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Quantification of Specific Surface Area of Aggregates Using an Imaging Technique

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Abstract: An imaging method is proposed to quantify the specific surface area of aggregates of different sieve sizes. The procedure for determining the specific surface areas of aggregate particles by the proposed method includes the following steps: (1) separating the aggregates into different standard sieve sizes, (2) placing the aggregate particles in a container and injecting a resin to bind them, (3) sawing the aggregate/resin specimen to obtain one to four cut planes, (4) using an image analyzer to take the aggregate particles images from the cut planes, (5) determining the specific surface areas and other aggregate particle properties, such as the slenderness ratio and the roughness from the images. The proposed method was used to determine the specific surface area of a crushed granite aggregate sample with the particle size ranging from passing 19*mm* to #50 sieve. The results were compared with the approximate specific surface areas for different aggregate sizes commonly used by the aggregate industry. The approximate specific surface areas were based on the average specific surface areas of the spheres having the diameters equal to the corresponding passing and retaining sieve opening sizes. The specific surface areas determined by the proposed method are higher, particularly for the aggregates passing #16, #30, and #50 sieve sizes, than those of the approximate values. The reason for the higher specific surface areas determined by the proposed method was primarily due to the irregular shapes and the rough textures of the crushed aggregate particles. The proposed method can be used for quantifying the aggregate properties, including the specific surface area, roundness, slenderness ratio, and roughness in the laboratory for the quality control of aggregate properties.

Key words*: Aggregate surface area; Feret diameter; Imaging techniques.*

Introduction

The asphalt film thickness has been known to have significant effects on the rutting and fatigue resistance, and on the durability of asphalt mixtures. The surface area of aggregates in an asphalt mixture can directly affect the asphalt film thickness in the mixture. Surface area of aggregates is also an important parameter affecting the behavior of flow of granular materials, and the flow characteristics of fluids in porous media. Quantifying the surface area of an aggregate blend, or even a single aggregate particle, is difficult due to the irregular shapes, and the roughness of surface texture of aggregate particles. An approximate method to quantify an aggregate surface area is by using the specific surface area factors [1]. These factors were determined by using the average specific surface area of the spheres having the diameters equal to the corresponding passing and retaining sieve openings.

The method based on the fractal dimension was proposed [2] to improve the accuracy for determining the surface area of particles 1*mm* in diameter or larger. For aggregate particles having isotropic shape, a single perspective is photographed in silhouette to determine the fractal dimensions of the particle's surface. For an aggregate particle of anisotropic shape, two to three mutually orthogonal perspectives are photographed in silhouette to determine the fractal dimensions of the surfaces of the particle. Areas are then determined for these surfaces and summed to derive the total surface area for the particle.

An imaging method for quantifying the specific surface area of aggregate particles is presented in this paper. Imaging techniques have the potential to quantify the surface area of aggregate particles more accurately. Results of the specific surface areas of crushed aggregates ranging from passing 19*mm* to #50 sieve sizes determined by the proposed method are presented and compared with the specific surface areas derived from the specific surface area factors.

Concept of Quantifying Specific Surface Area of Individual Particles

The method of quantifying the surface area of a single particle is first presented here to describe the basic concept behind the actual method used to quantify the surface area of a group of aggregate particles. Fig. 1 shows a single particle cut into equally spaced cross sections. The surface area and the volume of the particle can be approximated by the following equations.

$$S \approx \sum_{i=1}^{N} (p_{i-1} + p_i) H_{i-1,i} / 2 \tag{1}$$

$$V \approx (\sum_{i=1}^{N} a_{i-1} + a_i) h / 2 \tag{2}$$

where

h: equal spacing between any adjacent cross sections,

p_i: perimeter of the i^{th} cross section,

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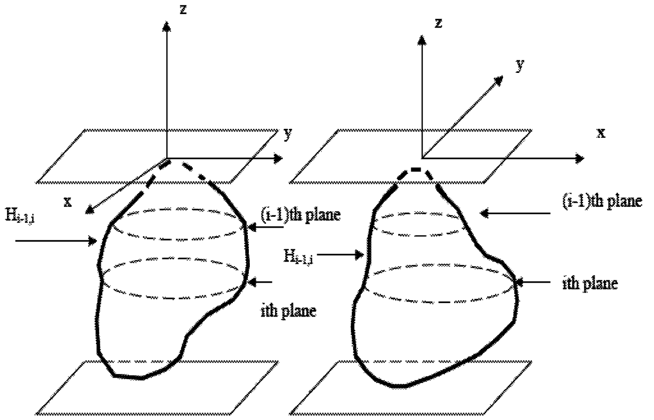


Fig. 1. The Concept of Quantifying Surface Area of Individual Particles.

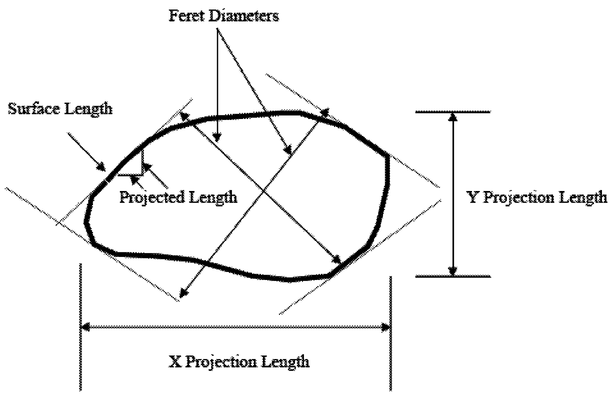


Fig. 2. Illustration of Surface Length vs. Projected Length.

a_i: area of the i^{th} cross section,
$H_{i-1,i}$: the average length of the surface between i^{th} and $(i-1)^{th}$ cross sections,
S: total surface area of the particle,
V: total volume of the particle, and
N: (total number of cross sections)-1; assume the top and bottom cross sections are tangent to the particle and have cross section area and perimeter equal to zero.

The specific surface area (*SA*) of the particle, which is here defined as the surface area per unit volume (*S/V*), can be determined by

$$SA = \frac{S}{V} \approx \frac{\sum_{i=1}^{N}(p_{i-1}+p_i)H_{i-1,i}/2}{\sum_{i=1}^{N}(a_{i-1}+a_i)h/2} = \frac{\sum_{i=1}^{N}(p_{i-1}+p_i)H_{i-1,i}/h}{\sum_{i=1}^{N}(a_{i-1}+a_i)} \tag{3}$$

In the Eqs. (1) to (3), the perimeter (p_i) and the area (a_i) of each cross section can be measured by the imaging techniques [3-5]. The average irregular length ($H_{i-1,i}$) between the adjacent cross sections is much more difficult to determine. The length ($H_{i-1,i}$) between the adjacent cross sections varies with respect to the orientations. As an example, Fig. 1 shows the differences of the length $H_{i-1,i}$ between the $(i-1)^{th}$ and i^{th} cross sections on the *x*- and *y*-projected plane. Therefore, to obtain the average length would require measuring the irregular length at many orientations. This would be difficult to implement for a single particle and will clearly be impractical for a group of aggregate particles. A statistically equivalent but indirect method would have to be developed to acquire this property.

In Eq. (3), it is clear that the values which really matter are the ratios of $H_{i-1,i}/h$, representing the ratio between the curved perimeter length and the projected length. For the entire cross section, the average ratio equals the ratio of perimeter to the projected length or the Feret diameter along *h* direction. The Feret diameter is the distance between two opposite sides of the particle's projection, (Fig. 2). Since Feret diameter varies with orientations, the use of two orthogonal projected lengths is more reasonable. Eq. (4) illustrates this concept, where the average of $H_{i-1,i}/h$ is approximated by the average of the ratios of perimeter over the sum of two orthogonal Feret diameters of many cross sections. The projected lengths are shown schematically in Fig. 2.

$$\frac{H_{i-1,i}}{h} = \frac{1}{N}\sum_{i=1}^{N}\frac{p_i}{x_i + y_i} = \alpha \tag{4}$$

α is defined as ***expansion factor***, and x_i and y_i are the projected lengths along *x*- and *y*- axes.

However, calculations of α from Eq. (4) may encounter a numerical computation problem when some particle cross sections are very small and close to the resolution limit of the image. For example, if we use the same magnification, boundary details of a very small particle cross section may not be captured. The cross section may appear as a square or a rectangle (representing 1, 2, or 4 pixels). Because of this concern, Eq. (5) is proposed for the determination of the approximate value of the expansion factor.

$$\frac{H_{i-1,i}}{h} \approx \frac{\sum_{i=1}^{N} p_i}{\sum_{i=1}^{N}(x_i + y_i)} = \alpha \tag{5}$$

In Eq. (5), the expansion factor is computed by dividing the total perimeter lengths of all the particles included in the analysis by the total projected lengths of the same particles. Using this approach, the error due to the distortion of the small cross section images can be minimized. The other reason for adopting this alternate approach for determining α is that we are more interested in the total surface area of a group of particles rather than that of the individual particles and the approximate value determined by Eq. (5) should approach the value determined by Eq. (4). Computations of the expansion factors by using Eqs. (4) and (5) were performed for a crushed aggregate passing #16 sieve and retaining on #30 sieve. The results shown in Fig. 3 indicate that the expansion factors by Eqs. (4) and (5) are 1.70 and 1.72, respectively.

The use of the *x*- and *y*- projected lengths in Eqs. (4) and (5) can be replaced by any set of two orthogonal Feret diameters, (Fig. 2), or by the average of multiple sets of orthogonal Feret diameters. Use of multiple Feret diameters should result in a more reasonable estimation of the expansion factor since we are attempting to determine the expansion factor for all the particle cross sections cut at different orientations and depths. Because of this, the average of multiple orthogonal Feret diameters was used in this study for the determination of the expansion factor. To test the sensitivity of the expansion factor determined using different Feret diameters, the

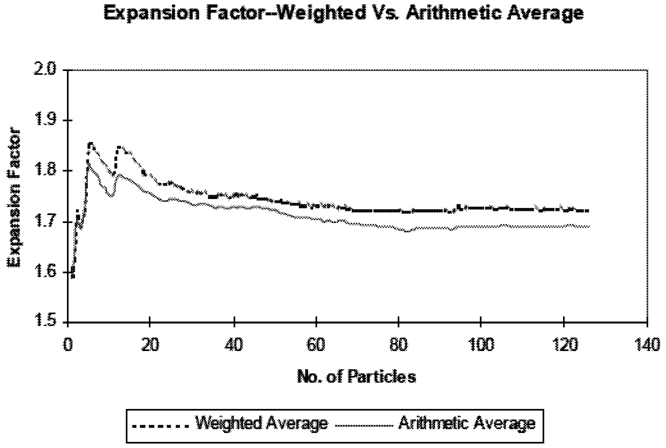


Fig. 3. Expansion Factor, Arithmetic Average vs. Weighted Average (Crushed Aggregates, Passing #16, Retaining on #30).

expansion factor using the maximum and minimum Feret diameters (length and breadth) was also analyzed in this study. The results are presented later.

It becomes clear from the above discussions that a reasonably accurate estimation of the specific surface area of a single particle would require taking the images of many closely spaced cross sections of the particle. This would be a very difficult task. To extend this method to a group of particles would make this approach impractical. However, the concept described in this section provides the basis for the development of a practical method for determining the specific surface area of multiple aggregate particles.

Quantifying Specific Surface Area of Multiple Particles

In this section the concept for determining the total surface area and the specific surface area of a group of particles with uniform size is presented. The uniform size is defined as the particles fit between any two adjacent standard sieve sizes, 19*mm* to 12*mm*, #50 sieve to #100 sieve, or any size ranges in between.

The following procedures describe this concept. First, obtain many particles of uniform size and place them in a plastic cylinder container. Next, pour a very low viscosity resin into the container to allow the resin to fill the voids among the particles. After the resin hardens, make several cuts across the particle/resin mixture specimen to reveal the particle cross sections, as shown schematically in Fig. 4. Fig. 5 shows one of the actual images taken from a crushed sand (passing the #50 sieve and retained on the #100 sieve) solidified in an epoxy resin. This same technique was also used to acquire images of particle cross sections of coarse aggregates.

The particle cross sections shown in Fig. 5 represent the cross sections of the particles cut at different orientations and depths of each particle. For randomly packed multiple particles and if the specimen size is large enough, particle cross sections from two different cut planes may possess similar statistical information of the particle cross sections. In other words, the properties of the particle cross sections from a single cut plane or from a relatively small number of cut planes might be sufficient for evaluating the specific surface area of a group of uniform size particles. This concept, together with the concept presented in the previous section forms the basis for determining the specific surface area of a group of uniform size particles.

Assume the total perimeter length and the total area of the particle cross sections (on the i^{th} cut plane, or i^{th} image of a single cut plane) are quantified by an image analyzer and are represented by p_i and a_i, respectively, and the spacing between any two imaginary adjacent cross sections is h. It will be shown later in Eq. (10) that calculation of the specific surface area is independent of the h value. Using the concepts of Eqs. (1) and (2) and the concept of the expansion factor which assumes a constant value for any cross section of aggregates with the same size range, the following equations can be obtained.

$$S \approx (\sum_{i=0}^{N} p_i)\alpha h \tag{6}$$

$$V \approx (\sum_{i=0}^{N} a_i)h \tag{7}$$

where

$$p_i = \sum_{j=1}^{n_i} p_j^i \tag{8}$$

$$a_i = \sum_{j=1}^{n_i} a_j^i \tag{9}$$

p_j^i , a_j^i are respectively the perimeter and cross section area of j^{th} particle on the i^{th} cross section,

$i=0$ *to* N,

n_i is the total number of particle cross sections on i^{th} plane.

Thus,

$$SA = \frac{S}{V} \approx \frac{\sum_{i=0}^{N}\sum_{j=1}^{n_i} p_j^i \alpha h}{\sum_{i=0}^{N}\sum_{j=1}^{n_i} a_j^i h} = \frac{\sum_{i=0}^{N} p_i \alpha h}{\sum_{i=0}^{N} a_i h} = \frac{\sum_{i=0}^{N} p_i}{\sum_{i=0}^{N} a_i}\alpha = \beta\alpha \tag{10}$$

β is defined as the ***specific area*** and is the ratio of the total perimeters of all particles to the total cross section area of the particles in all cut planes evaluated.

A one question remains, that is how many particle cross sections will be required for a statistically stable evaluation of the specific area and the expansion factor. This will be discussed in the following section.

Asymptotic Analysis of Specific Surface Area

Because particles are randomly packed, a random cut plane should cut through different particles at different depths. Therefore, the cross sections shown on any cut plane should statistically represent all the particles in the group cut at different orientations and at different depths. A study was conducted to evaluate the variation of the specific area (β) and the expansion factor (α) to the total number of particle cross sections. For coarse aggregates in the range of 19 to 12*mm*, 12 to 9*mm*, and 9*mm* to #4 sieve sizes, and fine aggregates of #4 to #8 and #8 to #16, one 100*mm* diameter by 100*mm* high aggregate/epoxy cylinder specimen was prepared for each of them.

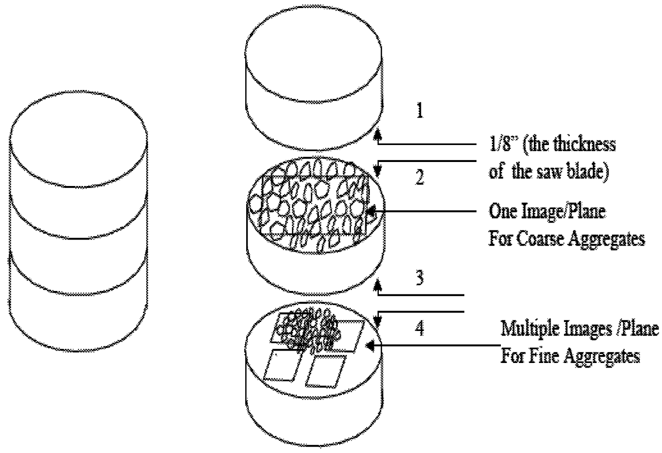


Fig. 4. Cutting of Specimens and Locations for Image Acquirement.

Table 1. Variation of the Sum of Perimeters and Cross Section Areas of Different Planes Cut from One Specimen (size range: 1/2 to 3/8*inch*).

Images Unit	No. of Particles	Particle Area (*mm*^{2})	Particle Perimeter (*mm*)	Sum of Feret Diameter (*mm*)	β(*1/mm*)	α*
1	59	3464.1	1878.9	550.2	0.542	1.708
2	47	3149.3	1685.9	454.2	0.535	1.856
3	55	2853.0	1579.2	468.4	0.554	1.686
4	54	2821.7	1537.9	445.3	0.545	1.727
5(1+2)	106	6613.4	3564.8	1004.4	0.539	1.775
6(5+3)	161	9466.4	5144	1472.8	0.543	1.746
7(4+6)	215	12288.1	6681.9	1918.1	0.544	1.742

*Analyzed by Multi-Feret Method.

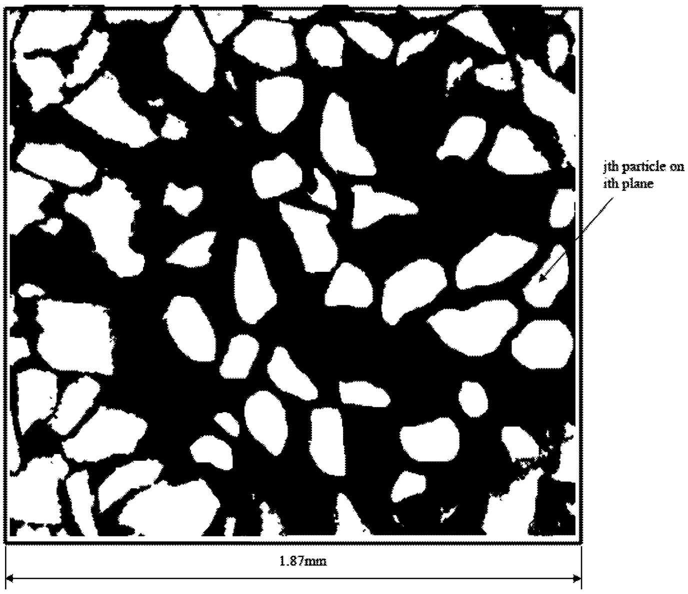


Fig. 5. A Typical Image from a Specimen (Crushed Aggregates, #50 to #100), (0.00366*mm*/pixel, 512×480).

Four cut planes from two saw cuts on each specimen were used in this investigation (Fig. 4).

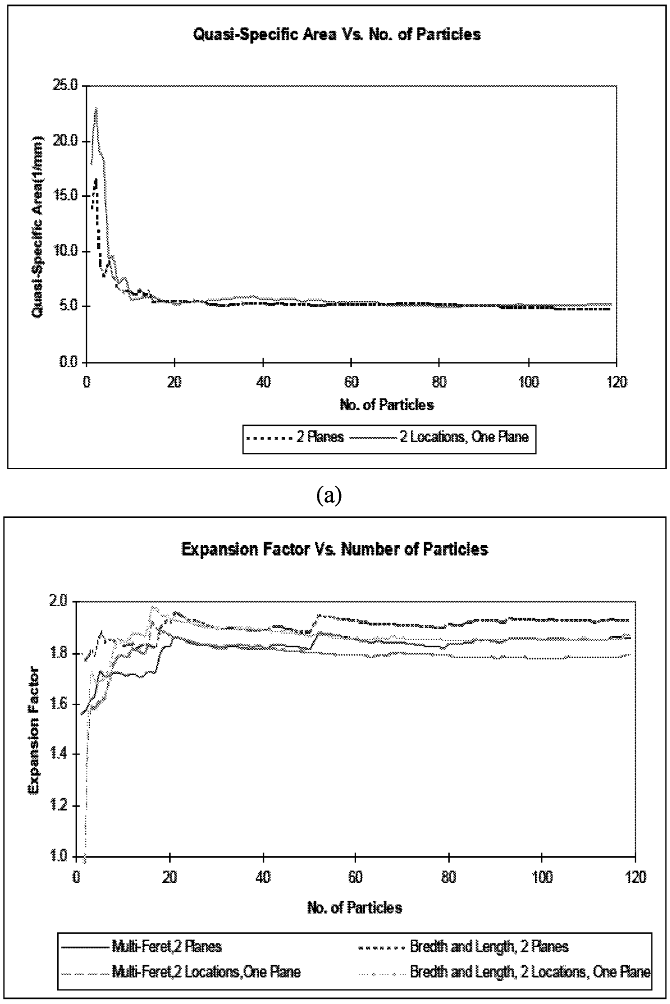
The images of these four cut planes were taken by an image analyzer, and the corresponding number of particle cross sections (n_i), the total perimeter length (p_i), and the total cross section areas (a_i) were determined for each cut surface and for the combination of 2, 3, and 4 cut surfaces. The expansion factor (α) and the specific area (β) for each of them were determined by Eqs. (5) and (10). Results for the crushed aggregates passing 12*mm* and retaining on 9*mm* are presented in Table 1. The Image Unit 1, 2, 3, and 4 in Table 1 represent each of the four cut planes; and the Image Unit 5, 6, and 7 represent the combinations of 2, 3, and 4 cut planes. Results shown in Table 1 indicate that the variation of β and α among these 7 image units is very small. For fine aggregates of #16 to #30, #30 to #50, and #50 to #100, one 20*mm* diameter and 30*mm* high aggregate/epoxy specimen was prepared for each of the size ranges. Multiple images from two cut planes were used to determine the specific area (β) and the expansion factor (α). Results similar to those shown in Table 1 were obtained.

Results of the analyses from the particle sizes ranging from passing a 19*mm* sieve to passing a #50 sieve indicated that the number of particle cross sections required for β and α to reach the stable value was between 100 to 200. For coarse aggregate particles, a cut plane of a 100*mm* diameter specimen contains 50 to 100 particle cross sections and 2 to 3 cut planes would be sufficient to achieve reasonably accurate determination of the β and α values.

For fine aggregate particles, a cut plane across a 20*mm* diameter specimen would contain several thousands of particle cross sections. To determine the particle cross section properties it became necessary to randomly select a small target area, containing approximately 50 to 100 particle cross sections, on the cut plane and magnifying it to an image frame of 512×480 pixel size. It was found that this magnification yielded adequate resolution to allow accurate determination of the particle cross section properties. Fig. 5 shows a 1.87 by 1.75*mm* target area magnified to a 512 × 480 pixel size image to reveal the detailed particle cross sections. Because 100 to 200 particle cross sections would be sufficient to achieve reasonable accurate determination of the β and α values as shown in Table 1, 2 to 3 small areas on the same cut plane can be used to determine these properties. To test the validity of this idea, an analysis of β and α with the information obtained from two images acquired from two locations on the same cut plane was compared with the analysis of two images acquired from two different cut planes. The results of these two analyses, as presented in Fig. 6, indicate that multiple images from one cut plane yielded the β and α values sufficiently close to that from the multiple cut planes. The use of multiple images from the same cut plane could save the efforts in the cutting, grounding, and polishing of the sample.

Statistical Evaluation of the Expansion Factor

The expansion factor (α) is defined as the ratio between the curved length and the projected length of a particle (Eq. (5)). For a particle cross section, the total curved length, which equals the perimeter, can be determined uniquely. However, projected lengths vary with orientations, which results in different expansion factors from the same curved length. An average Feret diameter along several orientations provides a good representation of the average projected length of a particle. To test the validity of this definition, six Feret



(a)

(b)

Fig. 6. Asymptotic Analysis of (a) Quasi-Specific Area and (b) Expansion Factor (#8 to #16) .

diameters in the 22.5°, 45°, 67.5°, 112.5°, 135°, and 157.5° orientations were averaged and used as the projected length for evaluating the expansion factor α. The averages of the maximum and minimum Feret diameters (breadth and length) of particle cross sections were also used for the projected length. The α values determined using these two definitions for the crushed aggregate in eight sieve size ranges were calculated and presented in Table 2. In all cases the α values determined based on the two definitions are very close.

The expansion factor for some common geometric shapes were also calculated and presented in Table 3. Compared with Table 3, the α for the crushed granite aggregates shown in Table 2 is larger than those of a circle and a square, and is close to that of an ellipse with an aspect ratio of 2.

Evaluation of the Specific Surface Area of Aggregates

Using the procedures described above, the expansion factors (α), the specific areas (β), and the specific surface areas (*SA*) of the crushed aggregate of different sieve sizes from passing 19*mm* to #50 were determined and presented in Table 4.

Table 2. Expansion Factor (α) Values by Two Different Definitions.

Sieve Size	α_1 By Multi-Feret Diameter	α_2 By Breadth And Length	α_1/α_2
3/4"–1/2"	1.79	1.90	0.94
1/2"–3/8"	1.82	1.91	0.95
3/8"–No.4	1.74	1.78	0.98
No.4–No.8	1.71	1.78	0.96
No.8–No.16	1.86	1.93	0.96
No.16–No.30	1.72	1.79	0.96
No.30–No.50	1.77	1.86	0.95
No.50–No.100	1.84	1.90	0.97

Table 3. The Expansion Factor (α) Values for Some Common Geometrical Shapes.

Shape	Perimeter/Projection Ratio
Circle	1.57
Ellipse(a/b=2,3,4)	1.74, 2.09, 2.76
Square	1.66
Equilateral Triangle	1.61
Rectangular(a/b=2,3,4,5)	1.85, 1.92, 1.95, 197

Table 4. Specific Surface Area (β) Values of Aggregates in Different Size Ranges.

Sieve Size	β(*1/mm*)	α (by Multi-Feret)	*SA*(*1/mm*)
3/4"–1/2"	0.50	1.79	0.89
1/2"–3/8"	0.54	1.82	0.99
3/8"–No.4	0.77	1.74	1.34
No.4–No.8	1.90	1.71	3.25
No.8–No.16	4.91	1.80	9.13
No.16–No.30	6.50	1.72	11.18
No.30–No.50	17.8	1.77	31.52
No.50–No.100	32.50	1.84	59.8

The approximate specific surface areas of aggregates commonly used by the aggregate industry were based on the averaged specific surface areas of the spheres (or cubes, both have the same specific surface areas of 6/d) having the diameters equal to the corresponding passing and retaining sieve opening sizes. These specific surface areas are usually expressed in terms of square foot per pound and have been widely used in various applications, including the determination of asphalt film thickness in the asphalt mixtures. The specific surface areas (both in terms of ft^2/lb and *1/mm*) of the spheres corresponding to the passing and the retaining sieve opening sizes and the average value of the two were computed for each aggregate sieve size and are presented in Table 5. Also presented in Table 5 is the Specific Surface Area Index derived from the Specific Surface Area Factors given in [1]. Compared with those approximate values, the specific surface areas determined by the method presented in this paper are higher in all cases.

For the fine aggregates (retained on #8 to #100 sieves), the ratios of the specific surface area determined by the proposed method to the specific surface area factor [1] of the aggregate particles retained on the same sieve size range from 1.3 to 2.1; while the ratios of the surface area determined by the fractal dimension method [2] to the surface area factor range from 1.06 to 1.2 .

The relatively higher value of the specific surface areas determined

Table 5. Specific Surface Area (*SA*) of Aggregates by Imaging Technique and by Sphere-Cube Estimation, Units: Square Foot/ Pound* (*1/mm*).

Sieve Size	*SA* By Imaging Techniques	*SA* of Cubes or Spheres Retaining Size	*SA* of Cubes or Spheres Passing Size	*SA* of Cubes or Spheres Average	*SA* Index **
3/4"–1/2"	1.65(0.89)	0.58(0.32)	0.87(0.47)	0.72(0.39)	2
1/2"–3/8"	1.81(0.98)	0.87(0.47)	1.16(0.63)	1.01(0.55)	2
3/8"–No.4	2.46(1.33)	1.16(0.63)	2.32(1.26)	1.74(0.95)	2
No.4–No.8	5.98(3.25)	2.32(1.26)	4.68(2.54)	3.50(1.90)	4
No.8–No.16	16.80(9.13)	4.68(2.54)	9.36(5.08)	7.02(3.81)	8
No.16–No.30	20.57(11.18)	9.36(5.08)	18.4(10.0)	13.88(7.54)	16
No.30–No.50	57.96(31.52)	18.4(10.0)	36.8(20.0)	27.60(15.0)	30
No.50–No.100	110.02(58.8)	36.8(20.0)	73.6(40.0)	55.20(30.0)	60

* The unit of specific area should be 1/L, the values in the parentheses are in *1/mm*. They were converted into square foot/pound by using 2.65 specific gravity for the aggregates.

** The *SA* Index values are derived from the surface area factor defined in [1].

determined by the proposed method than the corresponding values determined by the approximate method is primarily due to the irregular shapes and the rough textures of the crushed aggregate particles. To find out the effects of aggregate shapes and surface textures on the specific surface areas, an Ottwa sand passing #16 sieve and retaining on #30 sieve was determined according to the proposed method.

Fig. 7 shows the processed image (the binary black/white image converted from the gray image) of the Ottwa sand particles. Compared with Fig. 4, the difference in the particle shapes and surface textures between the Ottwa sand and the crushed sand is quite apparent. Results of the specific surface area, the roundness, and the slenderness ratio of the Ottwa sand particles are presented in Table 6 along with the same properties of the crushed sand in the same size range. The specific surface area of the Ottwa sand is about 7% lower than that of the crushed sand. The roundness and the aspect ratio of the Ottwa sand are also lower than those of the crushed sand. The roundness of a particle is defined as the ratio of the area of a circle having the same perimeter of the particle cross section to the actual cross section area. The slenderness ratio of a particle is defined as the ratio of the maximum Feret diameter to the minimum Feret diameter of the particle cross section [4].

Conclusions

The method presented in this paper using the imaging technique can be used to determine the specific surface areas of aggregates more accurately than the approximate method commonly used by the aggregate industry. The specific surface areas of crushed sand determined by the proposed method are higher, particularly for the aggregates passing #16, #30, and #50 sieves sizes, than that determined from the approximate method. The relatively higher value of the specific surface areas determined by the proposed method is primary due to the irregular shapes and the rough textures of the crushed aggregate particles. This proposed method has the potential to be used for quantifying the aggregate properties, including the specific surface area, roundness, slenderness ratio, and other relevant properties in the laboratory for the quality control of aggregate properties. Compared to other more advanced method [6], this method is applicable to both fine and coarse aggregates and conveniently to implement.

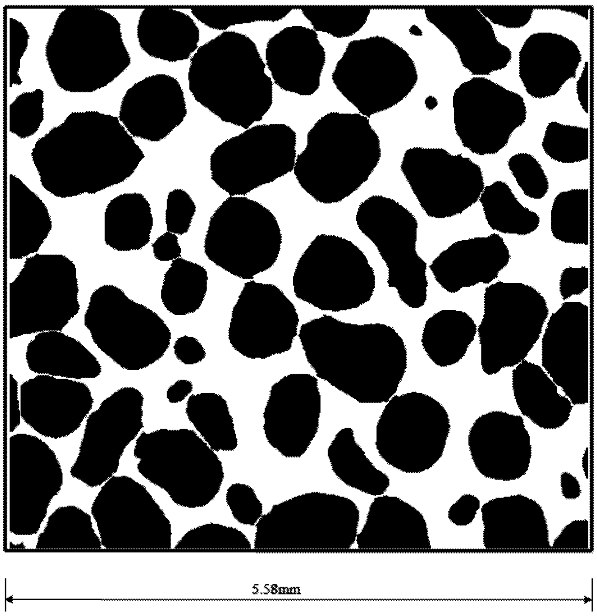


Fig. 7. An Image of Natural Sands (Ottwa and Passing #16, Retained on #30) (0.0109*mm*/pixel, 512×480).

Table 6. Cross Section Statistics of Crushed Aggregates vs. Natural Sands (#16 to #30 Aggregate Size).

Properties	Crushed Aggregates	Ottwa Sands
α	1.72	1.65
β(*1/mm*)	6.5	6.33
SA(*1/mm*)	11.18	10.44
Roundness	1.61	1.37
Slenderness Ratio	1.79	1.72
Number of Particles	126	113

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