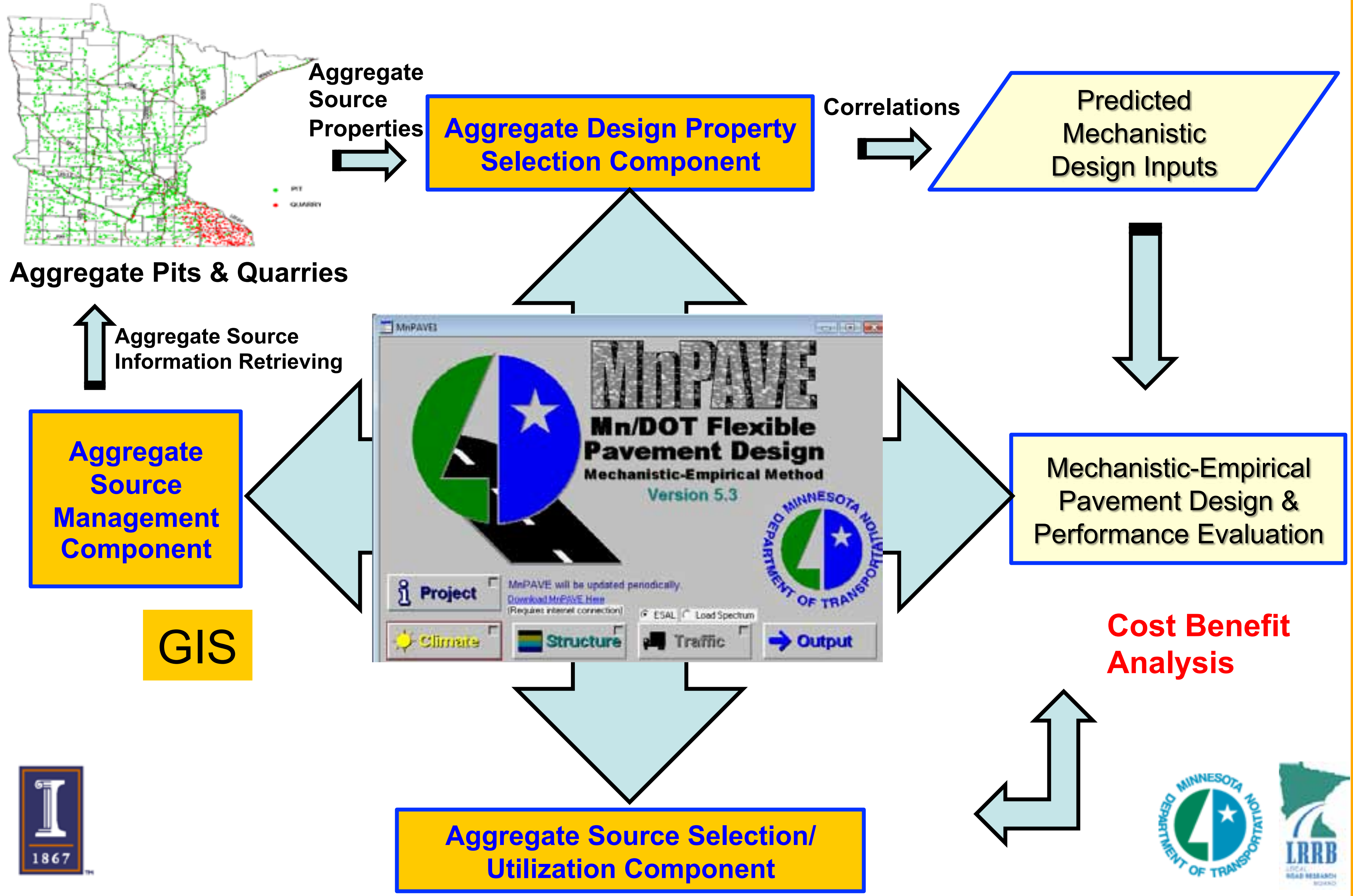
- source
- type
- quality

Implementation of Best Value Granular Material Tool Components into MnPAVE

This is an essential task for implementing research findings and coding developed modules/components into MnPAVE

- ***GIS-based Aggregate Source Management Component*** **provides candidate aggregate source locations & properties**
- ***Aggregate Property Selection Component for Design*** **determines modulus and strength input properties for mechanistic pavement analysis and design concepts**
- ***Aggregate Source Selection/Utilization Component*** **evaluates/optimizes aggregate cost and performance benefit and used in decision making for design**
- **Prepare Example Pavements & Case Studies**

Flowchart for Designing Components



Expected Benefits

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

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

(iv) 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*


Thank you!..