Quantification of Shape, Angularity, and Surface Texture of Base Course Materials

Vincent C. Janoo

January 1998
Abstract: A state-of-the-art review was conducted to determine existing test methods for characterizing the shape, angularity, and surface texture of coarse aggregates. The review found direct methods used by geologists to determine these characteristics. These methods involve physical measurements of individual aggregates and are very laborious and time consuming. Engineers have developed index tests (indirect methods) to quantify the combined effect of the shape, angularity, and surface texture of coarse aggregates in terms of changes in the voids in the aggregate bulk. A description of both the direct and indirect methods is provided in the report. Also, the effect of shape, angularity, and surface texture of coarse aggregates on the base course performance was reviewed. It was found that there is some contradiction in the published data on resilient modulus. Shape, angularity, and surface texture of coarse aggregates clearly influence the angle of internal friction.
PREFACE

This report was prepared by Dr. Vincent C. Janoo, Research Civil Engineer, Civil Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the State of Vermont Agency of Transportation.

Technical review of this report was provided by Christopher Benda, P.E., State of Vermont Agency of Transportation, and by Andrew Dawson, University of Nottingham, United Kingdom. The author especially thanks Lynette Barna, Sherri Orchino, and Tim Baldwin for assistance in finding the reports and papers needed for this review, and also thanks Gioia Cattabriga for editing the report.

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INTRODUCTION

The base course layer is identified as that unbound layer between the surface course (asphalt concrete or portland cement concrete) and the subgrade. This layer is sometimes subdivided into two parts: the upper layer, called the base, and the bottom, the subbase. The base is usually constructed with coarse gravel or crushed stone, and the subbase with either gravel or sand. Several factors affect the performance of these layers. The common factors usually cited are gradation, degree of compaction, amount of fines, moisture content, and permeability. The shape, angularity, and surface texture of the aggregates also have a significant effect on the engineering response of the layer.

Quantification of the shape, angularity, and surface texture of aggregates is difficult but not impossible. There are several methods that involve either direct measurement of the aggregates or indirect inference from aggregate properties. For example, geologists have developed a sophisticated system that involves physical measurements of the aggregates, and engineers have developed visual classification methods for characterization, shape, and angularity or index tests that use some engineering properties, such as porosity, to speculate on the shape, angularity, and surface texture of aggregates. However, none of the index tests developed by engineers make it possible to quantify separately the shape, angularity, or surface texture. Usually these characteristics are lumped together as geometric irregularities.

This report reviews test methods currently available to quantify the aggregate geometric irregularities and the effect of these irregularities on the performance of base course materials. A summary of the methods used by geologists to describe aggregates has been included. Even though these methods may not be practical for everyday engineering work, they have been used by researchers for quantifying base course performance (Barksdale and Itani 1994). A review of current methods used by engineers, including a discussion on the usage of image analysis for describing particle shape and roughness, is also presented.

CHARACTERIZATION OF COARSE AGGREGATE SHAPE, ANGULARITY, AND SURFACE ROUGHNESS

The description of the aggregate particles can be conducted directly using petrological methods or by using image analysis. The effect of particle shape, angularity, and surface texture on the engineering properties can also be inferred.

Petrological methods

The shape of the aggregate can be described by its length, width, thickness, sphericity, roundness, and angularity. The surface texture is difficult to quantify and several visual charts and some sophisticated test methods have been proposed. A description of these methods is presented below.

Description of aggregate shape

Sedimentary petrologists have described the shape of particles using methods developed as long ago as 1930. The description involves mea-
measurement of the aggregate dimensions (shortest, intermediate, and longest lengths). Based on these lengths, the shape of the aggregate is quantified in terms of both the flatness and elongation ratios or by the shape factor. The flatness ratio \( p \) is the ratio of the short length to intermediate length, and the elongation ratio \( q \) is the ratio of the intermediate length to the longest length.

An alternate method for describing the shape of the aggregate involves the shape factor \( F \) and sphericity \( \psi \) of the aggregate particles. The shape factor \( F \) is the ratio of the elongation ratio \( q \) and the flatness ratio \( p \), i.e.,

\[
F = \frac{p}{q}.
\]

A shape factor equal to 1 represents a rounded or cubic aggregate. Smaller than 1, the particle tends towards being elongated and thin. Blade-shaped materials have a shape factor greater than 1.

The sphericity \( \psi \) is defined as the ratio of the surface area of a sphere having the same volume as the particle in question to the surface area of the particle. The sphericity can also be determined from the flatness and elongation ratios as shown below:

\[
\psi = \frac{12.8 \left( \frac{3}{2} p^2 q \right)}{1 + p(1 + q) + 6 \left( 1 + p^2 (1 + q^2) \right)}.
\]

The shape factor, \( p \), \( q \), and sphericity are used to classify the aggregate as disc, equidimensional, blade- or rod-shaped using Figure 1. Equidimensional can mean either cubic or round. The definitions for disc, equidimensional, blade, and rod, based on descriptions by Lees (1964) and Barksdale and Itani (1994), are presented in Table 1.

Barksdale and Itani (1994), in their study on the effect of shape, angularity, and roughness of aggregates on base course performance, used this form of shape description for characterizing the five aggregates they used. The granite gneiss, limestone, shale, quartzite, and river gravel turned out to be disc, blade, blade, blade, and equidimensional in shape, respectively. Additional discussion on the results of his study is presented later in this report.

ASTM D 2488-90 (1996), Standard Practice for Description and Identification of Soils (Visual-Manual Procedure), describes the shape of aggregates as either flat or elongated, or flat and elongated using the criteria shown in Table 2. These criteria were developed basically for identifying flat and elongated aggregate and not as a general tool for describing the shape of coarse aggregates.

### Description of roundness

Roundness, as opposed to shape, has to do with whether the edges are sharp or round (Wadell 1932). The roundness of a particle is sensitive to abrasion and wear to which aggregates are subjected during processing and construction. The process for determining the roundness of a particle is fairly complex and involves tracing a magnified image of the particle. An inscribed circle is drawn within the aggregate tracing and the radius of the circle is determined. The radii of

<table>
<thead>
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<th>Aggregate shape</th>
<th>Description</th>
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<tr>
<td>Equidimensional</td>
<td>Neither slabby appearance nor elongated</td>
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<tr>
<td>Blade</td>
<td>Slabby appearance</td>
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<tr>
<td>Rod</td>
<td>Elongated, but not slabby in appearance</td>
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</table>

### Table 2. Criteria for describing particle shape.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Description</th>
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<td>Flat</td>
<td>Particles with width/thickness &gt; 3</td>
</tr>
<tr>
<td>Elongated</td>
<td>Particles with length/width &gt; 3</td>
</tr>
<tr>
<td>Flat and elongated</td>
<td>Particles that meet criteria for both flat and elongated</td>
</tr>
</tbody>
</table>

Figure 1. Aggregate classification chart.
the edges and corners of the particles also are determined. These radii are used to index the roundness of the aggregate as shown below. Details on this method can be found in the papers by Wadell (1932) and Krumbein (1941). Essentially, the roundness \( R \) of a particle is an average measure of curvature of the corners and edges. \( R \) is expressed as

\[
R = \frac{\sum r}{N}
\]

where \( r \) = radius of curvature of a corner of the particle surface
\( r' \) = radius of the maximum inscribed circle in the projected plane
\( N \) = number of corners.

Because this is a lengthy process, visual charts have been developed (Krumbein 1941) for estimating the roundness of aggregates. Figure 2 can be used to classify the roundness for 16- to 32-mm aggregates. By enlarging or reducing the chart, similar roundness charts could be made for other size aggregates (Krumbein 1941). The roundness \( R \) varies between 0.1 and 0.9. An \( R \) value greater than 0.6 indicates high roundness, \( R \) between 0.4 and 0.6 indicates medium roundness, and \( R \) less than 0.4, low roundness.

**Description of angularity**

Lees (1964) found that when using Krumbein’s (1941) method for determining the roundness number, it was possible to get the same roundness number for two very differently shaped aggregates. He found it to be especially true for crushed aggregates. Lees (1964) proposed a method for determining the degree of angularity, which accounts not only for the roundness of the corner but also how far the projection is from the inscribed circle (Fig. 3). The degree of angularity is calculated by the following equation:

\[
A_i = (180^\circ - a) \frac{x}{r}
\]

where \( A_i \) = degree of angularity
\( a \) = measured angle
\( x \) = distance to the tip of the corner from the center of the maximum inscribed circle
\( r \) = radius of the maximum inscribed circle.

The total degree of angularity (\( A \)) is the sum of all the values for all corners measured in three mutually perpendicular planes. Again, because of the high degree of complexity, Lees (1964) developed a visual chart for determining the degree of angularity of particles (Fig. 4).

**ASTM D 2488-90 (1996), Standard Practice for Description and Identification of Soils (Visual-Manual Procedure),** describes the angularity of coarse-grained material as either angular, subangular, 

**Figure 2. Roundness chart for 16- to 32-mm aggregates. (After Krumbein 1941.)**

**Figure 3. Parameters for determining the degree of angularity. (After Lees 1964.)**
subrounded, or rounded. The qualitative criteria, presented in Table 3, are used for describing the angularity. A visual chart for determining the angularity of the aggregate, similar to that found in ASTM D 2488-90, is presented in Figure 5.

**Description of surface texture**

The surface characteristics or texture of an aggregate are considered to have an effect on the engineering response of the material. Terzaghi and Peck (1967) defined texture as the degree of fineness and uniformity. They suggested qualitative expressions such as smooth, sharp, gritty, etc., to describe the texture.

Barksdale and Itani (1994) used a roughness scale to determine the surface texture (roughness) of aggregates. The surface roughness (SR) was based on visual inspection and indexed to a scale ranging from 0 (for glassy particles) to 1000 (for very rough particles).

Another method found in the literature was to coat a flat, sawed aggregate surface with asphalt (Bikerman 1964), which is then scraped to the sur-
face of the aggregate. The remaining asphalt on the aggregate is used as an indicator of the surface texture. This method determines the microtexture of the surface and the absorptive nature of the aggregate and is still an index to the roughness of the surface.

Wright (1955) developed a method for quantifying the surface texture of concrete aggregate particles using studies done on 19-mm stones. The test aggregates were first embedded in a synthetic resin. Once the resin hardened, the stones were cut into thin sections (approximately $2.5 \times 10^{-2}$ mm thick). The thin section was placed under a projection microscope and magnified 125 times. The unevenness of the surface was traced and the total length of the trace was measured. This length was then compared with an uneven line drawn as a series of chords (Fig. 6). The difference between these two lines was defined as the roughness factor. The reproducibility of this method was reported to be good (Wright 1955). However, to obtain a reliable average of roughness of any one aggregate size, it is necessary to take many sample measurements.

**Determination of aggregate characteristics using image analysis**

The direct measurement methods described in the previous sections are time consuming and labor intensive. Thanks to the power of present computing capabilities, computer-based image analysis has been developed for analyzing aggregate shape, angularity, and roughness. A feasibility study was conducted for the Federal Highway Administration (FHWA) on this technology (Wilson et al. 1995). The study was conducted on fine sands (manufactured versus natural), and the conclusion was that image analysis was a viable tool for distinguishing the shape and angularity of the particles. Wilson et al. (1995) developed the Roundness and Shape Indices to quantify the roundness and angularity of the particles, respectively. The method first involves capturing images of the aggregates using a high-resolution video camera. Then an image analysis computer program is used to identify, separate, and trace the edges of the aggregates. Based on the traces, algorithms in the programs are used to determine the different characteristics of the aggregates.

The Quebec Ministry of Transportation (QMOIT) uses image analysis on a routine basis for verifying the angularity of its hot mix aggregates. To study the feasibility of this method, samples of base course aggregates obtained from the Vermont Agency of Transportation (VAOT) were characterized using the QMOIT image analysis system. The samples included one sample of crushed gravel and two samples of crushed stone. The crushed stone was obtained from two different sources. Roughly thirty to forty randomly selected aggregates were placed on a light table and videotaped. The outlines of aggregates from the three sources, as reproduced by the image analysis program, are shown in Figures 7 to 9.

![Figure 7. Image of the Pike crushed stone prior to image analysis.](image1)

![Figure 8. Image of the crushed stone prior to image analysis.](image2)

![Figure 9. Image of the crushed gravel prior to image analysis.](image3)
The numbers on these figures are used to identify the measurements of the individual aggregates during the analysis process. The following basic measurements were made: 1) feature area, 2) feature perimeter, 3) feature ferets, and 4) x-y coordinates. In the image analysis method, the area of an aggregate is the sum of pixels present within the aggregate boundary (Fig. 10a). The perimeter is the sum of pixels surrounding the aggregate (Fig. 10b). Ferets are straight-line measurements made between two tangents (Fig. 10c). In this particular case, eight feret measurements are taken at 0, 22.5, 45, 67.5, 90, 112.5, 135, and 157.5 degrees. From these measurements, indices for roundness and roughness are derived. For example, the length and width of the aggregate are the longest and shortest feret measurements taken at the various angles mentioned above, respectively.

The roughness is defined as the ratio of the perimeter to the convex perimeter. The convex perimeter is defined as the string measurement around the tips of the eight ferets (Fig. 10d). For a smooth material, the roughness factor equals 1.00. As the roughness increases, the roughness factor also increases (Fig. 11a).

The roundness is defined as follows:

\[ R_n = \frac{4\pi A}{P^2} \]

where \( R_n = \) roundness index.

Figure 10. Material characterization using image analysis.

Figure 11. Definition of roughness and roundness.
Table 4. Image analysis results for crushed gravel.

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<th>Aggregate</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Breadth (mm)</th>
<th>Area (mm²)</th>
<th>Perimeter (mm)</th>
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</tr>
</tbody>
</table>

A = area of aggregate
P = perimeter of aggregate.

The roundness index for a perfect circle is 100. However, with image analysis, because of the square pixels matrix, the best that can be obtained is 95. As the material becomes angular, the roundness index decreases (Fig. 11b).

The results of the tests conducted on the VAOT aggregates are shown in Tables 4 to 6. The mean and variance of the roundness and roughness for the three aggregates are shown in Table 7. On the average, the results from crushed gravel as compared to the results from crushed stone indicate a decrease in roundness and an increase in roughness, suggesting that the crushed stone is more angular and rougher. The roundness index ranged from 78.54 to 72.36 for crushed gravel to crushed stone, respectively, indicating by definition that all the materials are fairly angular. The results appear to be close to one another and it is unclear at this time whether this is the range one can expect between crushed gravel and crushed stone. Visual examination of the crushed gravel and crushed stone showed that the crushed gravel mostly had one fractured face with the remainder of the body being rounded. The crushed stone had several fractured faces and was definitely more angular than the crushed gravel. Statistically, however, at the 95% confidence level, the roundness mean value between crushed gravel and crushed stone is significantly different. The mean roundness values between the crushed stones are not significantly different at the 95% confidence level.

The mean roughness values ranged from 1.031 to 1.050 for the crushed gravel and crushed stone, respectively. Again, the range is fairly small, even though the crushed gravel was fairly smooth and the crushed stone was rough. Statistically there is...
<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Length</th>
<th>Width</th>
<th>Breadth</th>
<th>Area</th>
<th>Perimeter</th>
<th>Roundness</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.855</td>
<td>13.388</td>
<td>16.732</td>
<td>51.576</td>
<td>82.543</td>
<td>1.0415</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>15.487</td>
<td>8.9365</td>
<td>14.376</td>
<td>73.427</td>
<td>67.576</td>
<td>1.0624</td>
<td></td>
</tr>
</tbody>
</table>
a difference between the crushed gravel and crushed stone. There was no difference in the mean roughness values between the crushed stones. From these very limited tests on coarse aggregates, and without additional strength/modulus related testing, it is not certain whether image analysis can clearly distinguish the shape, angularity, and roughness of different aggregates.

Determination of aggregate characteristics from indirect methods

It is clear from the above discussions that the determination of aggregate shape, angularity, and surface texture is a fairly lengthy and laborious task. An alternate approach taken by engineers is to infer these characteristics from the mass properties of the aggregates. Several indices for coarse aggregates, such as angularity number, particle index, rugosity, uncompacted void, and time index have been identified in the literature.

**Angularity number**

The angularity number (AN) developed by Shergold (1953) is recommended by British Standards (BS 812 1975) for indexing the angularity of natural and crushed aggregates used in concrete. Shergold found that when the aggregates were compacted in a prescribed manner, the percentage of voids in the aggregate mass decreased as the aggregates became more rounded. He also found that as the amount of round gravel increased in a mixture of natural and crushed aggregates, the percentage of voids also decreased. Based on his study of six aggregates, he found that the minimum percentage of voids in rounded gravel was approximately 33%. The tests were conducted on 19-, 12.7-, 9.5-, 6.35-, and 4.76-mm aggregates. The test procedure involved compaction of individually sized aggregates in three layers in a 2800-cm³ mold. Each layer was compacted with a tamping rod that weighed between 900 and 950 grams to 100 blows. The percentage of voids was calculated by using the net weight of the aggregate in the mold.

Using round gravel as a reference point, Shergold characterized the angularity of all other aggregates as the difference between the percentage of voids and 33%. Then, AN was found to range between 0 and 12:

\[
\text{AN} = \text{percentage of voids} - 33
\]

\[
\text{AN} = 67 - \frac{100M}{cG_a}
\]

where \( M \) = mass of standard volume of aggregate (g)

\( c \) = mass of water required to fill the same volume (g)

\( G_a \) = oven-dried specific gravity of the aggregate.

Several limitations of the angularity number were pointed out by Lees (1964). Primarily, the AN was developed based on results from only six samples of coarse aggregate. Furthermore, the angularity as described by Shergold, “angular to rounded,” was based on a consensus reached from visual examination of the test aggregate by 25 observers. Another quirk with the AN was that it was not to be applicable to all shapes (such as regular geometric objects [spheres and cubes]), and the AN for perfect spheres was found to be higher than for perfect cubes, which appears to be contradictory. Furthermore, the heavy compaction required may break the aggregates, causing artificial changes in angularity.

Gupta (1985) refined the AN model to account for the shape of the aggregate. The AN was calculated in the same manner as before, with the exception that Gupta defined the percentage of voids in an aggregate mass as a function of the shape and the average size of the aggregate (mm). Based on test results of the three different aggregates, angular limestone (6- to 50-mm range), subangular crushed quartzite (6- to 50-mm range), and rounded gravel (6- to 100-mm range), as well as different proportions of limestone and rounded gravel mixtures, he found that the percentage of voids (Fig. 12) can be expressed as

\[
\eta = C d^n
\]

where \( \eta \) = percentage of voids

\( C \) = shape factor

\( d \) = volume mean aggregate diameter (mm)

\( n \) = exponent.

The size (\( d \)) is determined by taking a known number of particles and soaking them in water
for 24 hours. The amount of water displaced by these particles is the volume of the aggregates. Gupta (1985) divides this volume by the number of particles to get the mean volume size of the individual particles. The mean volume size is then converted to the volume mean diameter. The exponent (n) was found to be a constant equal to –0.032 for all the materials and mixtures tested.

The coefficient $C$ was found to be a function of the aggregate shape. It was also found to be a function of the amount of rounded gravel in the mixture. Values of $C$ as reported by Gupta (1985) are presented in Table 8. The coefficient $C$ ranged between 39 and 45 and was found to decrease as the material changes from an angular to a rounded material. Also, $C$ decreased as the amount of rounded gravel in a mix increased.

Gupta (1985) also reported that the size of similarly shaped material had an effect on the percentage of voids. For all of the materials tested, he found that the percentage of voids decreased as the size of aggregate increased. For example, he reported a 5% decrease in porosity when the mean size of rounded gravel increased from 5 mm to 32 mm. Likewise, a 3% decrease in porosity was reported for a similar change in aggregate size for angular limestone. Therefore, the size of the particles has an effect on the AN value. When using AN to characterize angularity it is important to ensure that the comparison is done on material of the same size.

Table 8. Value of shape factor ($C$) for various materials. (After Gupta 1985.)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Value of $C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular limestone</td>
<td>45.43</td>
</tr>
<tr>
<td>Subangular crushed quartzite</td>
<td>41.44</td>
</tr>
<tr>
<td>Rounded gravel</td>
<td>37.89</td>
</tr>
<tr>
<td>Limestone + rounded gravel (0.875 : 0.125 v/v)</td>
<td>43.49</td>
</tr>
<tr>
<td>Limestone + rounded gravel (0.75 : 0.25 v/v)</td>
<td>42.63</td>
</tr>
<tr>
<td>Limestone + rounded gravel (0.50 : 0.50 v/v)</td>
<td>41.98</td>
</tr>
<tr>
<td>Limestone + rounded gravel (0.333 : 0.667 v/v)</td>
<td>40.58</td>
</tr>
<tr>
<td>Limestone + rounded gravel (0.167 : 0.835 v/v)</td>
<td>39.40</td>
</tr>
</tbody>
</table>

Particle index

The particle index ($I_a$) is based on the concept that the shape, angularity, and surface texture of a uniformly (single) sized aggregate affects not only the void ratio but also the rate at which the voids change when the aggregate is compacted in a standard mold (Huang 1962). Through experimentation with different types of molds and different types of aggregates, and with a specific procedure, Huang (1962) found a linear relationship between the number of compactive strokes (10 to 50) and the void ratio. There was no general relationship found with fewer than 10 compactive strokes. The resulting change in the void ratio became insignificant when more than 50 compactive strokes were used (Huang 1962). The hypothetical void ratio at zero strokes was linearly extrapolated from the measured void ratio at the end of 50 strokes and the rate of void change.
between 10 and 50 strokes. It was found to be dependent on the shape, angularity, and texture of the aggregates. Huang (1962) found that this “zero stroke void ratio” became smaller as the aggregate became more spherical, rounded, and smooth. He also found that this was more pronounced when the mold was rhombohedron shaped.

The particle index test initially was developed for three aggregate sizes: passing the 19-mm and retained on the 12.7-mm sieve, passing the 12.7-mm and retained on the 9.5-mm sieve, and passing the 9.5-mm and retained on the No. 4 (4.75-mm) sieve. For each size, the test involves tamping the uniform-sized aggregate into a mold in three equal layers using a standard tamping rod with 10 strokes per layer. The tamping rod is raised to a height of 50 mm from the top of the aggregate surface. At the end of the third layer, material is added to make sure that the aggregate surface is flush with the rim of the molds. The test is repeated using 50 strokes. The percentage of voids in the aggregate is calculated using the following equation:

\[ V_n = \left[ 1 - \frac{W_n}{s \cdot v} \right] \cdot 100 \]

where \( V_n \) = percentage of voids at \( n \) strokes per layer

\( W_n \) = net weight of aggregate in the mold at \( n \) strokes per layer (g)

\( s \) = bulk density of the aggregate (g/cc)

\( v \) = volume of mold (cc).

The particle index \( (I_a) \) is calculated using the formula

\[ I_a = 1.25V_{10} - 0.25V_{50} - 32 \]

where \( V_{10} \) = percentage of voids in aggregates at 10 strokes per layer

\( V_{50} \) = percentage of voids in aggregates at 50 strokes per layer.

Typical particle index results reported by Huang (1962) are shown in Table 9. Sizes 1, 2, and 3 represent aggregates passing the 19-mm and retained on the 12.7-mm sieve; passing the 12.7-mm and retained on the 9.5-mm sieve; passing the 9.5-mm and retained on the No. 4 (4.75-mm) sieve, respectively. Shapes, a, b, and c represent bulky, elongated, and flat particles, respectively. Gravel (ii) was visually classified as gravel with smooth surfaces and rounded corners. Gravel (iii) was classified as gravel with rough surfaces and sharp corners and edges. Crushed gravel (p) was made up of gravel aggregates as received from the plant. No screening between crushed and uncrushed gravel was made. Crushed gravel (pp) was made up of those that were sorted to have at least one crushed face. The shapes, angularity, and roughness classifications were based on visual observations by several operators and were not based on any measurements (Huang 1962). The results indicated that the test method is capable of distinguishing the difference between smooth, rounded and rough, angular aggregates by the increasing particle index from gravel to crushed stone. It also appears that this index is capable of distinguishing different levels of crushed gravel. A modified version of this test has been standardized by ASTM. The test is designated as ASTM D 3398-93 (1996), Standard Test Method for Index of Aggregate Particle Shape and Texture (1996), and it covers both coarse and fine aggregates. For the coarse portion, the maximum size has been increased to 38 mm. Depending on the size of the aggregates, different size molds are used, as shown in Table 10. The mold as prescribed by this standard is cylindrical in shape. Although the effect of this test method was more pronounced in a rhombohedron-shaped mold, it could also be seen to a lesser degree with a circular mold.

The problem with this test method, with respect to coarse aggregates, is in the determination of the volume of voids. Initially, the voids were calculated based on the volume of the mold. This required making certain that the aggregates were filled to the rim of the mold and the aggregates’ surfaces were flush with the rim. Because of this it was found that the results were operator dependent.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Size 1</th>
<th>Size 2</th>
<th>Size 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shape a</td>
<td>Shape b</td>
<td>Shape c</td>
</tr>
<tr>
<td>Gravel (ii)</td>
<td>7.5</td>
<td>8.7</td>
<td>9.8</td>
</tr>
<tr>
<td>Gravel (iii)</td>
<td>8.8</td>
<td>10.0</td>
<td>13.2</td>
</tr>
<tr>
<td>Crushed gravel (p)</td>
<td>9.5</td>
<td>11.7</td>
<td>13.6</td>
</tr>
<tr>
<td>Crushed gravel (pp)</td>
<td>11.3</td>
<td>14.6</td>
<td>14.8</td>
</tr>
<tr>
<td>Crushed stone</td>
<td>13.4</td>
<td>16.0</td>
<td>16.9</td>
</tr>
</tbody>
</table>

Table 9. Results of particle index tests for various aggregates. (After Huang 1962.)
Huang (1965) modified the test method to measure the actual volume of the compacted aggregate mass. This involved a special device called a volumeter, which fitted exactly over the mold. The volumeter was made up of a bottom thin flexible membrane and a standpipe. The procedure for compacting the sample remained the same, except that at the end of the last layer, a flexible membrane was placed on top of the surface and water was poured through the standpipe to a prescribed height. The idea here is that when water is introduced on top of the membrane, the thin membrane will deform to match the surface. Knowing the volume of the mold and the volume of water in the volumeter, the actual volume of the aggregate mass is calculated. Using this method for volume measurement, more reproducible results were obtained (Huang 1965).

In addition to modifying the method for measuring the volume of the compacted aggregates, Huang modified the test to determine particle index of fine aggregates (passing #4 and retained on the #200 sieve).

Bindra and Al-Sanad (1983) conducted tests on aggregates that ranged from natural aggregates to blast furnace slags. They also looked at the effect of different gradations (open graded to dense graded) and concluded from their study that gradation did not affect the weighted particle index value. It should be noted that the gradation study included both the coarse and fine fractions. The weighted particle index for a given gradation is the weighted mean of the percent retained in each sieve multiplied by the particle index for that size. The procedure for determining the weighted particle index is presented in ASTM D 3398 (1996). Bindra and Al-Sanad (1983) also concluded from their study that the particle index for smooth-surfaced, rounded aggregates averaged around 6.5, and for crushed, high angularity, rough-textured aggregates, the average was around 17.5.

They also proposed a new method for calculating the volume of the aggregate mass in the mold. Instead of using the volumeter device developed by Huang (1965), they proposed a sand replacement technique. This method involves placement of a thin flexible membrane on top of the aggregate surface. Sand (passing the #25 and retained on the #50 sieve) is then poured onto the surface of the membrane to the top of the mold. The net weight of sand required to fill to the rim of the mold is obtained and the volume to fill the mold is obtained. The volume of the compacted aggregate mass is the difference between the volume of the mold and the volume of sand required to fill the mold. This method appears to be easier and less cumbersome than the volumeter method.

<table>
<thead>
<tr>
<th>Aggregate size (mm)</th>
<th>Mold/Rod designation</th>
<th>Aggregate specimen size (kg)</th>
<th>Mold diameter (mm)</th>
<th>Mold height (mm)</th>
<th>Rod diameter (mm)</th>
<th>Rod length (mm)</th>
<th>Mass of rod (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.1</td>
<td>25.4</td>
<td>A</td>
<td>13.6</td>
<td>203.2 ± 0.2</td>
<td>237.0 ± 0.2</td>
<td>21.2 ± 0.2</td>
<td>814 ± 0.2</td>
</tr>
<tr>
<td>25.4</td>
<td>19.0</td>
<td>B</td>
<td>13.0</td>
<td>152.4 ± 0.2</td>
<td>177.8 ± 0.2</td>
<td>15.9 ± 0.2</td>
<td>610 ± 0.2</td>
</tr>
<tr>
<td>19.0</td>
<td>12.7</td>
<td>B</td>
<td>13.0</td>
<td>152.4 ± 0.2</td>
<td>177.8 ± 0.2</td>
<td>15.9 ± 0.2</td>
<td>610 ± 0.2</td>
</tr>
<tr>
<td>12.7</td>
<td>9.5</td>
<td>C</td>
<td>4.0</td>
<td>101.6 ± 0.2</td>
<td>118.5 ± 0.2</td>
<td>10.6 ± 0.2</td>
<td>406.9 ± 0.2</td>
</tr>
<tr>
<td>9.5</td>
<td>4.75</td>
<td>C</td>
<td>4.0</td>
<td>101.6 ± 0.2</td>
<td>118.5 ± 0.2</td>
<td>10.6 ± 0.2</td>
<td>406.9 ± 0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aggregate size (mm)</th>
<th>Inside diameter of mold (mm)</th>
<th>Inside height of mold (mm)</th>
<th>Diameter of tamping rod (mm)</th>
<th>Length of tamping rod (mm)</th>
<th>Weight of tamping rod (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–50</td>
<td>250.0</td>
<td>291.6</td>
<td>26.00</td>
<td>1045</td>
<td>4120</td>
</tr>
<tr>
<td>2.36–20</td>
<td>152.4</td>
<td>177.8</td>
<td>15.88</td>
<td>610</td>
<td>930</td>
</tr>
</tbody>
</table>

Table 10. Mold size and dimensions of tamping rods for the particle index test. (After ASTM D 3398-93.)

Table 11. Dimensions of mold and tamping rods. (After Bindra and Al-Sanad 1983.)
Specific rugosity index

Tons and Goetz (1968) developed the packing volume concept to characterize the shape, angularity, and roughness of the aggregates used in bituminous mixtures. The test was developed for both the coarse (12.7-mm max) and fine fractions. They decided that the shape of the particle could possibly be quantified as a separate value; however, it was difficult to separate the interaction of angularity and roughness on aggregate performance. They proposed that the effect of both angularity and roughness be combined and considered in one term, “rugosity.”

The assumption is that the volume of an individual particle in an aggregate mass determines the density and voids in the bulk. This volume, called the “packing volume,” had to account for the volume of the solid particle, the volume of internal voids, and the volume of “outside voids.” The “outside voids” volume is made up of the volume of the dips and valleys on the aggregate surface (Fig. 13). The packing volume can be imagined as a membrane around the aggregate.

The packing volume membrane divides the voids into two components, the interparticle voids and particle surface voids (Ishai and Tons 1977) (Fig. 13). For one-sized particles, it is assumed that the interparticle voids are constant and this porosity is the same as that obtained from same one-sized smooth spherical particles. Tons and Goetz (1968) assumed that aggregate shape can be mathematically defined as ellipsoids. They found that the porosity calculated from ellipsoids or spheres of the same size had the same amount of voids. Any difference, then, between the porosity of the smooth spherical particles and the aggregates is due to the irregularities of the aggregates.

Ishai and Tons (1971) developed a specific rugosity ($S_{rv}$) index to express the total geometric irregularity of the particle. $S_{rv}$ will be approximately equal to zero for smooth, spherical particles:

$$S_{rv} = 100 \left( \frac{V_{sr}}{V_p} \right) = 100 \left[ 1 - \left( \frac{G_{px}}{G_{ap}} \right) \right]$$

where $S_{rv}$ = specific rugosity (%)  
$V_{sr}$ = volume between the packing volume membrane and the volume of macro and micro surface voids  
$V_p$ = packing volume of the particle  
$G_{px}$ = packing specific gravity  
$G_{ap}$ = apparent specific gravity.

The apparent specific gravity of the aggregates can be calculated using ASTM Test for Specific Gravity and Absorption of Coarse Aggregate (C 127). $G_{px}$ is determined from the pouring test developed by Ishai and Tons (1977). The test involves taking two one-sized particles and pouring them into a standard container using a standard procedure. One of the particles is used as a standard (smooth, spherical glass beads) with a known packing specific gravity, $G_{ps}$. The other is the test particle for which $G_{px}$ is sought. $G_{px}$ is a function of the ratio of the weight of the test particle to the standard particle:

$$G_{px} = \left( \frac{W_x}{W_s} \right) G_{ps}$$

where $W_s$ = weight of the standard  
$W_x$ = weight of the test material  
$G_{ps}$ = packing specific gravity of standard material  
$G_{px}$ = packing specific gravity of test material.

A schematic of the pouring test is given in Figure 14. The specifications for the pouring test apparatus for the coarse aggregate fraction are given in Table 12.

Some typical results as presented by Ishai and Tons (1977) are shown in Figure 15. The specific rugosity of two sizes, 12.7 to 15.9 mm and #3 to #4 sizes for natural gravel, crushed gravel, limestone, and beach pebbles are plotted. The specific rugosity increases as the material becomes more
angular and rougher. Also shown in the figure is the effect of aggregate size on the specific rugosity. The value of the specific rugosity increases as the size of the material decreases.

Uncompacted voids in aggregates

This test method is similar to the specific rugosity test. Initially developed for fine aggregates by the National Aggregate Association, it involves allowing the fine aggregates to freely fall into a calibrated cylinder from a specified height. The exception here is that the aggregates are not separated into various sieve sizes, as is done with the other index tests. The test for fine aggregates is designated by ASTM as Test Method C 1252. The weight of aggregate and the bulk specific gravity are used to calculate the uncompacted void content:

$$UVC = \frac{V_{cyl} - \frac{M}{G_{sb}}}{V_{cyl}} \times 100$$

where $UVC =$ uncompacted void content (%)$\quad V_{cyl} =$ volume of cylinder (cm$^3$)$\quad M =$ mass of aggregate in cylinder (g)$\quad G_{sb} =$ bulk specific gravity of aggregates.

$UVC$ increases with increasing angularity and roughness of the aggregates. Aldrich (1996) modified this test for coarse aggregates. A schematic of his test apparatus is shown in Figure 16. The coarse aggregate for the test passed the 19-mm sieve and was retained on the #4 sieve. The test

| Table 12. Specific setups for coarse fractions for the pouring test. (After Ishai and Tons 1977.) |
|---|---|---|
| Dimensions (cm) | Coarse fractions |
| 12.7 to 15.9 mm | #3 to #4 |
| Bin diameter | 16.0 | 16.0 |
| Funnel orifice diameter | 3.0 | 1.44 |
| Aggregate head | 12.0 | 12.0 |
| Pouring height | 21.0 | 21.0 |
| Container diameter | 12.2 | 10.3 |
| Container height | 15.2 | 11.8 |
| Bead diameter (avg.) | 16.0 | 6.0 |

Figure 14. Schematic description of the pouring device. (After Ishai and Tons 1977.)

Figure 15. Packing specific gravity and rugosity for different aggregates.
apparatus, as pointed out by Aldrich (1996), is similar to that developed by Ishai and Tons (1977) for the Specific Rugosity Tests. The test method is similar to that used for fine aggregates and the uncompacted void content is calculated using the same equation used for the fine aggregates. Aldrich (1996) reported that the UCV increased with increasing angularity of the aggregates.

**Time index**

Several test methods exist for fine aggregates where the rate of flow through a standardized orifice is used to index the material shape, angularity, and texture (Rex and Peck 1956, Tobin 1978). The time of flow is usually compared to a standard material, such as Ottawa sand. A similar test apparatus, as pointed out by Aldrich (1996), is similar to that developed by Ishai and Tons (1977) for the Specific Rugosity Tests. The test method is similar to that used for fine aggregates and the uncompacted void content is calculated using the same equation used for the fine aggregates. Aldrich (1996) reported that the UCV increased with increasing angularity of the aggregates.

\[
C_e = \frac{t \times G_{sb}}{k}
\]

where \(C_e\) = flow coefficient
\(t\) = time (sec)
\(G_{sb}\) = bulk specific gravity
\(k\) = constant (1 second).

The test involves first drying 10 kg of aggregate. This amount is then placed into the sample tube. The vibrating table is turned on and 1 kg of material is allowed to collect in the pan on the floor. The pan is set on a scale and the weight of the aggregate in the pan is monitored. After 1 kg of material has collected in the pan, a stopwatch is stopped when an additional 7 kg of material has collected in the pan. The amount of time for 7 kg to collect in the pan is noted. The test is repeated five times and the average time value is determined.

The same material used for the image analysis was tested using this equipment. The results are shown in Table 13. The bulk specific gravity of the aggregates was assumed to be 2.6.

The results indicate that, based on the flow coefficients, crushed stone is more angular than crushed gravel. This test can be conducted quickly; further work in this area is warranted.

<table>
<thead>
<tr>
<th>Material</th>
<th>Average time (s)</th>
<th>Flow coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed gravel</td>
<td>33.45</td>
<td>92.2</td>
</tr>
<tr>
<td>Crushed stone</td>
<td>44.13</td>
<td>114.7</td>
</tr>
<tr>
<td>Pike crushed stone</td>
<td>44.62</td>
<td>116.0</td>
</tr>
</tbody>
</table>
LABORATORY RESPONSE OF ANGULAR MATERIAL

From static triaxial tests, it has been shown that rounded aggregate materials produce significantly higher permanent deformation than angular aggregate soils. This is reflected in the angle of internal friction ($\phi$). During compression, it is commonly found that rounded particles are able to slip easily, whereas angular materials have to overcome the higher frictional forces at the contact interfaces. Generally, $\phi$ increases with increasing angularity (Holtz and Kovacs 1981). Holtz and Kovacs (1981) also found that as the surface roughness increased, so did $\phi$. The effects on $\phi$ by angularity, surface roughness, and other factors are shown in Table 14.

Table 14. Summary of factors affecting $\phi$. (After Holtz and Kovacs 1981.)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void ratio ($e$)</td>
<td>$e \uparrow \phi \downarrow$</td>
</tr>
<tr>
<td>Angularity ($A$)</td>
<td>$A \uparrow \phi \uparrow$</td>
</tr>
<tr>
<td>Grain size distribution</td>
<td>$C_p \uparrow \phi \uparrow$</td>
</tr>
<tr>
<td>Surface roughness ($R$)</td>
<td>$R \uparrow \phi \uparrow$</td>
</tr>
<tr>
<td>Moisture content ($w$)</td>
<td>$w \uparrow \phi \downarrow$ slightly</td>
</tr>
<tr>
<td>Particle size ($S$)</td>
<td>No effect (with constant $e$)</td>
</tr>
<tr>
<td>Intermediate principal stress</td>
<td>$\phi_{ps} \geq \phi_{pa}$</td>
</tr>
<tr>
<td>Overconsolidation or prestress</td>
<td>Little effect</td>
</tr>
</tbody>
</table>

The information in Table 14 relates to static loading conditions. However, the loading condition on a pavement structure is not static, but cyclic. Also, the load levels applied are usually not near the shear strength of the material except when the material is saturated, as is the case during spring thaw. The data in Table 14 may or may not apply to pavement structures. Very little data are published on the performance of base course materials under cyclic loading. This is probably due to the erroneous assumption that failure of base course materials does not occur.

With the advent of mechanistic pavement design procedures, several studies have been presented on the resilient modulus of base materials. Base materials have been identified as stress dependent and several models exist for predicting the resilient modulus of base materials, such as the $K_1$–$K_6$ model in SUPERPAVE (Lytton et al. 1993) and the "universal" $K_1$–$K_3$ model (Witczak and Uzan 1988). However, the resilient moduli reported in the literature for natural gravel and crushed rock were quite similar to one another (Thompson and Smith 1990). They reported the range to be about 200 to 240 MPa under a bulk stress of 138 kPa. Ishai and Gelber (1982) also found similar trends for bituminous mixes. They suggested that this was to be expected because in the resilient modulus test, the applied stress levels are very low and only with near-failure conditions will the effect of the geometric irregularities be evident; for example, in terms of particle interlocking. However, the deformation under the same applied stress level, when the base course is saturated, will be high, and the angularity and roughness of the aggregates will have a greater effect on pavement performance.

There is very little information in the literature on the performance of base course layers as a function of the shape, angularity, and roughness of the aggregates. The results of only two studies on the effect of aggregate geometry and surface roughness were found in the literature. One was by Holubec and Wilson (1970) and the other by Barksdale and Itani (1994). Holubec and Wilson (1970) used crushed gravel and crushed stone in their study. They looked at the effects of angularity and the proportion of crushed material on base course performance. The samples were compacted at an optimum moisture content of 4.5% using a 4.5-kg hammer dropped 457 mm and applying 25 blows per layer. The test samples were 102 mm in diameter and 203 mm in height. The maximum aggregate size was 9.5 mm.

Holubec and Wilson (1970) report in terms of the cyclic creep strain. The definition of cyclic creep strain is unclear in the report and is taken by this author to refer to the total strain minus the elastic strain. They found that the cyclic creep strain after 5000 load repetitions decreased as the percent of crushed particles increased (Fig. 18). The samples were made by blending different amounts of crushed aggregate with the parent rounded gravel aggregates. With respect to sphericity and angularity, they reported that, as the aggregates became angular, the cyclic creep strain, after 5000 load repetitions, increased (Fig. 19). The results appeared to be contradictory, as one would expect the creep strains to decrease with increasing angularity. The results may be explained by the fact that there is a larger contact area with rounded material than with angular material. Thus it will require a larger shear force at the points of contact to move the aggregates. This could also explain why the resilient modulus reported in the literature for rounded and angular materials are similar. This is only speculation and
further work in this area may be required. In the same study, the friction angle was found to increase with increasing angularity (Fig. 20). Based on their study, Holubec and Wilson recommended that repeated load tests be conducted on characterizing the performance of base course materials and cautioned on the use of the angle of internal friction as a parameter for predicting base course performance. In my opinion, with thawing soils, the friction angle may be a good indication of the ability of the base course to resist permanent deformation. When the base is saturated, the load levels commonly applied on pavement structures when they are dry may be high enough to move the base response from the elastic to the plastic (failure) zone.

The other work was done by Barksdale and Itani (1994). They presented results of the effect of aggregate shape on the resilient and permanent deformation behavior of five base course materials. The gradation used in the study is shown in Table 15. The medium gradation in Table 15 is similar to the VAOT fine gradation for subbase of crushed gravel.

Table 15. Gradation of test aggregates. (After Barksdale and Itani 1994.)

<table>
<thead>
<tr>
<th>Percent passing</th>
<th>38.1 mm</th>
<th>19 mm</th>
<th>9.5 mm</th>
<th>No. 4</th>
<th>No. 40</th>
<th>No. 200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>100</td>
<td>80</td>
<td>60</td>
<td>45</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>Coarse</td>
<td>100</td>
<td>65</td>
<td>43</td>
<td>27</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Fine</td>
<td>100</td>
<td>85</td>
<td>70</td>
<td>58</td>
<td>25</td>
<td>10</td>
</tr>
</tbody>
</table>
The test materials, shape, and surface characteristics as reported by Barksdale and Itani (1994) are shown in Figure 21. The samples were compacted using a vibratory compactor at the optimum moisture content. The test specimens were 152 mm in diameter and 305 mm in height. These dimensions are acceptable provided the maximum size of the aggregates is no more than 25 mm. Sweere (1990) found that testing aggregates containing 51-mm particles in a 152-mm-diameter mold produced inconsistent results. He recommended that, for large particle sizes, the specimen diameter be at least six to seven times the maximum particle size, to minimize the boundary effects by the large aggregates. Scalping of large aggregates and replacing equivalent amounts of smaller aggregates changes the overall structure of the material. Dawson* reported that in unreported experiments at the University of Nottingham, similar results were obtained on dry specimens in which the grading curve was

* Personal communication, Andrew Dawson, University of Nottingham, United Kingdom, 1992.
either translated laterally or truncated. This in turn produces resilient and plastic responses that may not be representative of the actual material. If there is a sufficient amount of large aggregates (greater than 10%), large-scale triaxial testing is recommended. Besides aggregate geometry, Barksdale and Itani (1994) looked at the influence of the fines, the plasticity of the fines, gradation, and moisture content on base course performance.

To quantify the effect of the aggregate geometry and surface roughness, Barksdale and Itani (1994) developed the aggregate influence factor (AIF), which was based on a multiple regression between observed laboratory performance and various indices that described the aggregate shape and texture. For the aggregates tested, they found that the AIF was a function of the sphericity, roundness, surface roughness, and angularity of the aggregate. They employed methods used by geologists to quantify sphericity and roundness as described earlier in this report. For surface roughness, Barksdale and Itani (1994) used a scale from 0 to 1000 to quantify glassy to very rough particles, respectively. They then rated the roughness of the aggregates based on visual examination. For example, for the aggregates in the study, the AIF was as follows:

\[
AIF = 2500 \times (\psi + R) - (A + SR)
\]

where AIF = aggregate angularity factor
\(\psi\) = average sphericity value
\(R\) = average roundness value
\(SR\) = surface roughness coefficient.

This AIF value is specific to the aggregates tested by Barksdale and Itani (1994) and is not recommended for other aggregates. If this approach is taken to characterize base course performance, new AIF values will have to be developed for other aggregates. The AIF values for the test aggregates are presented in Table 16. The AIF values decrease with increasing angularity and roughness.

The resilient modulus test was conducted using the procedure prescribed in AASHTO T-274-82. For permanent deformation studies, the specimens were subjected to 41 kPa confining pressure and subjected to 70,000 load repetitions at a principal stress ratio of four or six. Barksdale found the resilient modulus of rough angular materials to be higher than the rounded material by about 50% at low bulk stress values and about 25% at high bulk stress values (Fig. 22). This is much higher than the values reported by Thompson and Smith (1990). There appears to be some inconsistency in the results found in the literature. The effect of moisture was also pronounced. Barksdale and Itani (1994) reported that under drained conditions, the resilient modulus

### Table 16. AIF values of test aggregates.

<table>
<thead>
<tr>
<th>Base material</th>
<th>AIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite gneiss</td>
<td>500</td>
</tr>
<tr>
<td>Limestone</td>
<td>50</td>
</tr>
<tr>
<td>Shale</td>
<td>1675</td>
</tr>
<tr>
<td>Quartzite</td>
<td>150</td>
</tr>
<tr>
<td>River gravel</td>
<td>3700</td>
</tr>
</tbody>
</table>

Figure 22. Influence of material type and state of stress on resilient modulus. (After Barksdale and Itani 1994.)
decreased by 50% (compared to the optimum moisture content) for river gravel at a bulk stress of 103 kPa. For undrained conditions, this reduction will be much higher. He also reported that the amount of fines in the base course materials had a significant effect on the amount of plastic strain (Fig. 23).

SUMMARY AND CONCLUSIONS

There are several methods for quantifying the shape, angularity, and roughness of base course aggregates. Methods developed by geologists can be classified as direct methods and involve actual measurements on the aggregates. Basic measurements of lengths are used to quantify the shape of aggregates. The angularity and roughness can also be determined with complex measurements, but several charts have been developed for simplifying the process. These methods are more involved and time consuming. However, they can be considered as standards.

Indirect methods for quantifying the shape, angularity, and roughness have been developed. The shape, angularity, and roughness are usually combined together as it is fairly difficult to separate the effects of the individual components. Most indirect measurements are based on the change in the voids of a single-sized bulk mass of aggregates. The tests are similar to one another and involve compaction of the aggregate mass in a given level. Some of the indices developed are the angularity number, particle index, and rugosity. Another index test involves the amount of time required for a given aggregate gradation to flow through a known orifice. This method is fairly simple and has been used for fine aggregates; it can be modified for coarse aggregates up to 50 mm in diameter.

Several research studies have shown that the shape, angularity, and roughness have a significant effect on base performance. Some of these studies have shown that there can be up to 50% change in resilient modulus of base materials due to geometric irregularities. It is not conclusive whether the resilient modulus is a good indication of the effects due to changes in shape, angularity, and roughness of the aggregates. However, what is clear in the literature is that moisture and amount of fines have a significant effect on base course performance. Increasing moisture content, as during the spring thaw, can increase the failure rate of the base course. Further study is needed to consider the combined effect of aggregate irregularities, moisture, and fines content on base course performance.

RECOMMENDATIONS

The results of this review indicate that for base course materials with maximum sizes ranging between 25 mm and 50 mm, the particle index test is best suited for indexing the angularity of the material. The term “angularity” as used in this recommendation includes the shape and surface characteristics of the aggregate. One of the drawbacks of using this test is that it is time consuming.

VAOT requirements state that any test method used for characterizing the angularity of base course materials should be able to quantify the shape, angularity, and roughness in a time-efficient manner. Therefore, the particle index test is recommended for this purpose.

Figure 23. Influence of material type, stress level, and percent fines on plastic strain. (After Barksdale and Itani 1994.)
course materials be simple and quick to use. Either the flow coefficient or the uncompact ed void tests have the greatest potential to meet the above requirements. Currently, these tests are limited to aggregates with a maximum size of 20 mm, and modifications to both the equipment and test procedures are required. It is recommended that a research program be conducted to develop an index test for angularity of aggregates to a maximum size of 50 mm using both the flow coefficient and the uncompacted void tests. The results from both these tests will be correlated with the particle index, because this index has been developed for larger size aggregates.

It is also advisable, but optional, that the shape, angularity, and surface texture of the aggregates be characterized using the techniques developed in the geological arena. These will be used to calibrate the index results obtained from the flow coefficient and the uncompacted void tests using a similar method developed by Barksdale and Itani (1994). The geological characterization can also be used to correlate resilient modulus and shear strength test results using a similar approach used by Barksdale and Itani (1994) again.

The index angularity measurements need to be tied to the resilient and strength properties of the aggregates. Ideally, the resilient modulus and shear strength tests should be conducted under optimum moisture and saturated conditions. The critical time for the base courses in seasonal frost areas is during spring thaw. Therefore as a minimum it is recommended that the tests be conducted on saturated samples under undrained conditions. As a corollary to the testing program, moisture density relationships will be developed using the large-scale Proctor testing device. These relationships will be compared with those obtained from standard testing procedures used at VAOT.

**LITERATURE CITED**


Quantification of Shape, Angularity, and Surface Texture of Base Course Materials

Vincent Janoo

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

State of Vermont Agency of Transportation
133 State Street
Montpelier, Vermont 05602

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A state-of-the-art review was conducted to determine existing test methods for characterizing the shape, angularity, and surface texture of coarse aggregates. The review found direct methods used by geologists to determine these characteristics. These methods involve physical measurements of individual aggregates and are very laborious and time consuming. Engineers have developed index tests (indirect methods) to quantify the combined effect of the shape, angularity, and surface texture of coarse aggregates in terms of changes in the voids in the aggregate bulk. A description of both the direct and indirect methods is provided in the report. Also, the effect of shape, angularity, and surface texture of coarse aggregates on the base course performance was reviewed. It was found that there is some contradiction in the published data on resilient modulus. Shape, angularity, and surface texture of coarse aggregates clearly influence the angle of internal friction.

Angularity Roughness
Coarse aggregates Shape
Resilient modulus

Report Date: January 1998