Imaging Based Size, Gradation & Shape Characterizations of Aggregate Particles

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Aggregates make up more than 85% of Portland cement concrete and 90% of asphalt pavements.

Coarse aggregate constitute the skeleton and occupies by far the highest weight or volume.
Shape Properties of An Aggregate Particle

Key Physical Shape Properties of an aggregate particle

- Volume
- Surface Area

Roughness or irregularity at a micro level in contrast with angularity at a macro level
Introduction

✓ Aggregate shape factors, such as **flatness and elongation**, **angularity**, **surface texture** and **surface area** influence pavement behavior and performance.

✓ Aggregate shape has been related to **permanent deformation and fatigue/cracking resistance** of the pavement.

✓ Based on current knowledge & past experience:
  ✓ Equi-dimensional preferred over Flat & Elongated (F&E)
  ✓ Crushed (angular) preferred over rounded
  ✓ Rougher surface textured preferred over smooth
  ✓ Larger specific surface area preferred for better bonding/binding with Portland cement/asphalt cement
Means of Assessing Aggregate Shape Properties

Visual Inspection Based Assessment
– (Angularity) Krumbein (1941)
## Conventional Methods of Assessing Aggregate Shape Properties

<table>
<thead>
<tr>
<th>Shape Property</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat and Elongated Ratio (checks</td>
<td>Proportional calipers</td>
</tr>
<tr>
<td>for undesirable shapes and sizes)</td>
<td>ASTM D 4791</td>
</tr>
<tr>
<td>Angularity (provides for strong,</td>
<td>Coarse: Visual inspection of fractured faces ASTM D 5821</td>
</tr>
<tr>
<td>stable aggregates)</td>
<td></td>
</tr>
<tr>
<td>Texture (provides for strong, stable</td>
<td>Particle Index Test</td>
</tr>
<tr>
<td>aggregates)</td>
<td>ASTM C 3398</td>
</tr>
<tr>
<td></td>
<td>Uncompacted Air Voids Test</td>
</tr>
<tr>
<td></td>
<td>ASTM C 1252-98, AASHTO TP56</td>
</tr>
</tbody>
</table>
Notes on Current Tests for Aggregate Shape Properties

• Some of the tests are time consuming (flat & elongated coarse aggregate test)

• No test for texture; combined with shape and angularity (particle index & uncompacted void tests)

• Current tests provide an average value and not a distribution of shape properties!

• There are contradictory findings in the literature on the influence of shape on performance
University of Illinois Aggregate Image Analyzer - UIAIA

- Developed with funding from FHWA & Illinois DOT
- Used in various State and Federal pooled fund studies [TPF-5(023)] for evaluating coarse aggregate & linking aggregate shape to pavement performance
- In 2005, selected by the NCHRP 4-30 (Test Methods for Characterizing Aggregate Shape, Texture, & Angularity) study as one of the 2 promising aggregate image analysis systems
- The only system to use 3 orthogonally positioned cameras to capture 3-D shape properties
• Conveyor speed of 3 in./second
• Particles placed 10 in. apart
• Images captured within 0.1 second in succession
Conveyor speed of 3 in./second
Fiber Optic Motion Sensor
Progressive Scan Video Cameras

Imaging Device in the TPF-5(023) Pool Fund Project
UIAIA Virtual Instruments (VI):

- **Image Acquisition**
- **Aggregate Size**
  - 1-D: Max., Min. & Inter. Dimen.
  - 3-D: Volume & Surface Area
- **Aggregate Morphology**
  - F & E Ratio
  - Aggregate Angularity
  - Surface Texture

Software Module — **UIAIA VIs**

National Instruments
- Labview
- IMAQ Vision
University of Illinois Aggregate Image Analyzer – Image Acquisition

- Capture three orthogonal views of a particle
  - Top
  - Front
  - Side
4-pixel image → Convert to Array

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>255</td>
<td>255</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>255</td>
<td>255</td>
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<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Maximum dimension - longest size of the particle from all three views

Minimum dimension - Smaller of the two perpendicular intercepts of the particle in the direction perpendicular to the maximum dimension

(for Flat and Elongated Ratio)

Intermediate dimension controls Gradation compared to that by Mechanical Sieve Analysis
Imaging Based Flat & Elongated – (F&E) Ratio

F&E Ratio = Longest dimension / Shortest dimension

Plane of **Longest** and **Shortest** Dimensions

All 3 views are analyzed for the longest and shortest dimensions
<table>
<thead>
<tr>
<th>Test Method</th>
<th>F &amp; E Ratio Category</th>
<th>&lt; 3:1</th>
<th>&gt; 3:1 &amp; &lt; 5:1</th>
<th>&gt; 5:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual UI</td>
<td></td>
<td>56.7</td>
<td>39.0</td>
<td>4.3</td>
</tr>
<tr>
<td>Manual IDOT</td>
<td></td>
<td>61.5</td>
<td>36.1</td>
<td>2.5</td>
</tr>
<tr>
<td>WipShape</td>
<td></td>
<td>66.5</td>
<td>31.4</td>
<td>2.1</td>
</tr>
<tr>
<td>GA Tech</td>
<td></td>
<td>72.2</td>
<td>27.5</td>
<td>0.3</td>
</tr>
<tr>
<td>UIAIA trial 1</td>
<td></td>
<td>63.4</td>
<td>34.2</td>
<td>2.4</td>
</tr>
<tr>
<td>UIAIA trial 2</td>
<td></td>
<td>62.2</td>
<td>34.9</td>
<td>2.9</td>
</tr>
<tr>
<td>UIAIA trial 3</td>
<td></td>
<td>62.1</td>
<td>35.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>
UIAIA Imaging Based Particle Size Distribution — an Example

Based on the Intermediate Dimension defined in UIAIA

High Repeatability and Accuracy
Three Dimensional Aggregate Size
– Volume Computation

A particle consists of volume element: voxels

Principle:

Each voxel has three projections: pixels, following the coordinates correspondence as shown.

The 3 pixels have intensity of 255, compared with 0 for that of the background.

If its three pixels all have intensity of 255, voxel is judged as belonging to the particle.
Weights of 50 Random Particles of Different Types
– Volume Validation

Total wt. = 194.3 g
Predicted total wt. = 196.4 g

Average absolute error = 1.08%

F&E ratio is obtained based on % by weight

Specific gravity is all that is needed to compute weights
Three Dimensional Aggregate Size
– Surface Area Computation: Principle

**Principle:** with consideration of aggregate shape curvature, summation of the 2-D $\Delta S_i$ elements contained in voxels forming the particle surface gives the surface area of the particle.

*How to Locate the Surface Voxels? and How to Determine Magnitude of 2-D $\Delta S_i$?*
In the smallest box that contains the particle, searching for the voxels:

1) Belonging to agg. particle
   - Intensity of three projection pixels
2) On particle surface
   - Six surrounding voxels
   - Voxel intensity = 255, or 0?
Voxels at different locations on particle surface contain 2-D $\Delta S_i$ elements of different magnitudes.

## Surface Area Computation: 2-D $\Delta S_i$ on particle surface

<table>
<thead>
<tr>
<th>Central Voxel Faces on Particle Surface</th>
<th>Number of Cases</th>
<th>Designated $2D S_i$</th>
<th>Magnitude</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1 Pixel Area</td>
<td>Horizontal or vertical planar surface</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>$\sqrt{2}$ Pixel Area</td>
<td>Slope planar surface</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2 Pixel Area</td>
<td>Texture level: thin chip</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>$\sqrt{5}$ Pixel Area</td>
<td>Texture level: thin chip at edges</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>$\sqrt{6}$ Pixel Area</td>
<td>Curved surfaces</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>$\pi$ Pixel Area</td>
<td>Texture level: Connecting rods</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>4 Pixel Area</td>
<td>Texture level: thin chip next to tips</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>5 Pixel Area</td>
<td>Texture level: Stick-out tips</td>
<td></td>
</tr>
</tbody>
</table>
Three Dimensional Aggregate Size (cont’d)
– Surface Area Validation: *Real Aggregate Particles*

3-D Laser Scanner used in calculating surface area magnitudes of 11 aggregate particles of different types.

3-D Laser Scanner: 1 particle/90 minutes;
UIAIA: 1000 particle/70 minutes

Roland LPX-1200

Surface area results from 3-D Laser Scanner compared to those computed by UIAIA.
Three Dimensional Aggregate Size (cont’d)
– Surface Area Validation: Real Aggregate Particles

<table>
<thead>
<tr>
<th>Particles</th>
<th>Area (mm²)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UIAIA</td>
<td>LPX-1200</td>
</tr>
<tr>
<td>1-in. diameter sphere</td>
<td>2015</td>
<td>2026.83</td>
</tr>
<tr>
<td>0.5-in. diameter sphere</td>
<td>498.454</td>
<td>506.707</td>
</tr>
<tr>
<td>large gravel</td>
<td>992.285</td>
<td>1029.03</td>
</tr>
<tr>
<td>small gravel</td>
<td>419.428</td>
<td>440.35</td>
</tr>
<tr>
<td>crushed limestone</td>
<td>878.773</td>
<td>915.33</td>
</tr>
<tr>
<td>crushed granite</td>
<td>635.168</td>
<td>648.54</td>
</tr>
<tr>
<td>2-face crush gravel</td>
<td>526.051</td>
<td>525.91</td>
</tr>
<tr>
<td>1-face crush gravel</td>
<td>566.645</td>
<td>569.35</td>
</tr>
<tr>
<td>long gravel</td>
<td>654.016</td>
<td>625.15</td>
</tr>
<tr>
<td>flat gravel</td>
<td>370.296</td>
<td>357.081</td>
</tr>
<tr>
<td>cubical gravel</td>
<td>612.539</td>
<td>582.084</td>
</tr>
</tbody>
</table>

**Overall Error Rate: 2.79%**

$R^2 = 0.99$: high correlation with the LPX-1200 3D scanner results
Imaging Based Angularity Index (AI)

- Extract coordinates of the outline
- Approximate the particle to a n-sided polygon
- Compute angle at vertices, $\alpha_1, \alpha_2, \ldots, \alpha_n$
- Determine change in angle at each vertex, $\beta_1, \beta_2, \ldots, \beta_n$
- Obtain frequency distribution of $\beta_1, \beta_2, \ldots, \beta_n$

$n = \text{no. of sampling points} = 24$

Angle at Vertex ‘1’ = $\alpha_1$ ......

Angle at Vertex ‘n’ = $\alpha_n$

$\alpha_1 - \alpha_2 = \beta_1$

$\alpha_1 - \alpha_2 = \beta_2$

..............

$\alpha_n - \alpha_1 = \beta_n$
Imaging Based Angularity Index (AI)

For,

\[ e = 0, 10, 20, 30, ..., 170 \text{ for Class Interval } 0-10, 10-20, 20-30, ..., 170-180 \]

Angularity, \( A = \sum_{e=0}^{170} e \cdot P(e) / n \)

Theoretically, \( A = 0 \) for a circle

Angularity Index = \( AI = \frac{A_1 \cdot \text{Area}1 + A_2 \cdot \text{Area}2 + A_3 \cdot \text{Area}3}{(\text{Area}1 + \text{Area}2 + \text{Area}3)} \)

Frequency Distribution of \( \beta \)-values

Class Interval

<table>
<thead>
<tr>
<th>Class Interval</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td></td>
</tr>
<tr>
<td>10-20</td>
<td></td>
</tr>
<tr>
<td>170-180</td>
<td></td>
</tr>
</tbody>
</table>
AI for Gravel, Crushed Stone, & Blend

Percentage particles by weight

AI with \( n=24 \)
Image Processing Technique: Erosion and Dilation

- Erosion cycles followed by the same number of dilation cycles change the original image
- The rougher the particle, the less close the rebuilt image is to the original
\[ ST = \frac{A_1 - A_2}{A_1} \times 100 \]

\[ ST_{\text{particle}} = \frac{\text{Area}_{\text{front}} \times ST_{\text{front}} + \text{Area}_{\text{top}} \times ST_{\text{top}} + \text{Area}_{\text{side}} \times ST_{\text{side}}}{\text{Area}_{\text{front}} + \text{Area}_{\text{top}} + \text{Area}_{\text{side}}} \]

\( A_1 = \) Area (in pixels) of the 2-D projection of the particle in the image
\( A_2 = \) Area (in pixels) of the particle after performing a sequence of \( \text{“} n \text{”} \) cycles of erosion followed by \( \text{“} n \text{”} \) cycles of dilation
Samples Used In ST Index Development & Calibration

Rough Crushed Stone

Smooth Gravel

Limestone
ST for Gravel vs Limestone

Average ST for Gravel = 0.47
Average ST for Limestone = 1.57
## Typical Ranges of Angularity and Surface Texture Indices

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Angularity Index (AI)</th>
<th>Surface Texture (ST) Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>Uncrushed Gravel</td>
<td>250-350</td>
<td>300</td>
</tr>
<tr>
<td>Crushed Gravel</td>
<td>300-450</td>
<td>400</td>
</tr>
<tr>
<td>Crushed Limestone</td>
<td>400-550</td>
<td>475</td>
</tr>
<tr>
<td>Crushed Granite</td>
<td>500-650</td>
<td>550</td>
</tr>
</tbody>
</table>
Performances of Aggregate Materials in Pavement Structural Layers

Unbound Aggregate Base Resilient Response

\[ y = 152281e^{0.001x} \]
\[ R^2 = 0.86 \]

\[ y = 166430e^{0.1848x} \]
\[ R^2 = 0.91 \]
Performances of Aggregate Materials in Pavement Structural Layers

Aggregate Interlock depends on Aggregate Angularity
More Than Surface Texture Property!

\[ M_R = k_1 p_a \left( \frac{\theta}{p_a} \right)^{k_2} \left( \frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \]
Performances of Aggregate Materials in Pavement Structural Layers

\[ y = 0.4291 \ln(x) - 2.5797 \]
\[ R^2 = 0.44 \]

\[ y = 0.4029 \ln(x) - 2.7092 \]
\[ R^2 = 0.96 \]

\[ y = 0.2479 \ln(x) - 1.7112 \]
\[ R^2 = 0.99 \]

Surface Texture Property Contribute to Mitigating Dilation More Than Aggregate Angularity does!
Performances of Aggregate Materials in Pavement Structural Layers

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean AI</th>
<th>Shear Properties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed Stone</td>
<td>436</td>
<td>Φ (deg)</td>
<td>46.2</td>
<td>C (psi)</td>
</tr>
<tr>
<td>Gravel</td>
<td>322</td>
<td>Φ (deg)</td>
<td>40.7</td>
<td></td>
</tr>
<tr>
<td>Blend</td>
<td>200</td>
<td>Φ (deg)</td>
<td>41.4</td>
<td></td>
</tr>
</tbody>
</table>

*Rutting* is an aggregate performance indicator controlled by shear strength

![Graph showing Angularity Index vs. Rutting resistance for different materials: Crushed Stone, 50-50 Blend, Gravel.](image)
Performances of Aggregate Materials in Pavement Structural Layers

Resilient Response of Asphalt Mix Specimens

- Gradation TRZ
- Gradation BRZ
- Fit (Gradation TRZ)
- Fit (Gradation BRZ)

Compiled by "I 1867"

Composites AI

- Resilient Modulus (MPa)
- Composite AI

Composites ST Index

- Resilient Modulus (MPa)
- Composite ST Index

Equations:
- $y = 628.95e^{0.0027x}$
  \[ R^2 = 0.0141 \]
- $y = 213.32e^{0.0052x}$
  \[ R^2 = 0.7408 \]
- $y = 3589.1e^{-0.3441x}$
  \[ R^2 = 0.0234 \]
- $y = 910.84e^{0.5731x}$
  \[ R^2 = 0.6009 \]
Performances of Aggregate Materials in Pavement Structural Layers

Permanent Deformation of Asphalt Mix Specimens

\[ y = 0.0135x - 2.7465 \]
\[ R^2 = 0.7318 \]

\[ y = 1.6874x + 0.6257 \]
\[ R^2 = 0.7689 \]
Performances of Aggregate Materials in Pavement Structural Layers

Asphalt Concrete Mix Rutting Performances – NCAT Test Track

- For F & E Ratio Index > 5:1 (percent by weight):
  \[ y = 563.6x + 0.695 \]
  \[ R^2 = 0.75 \]

- For Al Index:
  \[ y = -0.0203x + 10.541 \]
  \[ R^2 = 0.80 \]

- For ST Index:
  \[ y = -3.632x + 6.9924 \]
  \[ R^2 = 0.94 \]
Effect of Hot Mix Type or 3D Aggregate Skeleton?

Dense Graded Mix

Texture very important

SMA Mix or Stone Skeleton Mix

Angularity as important?
Performances of Aggregate Materials in Pavement Structural Layers

Early Age Cracking of Portland Cement Concrete

12-hour Fracture Energy

\[ y = 3E+06x^{-1.3509} \]

\[ R^2 = 0.74 \]
Methodology for 3D Aggregate Imaging Based Discrete Element Modeling (DEM)
3D DEM Aggregate Model

Radius = 0.5 mm
Totally 5837 elements
Reconstruct 3D Digital Aggregate Microstructure

3-D UIAIA or X-ray CT images of aggregates

PFC3D DEM Model

Characterize pavement layers through reconstructing 3D aggregate microstructures and computational simulations based on the 3D microstructure !..
Anticipated Benefits of Combining Imaging and DEM Techniques

- Better understand mechanisms of deterioration by studying through DEM inter-particle slippage, particle rotation, particle separation, fracture at particle contacts, binder cracking, and bond fracture.

- Study effects of 3D aggregate microstructure on sample/pavement layer strength, stiffness, and resistance to permanent deformation.

- Better understand influence of aggregate shape, size, orientation, angularity, gradation on performance of pavement structural layers.
Testing of OMP Aggregates for Shape Properties

O’HARE Airport Modernization Research Project

Project Investigator: Erol Tutumluer
Research Assistant: Tongyan Pan

OBJECTIVES

✓ Quantify shape, texture, angularity, and surface area properties of the coarse aggregates to be used by OMP in the various layers of new runway, taxiway, and shoulder pavements

✓ Provide OMP with an aggregate shape property database to efficiently rank and utilize sources of aggregate stockpiles according to shape properties available to them

✓ Establish a means to develop improved and adaptable Portland cement concrete and asphalt mixture design methods and specifications that can accommodate aggregates with a wide range of physical characteristics and aggregate blending alternatives
Significance of the Project

✓ Provide OMP with
  ✓ improved aggregate selection criteria
  ✓ optimized aggregate resource utilization
  ✓ construction cost reductions

✓ Identification and quantification of the influence of aggregate properties on end-use performance to identify aggregate issues & optimize performance linked to acceptable limits of aggregate

  • shape
  • angularity
  • texture
  • surface area
Concluding Remarks

- Through the use of **imaging based indices**, UIAIA can quantify **shape, texture, angularity, and surface area** properties of the coarse aggregates used in various layers of **road and airfield pavements**.

- UIAIA can be used to establish
  - **aggregate shape property database** to efficiently rank and utilize the sources of aggregate stockpiles according to shape properties available to them.
  - A means to **develop improved and adaptable Portland cement concrete and asphalt mixture design methods and specifications** that can accommodate aggregates with a wide range of physical characteristics and aggregate blending alternatives.
Thank you!