Granular Material Selection for Best Value Pavement Performance

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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

Aggregate Base
- Class 5
- Class 6
- Class 7
Mn/DOT Research Background

- 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")

- 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.

- 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.
Research Project 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
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**

**Database Spreadsheets**

ASIS Online Web Interface
• 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 Pins

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DBMS Functions:
- Search
- Store
- Retrieve
- Display

GIS based Aggregate Index Property Database
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

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

\[
k_1 = 10
\]

\[
k_2 = 1.60611 - 0.01197\theta + 0.00569P_a - 0.0001512\frac{\gamma_{\max}}{P_{40}} - 0.00387\gamma_u - 0.4269\gamma_c - 0.0110\gamma_{3/4}''
\] (Eq. 1)

\[
k_3 = -9.86685 + 0.00065186\frac{\gamma_{\max}}{P_{40}} + 0.007\gamma_u + 0.067\gamma_c + 0.015\gamma_{3/4}'' + 0.00894P_{40}
\]

(R² = 0.3940; Adj. R² = 0.3858; p<0.0001; MSE=0.1740)

(R² = 0.3177; Adj. R² = 0.3066; p<0.0001; MSE=0.0252)

(R² = 0.1399; Adj. R² = 0.1307; p<0.0001; MSE=0.0246)

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

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<th>Average Values</th>
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Regression Models Developed for Predicting Modulus from Aggregate Source Properties

\[
M_R = k_1P_a\left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct} + 1}{P_a}\right)^{k_3}
\]

\[
k_1 = 10
\]

\[
k_2 = 1.573 + 0.007\tau_{d} - 0.0009\frac{\sigma_{\max}^2}{P_{40}} - 0.013P_{10} - 0.046P_{200}
\]

\[
k_3 = -15.914 + 0.041FE\_Ratio + 0.004A_1 - 0.015\tau_{d} + 0.488\frac{\omega}{\omega_{opt}} - 0.0009\frac{\sigma_{\max}^2}{P_{40}} + 0.246\frac{P_{200}}{\log C_{u}} + 0.145P_{200} - 0.05P_{10}
\]

\[
(R^2 = 0.5523; \text{ Adj. } R^2 = 0.5313; p < 0.0001; \text{ MSE } = 0.0178)
\]

\[
(R^2 = 0.5062; \text{ Adj. } R^2 = 0.4910; p < 0.0001; \text{ MSE } = 0.0174)
\]

\[
(R^2 = 0.6633; \text{ Adj. } R^2 = 0.6419; p < 0.0001; \text{ MSE } = 0.8328)
\]

Improved Correlations with Imaging based Aggregate Shape Properties
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, Al, & ST)**

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

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

- 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

Wheel load = 9 kip
Type pressure = 80 psi

Asphalt
Concrete
(AC)

High, Medium & Low Quality
Unstabilized
Aggregate Base

Beltrami &
Olmsted

Base

Traffic

High, Medium & Low Quality
Aggregate Subbase

Subbase

Engineered Soil
E = 2, 4, 7, 10 ksi

Subgrade

Undisturbed Soil
50% * E

12” - 36”

2592 Pavement Sections; 51,840 MnPAVE Analyses

1 in. = 25.4 mm
Representative Moduli for Base Layer

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

(MEPDG Model)
Representative Moduli for Subbase Layer

Gravel Subbase

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<th>Quality Level</th>
<th>K₁</th>
<th>K₂</th>
<th>K₃</th>
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<tr>
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(MEPDG Model)
Typical Nonlinear $M_R$ Distributions Predicted in Base/Subbase Layers

Wheel load = 9 kip
Tire pressure = 80 psi

GT-PAVE Finite Element Analyses

1 of 2,592 Pavement Sections Analyzed

Base $M_R$ in ksi

Subbase $M_R$ in ksi

Asphalt Concrete (AC)
Base (High Quality)
Subbase (Low Quality)
Engineered Soil
Undisturbed Soil

E = 10 ksi
50% * E

NOT to Scale
Equivalent Avg $M_R$ Values Linked to Quality

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

(Full-season Fatigue Life)

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 County - 0.6M ESALs

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 ???

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

Aggregate Source Properties

Aggregate Design Property Selection Component

Predicted Mechanistic Design Inputs

Correlations

Aggregate Source Selection/Utilization Component

Mechanistic-Empirical Pavement Design & Performance Evaluation

Cost Benefit Analysis

GIS

Aggregate Source Management Component

Aggregate Source Information Retrieving

Aggregate Pits & Quarries
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!..