

# Analyzing the Gradation of Asphalt Mixtures Based on Industrial Computerized Tomography

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**Abstract:** The performance of asphalt pavement is influenced by the gradation of asphalt mixtures. Using industrial computerized tomography, which is a nondestructive test technique to obtain slice images, analyzing these 2D slice images, and applying probability statistical theory, the 3D volumetric gradation of asphalt mixtures under the assumption of spherical aggregates can be estimated from 2D sectional gradation. There is error between the gradations of spherical aggregate assumption and mechanical sieving and a correction method is therefore developed to convert the gradation of spherical aggregate assumption to that of mechanical sieving. By introducing correction factor *C*, the error becomes less than 5%, which can meet engineering requirements. The results of this study indicate that this new method of determining gradation has the advantage of improved efficiency with reasonable accuracy.

**Key words:** Asphalt mixture; Digital image processing; Gradation; Industrial CT; Road engineering.

Asphalt mixture is a complicated composite with 80% to 90% of its volume occupied by aggregates of different sizes. Therefore, aggregates characteristics and gradation affect the performance of asphalt pavement [1]. In recent years, with the progress of image acquisition and computer technologies, digital image processing has been used in many areas, including in civil engineering[2-4]. Many researchers have studied 2D sectional gradation by cutting specimen to acquire section image, as indicated in references[5-7]. Wang[8] also developed a method to study 3D volumetric gradation using the 2D sectional gradations with a constant ratio of aggregate's thickness to its width theory.

Since aggregates in asphalt mixtures have 3D characteristics, a new methodology is presented in this technical note that uses the industrial computerized tomography (CT), which is a nondestructive test technique to obtain slice images, analyzes these 2D slice images, and estimates the 3D volumetric gradation from the 2D sectional gradations y applying probability statistics.

## Introduction of Industrial CT

Industrial CT is a new imaging technique in which a computer is used to re-composite the image of slices generated from an X-ray scanning device, and it can detect the structure of non-transparent object nondestructively. When the X-ray penetrates material, the strength of the X-ray will attenuate exponentially. Because different material has a different absorption coefficient, the density of the material will be reflected in the X-ray's attenuation.

A quantitative description of industrial CT is CT No., and the

relation between tested material's absorption coefficient and CT No. is shown in Eq. (1):

$$CT\ No. = \frac{\mu - \mu_w}{\mu_w} \times 1000 \quad (1)$$

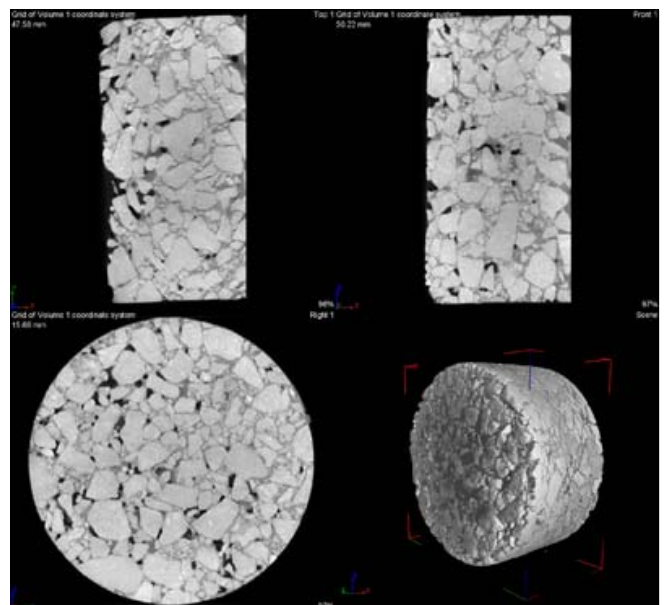
where,  $\mu_w$  = water's absorption coefficient, and  $\mu$  = material's absorption coefficient.

A piece of complete CT image is generated according to brightness, which is proportional to CT No.

Fig. 1 shows the example of an asphalt mixture image that was scanned by industrial CT.

## Relation between Volumetric and Sectional Gradation

Aggregates in the 2D section are from a random cutting of a particle and, therefore, the 2D sectional gradation of aggregates cannot be



**Fig. 1.** Image of Asphalt Mixture Specimen.

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**Table 1.** Gradation of SMA-16.

	Percent Passing the Following Sieves (mm)										
Gradation	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
SMA-16	100	91.0	75.0	55.0	30.0	21.5	17.5	14.0	11.5	9.5	8.5

regarded as 3D volumetric gradation. However, they must contain some information about 3D volumetric gradation of specimen. A reference [10] indicates that 3D volumetric gradation could be estimated by analyzing aggregate distributions that were obtained from a batch of 2D slice images with the probability theory.

Saltykov and DeHoff [10] conducted a spatial geometric analysis on the issue and concluded that under the condition of spherical aggregate assumption, all the circles in the 2D section were divided into  $m$  groups according to their diameter, where the circle's diameter of group  $j$  was  $d_j$  and distribution frequency was  $N_A(j)$  for group  $j$ . Relatively, all the spherical aggregates were divided into  $n$  groups according to their diameter, where the aggregate's diameter of group  $i$  was  $D_i$  and distribution frequency was  $N_V(j)$  for group  $i$ . A correlation exists between the distribution frequency of circles from the 2D section and that of aggregates, as shown in Eq. (2):

$$N_A(j) = 2\Delta \sum_{i=j}^n k_{ji} N_V(i) \quad (2)$$

where,  $N_A(j)$  = distribution frequency of circle for group  $j$ ;  
 $N_V(j)$  = distribution frequency of spherical aggregate for group  $i$ ;  
 $k_{ji}$  = conversion factor; and  
 $\Delta$  = group space.

Solving Eq. 2, it could be obtained as following:

$$N_V(i) = \frac{1}{2\Delta} \sum_{j=i}^n \alpha_{ij} N_A(j) \quad (3)$$

where,  $\alpha_{ij}$  = inverse matrix of  $k_{ji}$ .

The equation of calculating  $k_{ji}$  can be determined as follows [11]:

$$k_{ji} = 0 \quad (j \neq i, j > i)$$

$$k_{ji} = [(i - \frac{1}{2})^2 - (j - 1)^2]^{1/2} = (i - \frac{3}{4})^{1/2} \quad (i = j) \quad (4)$$

$$k_{ji} = [(i - \frac{1}{2})^2 - (j - 1)^2]^{1/2} - [(i - \frac{1}{2})^2 - j^2]^{1/2} \quad (i \neq j, i > j)$$

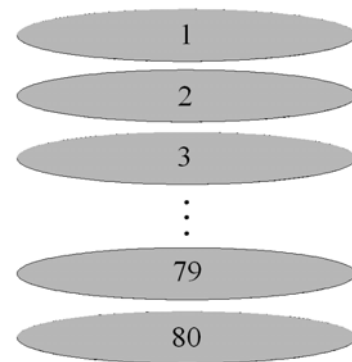
The aggregate's distribution frequency in 2D section,  $N_A(j)$ , can be calculated using a batch of slice images acquired from industrial CT and then the corresponding 3D volumetric gradation can be determined using Eq. 3.

**Test Design**

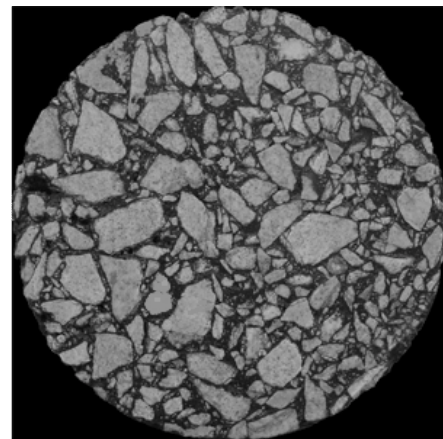
Asphalt mixture specimens of SMA-16 with a diameter of 150mm were compacted using a superpave gyration compacter (SGC). Granite was used as an aggregate, limestone as mineral powder, and 70# base asphalt as asphalt binder in this test. Gradation of asphalt mixture is shown in Table 1.

Specimens were compacted to a height of 75mm. A industrial CT

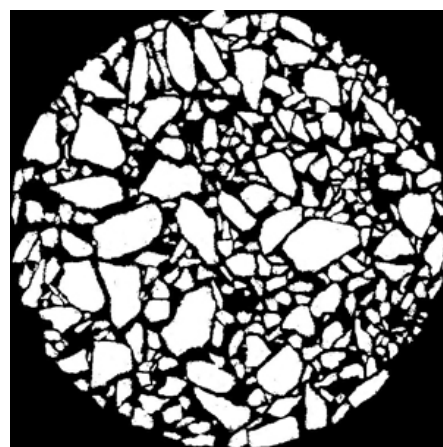
was used to scan specimens, and about 400 images were acquired for each specimen. For the convenience of processing, 80 slices of images with the same space were saved for gradation analysis as demonstrated in Fig. 2.



**Fig. 2.** Saving Slice Images.



**Fig. 3.** Image of SMA-16.



**Fig. 4.** Binary of Image.

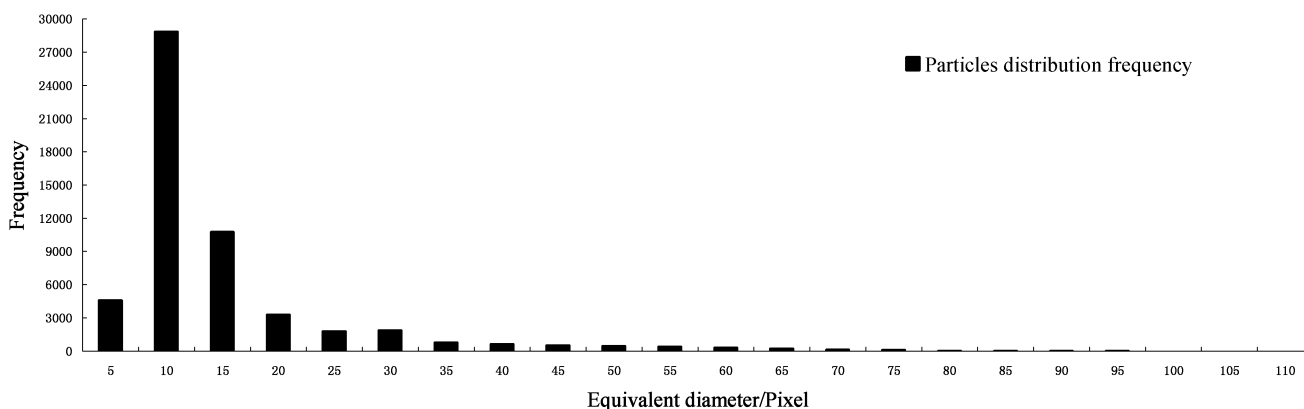


Fig. 5. Particles' Distribution Frequency in 2D Section.

Pre-processing on all the slice images was conducted for image enhancement and noise elimination, as shown in Fig. 3. Then a binary operation using the double-peak method [12] was conducted to separate aggregates' form binder, as shown in Fig. 4. The size of this image is 750 pixels × 750 pixels, and each pixel represents 0.2mm.

Several parameters were measured after image processing, including the particles' amount, aggregates' area, and equivalent diameter. The equivalent diameter was determined using the Feretmeter [13] method, as shown in Eq. (5):

$$Feretmeter = 2\sqrt{Area / \pi} \tag{5}$$

where, *Feretmeter* = equivalent diameter, and *Area* = aggregate's area in a section.

The statistic result of 80 images similar to the one presented in Fig. 4 is as follows: particles' amount was 54812 and the maximum equivalent diameter was 109 pixels. So these particles were divided into 22 groups and the group space was 5 pixels. Fig. 5 is the distribution frequency histogram of particles described in the equivalent diameter.

### Result Analysis and Error Correction

The distribution frequency of spherical aggregate,  $N_p$ , for each individual equivalent diameter was calculated by substituting the distribution frequency of circle  $N_A(j)$  of the corresponding equivalent diameter determined from the digital image processing into Eq. (3), and it was then further converted into a volume percentage under the condition of spherical aggregate assumption. For the purpose of a demonstration on the study method and also considering the accuracy of image recognition, only particles larger than 4.75mm were analyzed in this technical note.

Since aggregates coming from the same source will have the same density, it is believed that the quality percentage of aggregates is equal to their volume percentage. The gradation under the condition of spherical aggregate assumption was then calculated and is shown in Fig. 6 with the results of mechanical sieving given in Table 1.

It can be seen in Fig. 6 that the passing percentage under the assumption of spherical aggregates is larger than that of mechanical

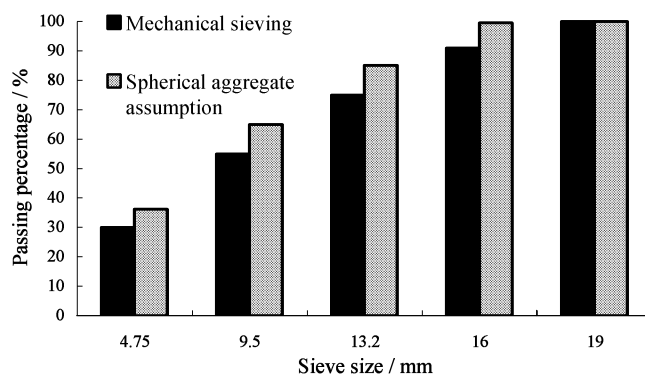
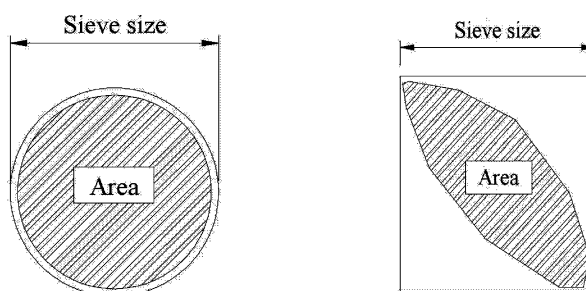


Fig. 6. Gradation of Spherical Aggregate Assumption and Mechanical Sieving.



(a) Circular sieve (b) Square sieve

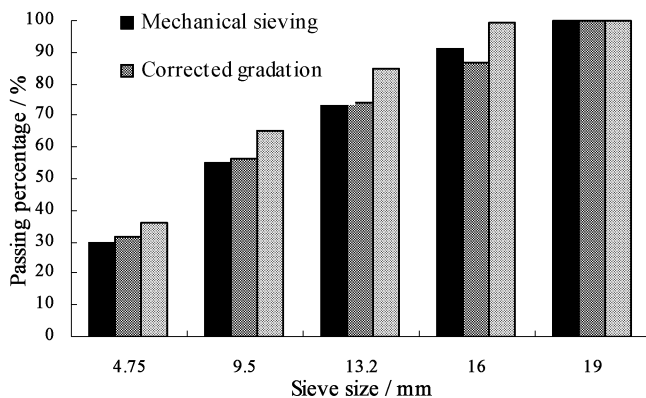
Fig. 7. Passing Capability of Circular and Square Sieve.

sieving. Obviously, the assumption of spherical aggregates will cause some errors when predicting the percentage of passing. The error is small for aggregates with the shape close to a polyhedron with many surfaces but is large for aggregates with the shape close to a tetrahedral, cube, octahedron, cone, and cylinder. So some shape correction needs to be made for real aggregates with shapes different from a sphere.

Since mechanical sieving has square openings opposite to circle openings of spherical aggregate assumption, it is believed that the size of circular sieve is smaller than that of a square sieve when aggregates with the same area pass through them, as shown in Fig. 7.

**Table 2.** Calculation Errors of Spherical Aggregate Assumption.

Sieve Size (mm)	Passing Percentage of Mechanical Sieving (%)	Passing Percentage of Spherical Aggregate Assumption (%)	Errors of Spherical Aggregate Assumption (%)	Passing Percentage after Correction(%)	Errors after Correction (%)
19.0	100	100	0	100	0
16.0	91.0	99.5	9.34	86.6	4.84
13.2	75.0	85.1	13.47	74.0	1.33
9.50	55.0	65.0	18.18	56.6	2.90
4.75	30.0	36.2	20.67	31.5	5.00
Ave. Error	—	—	15.41	—	3.52

**Fig. 8.** Gradation of Corrected and Mechanical Sieving.

In order to make a circular sieve and square sieve equal in passing capability, the results from the spherical aggregate assumption need to be corrected, and a correction factor  $C$  is introduced. There is an explanation in *Technical Specification for Construction of Highway Roadbase in China (JTJ034-2000)* that the maximum diameter of aggregates is 1.2-1.25 times larger when passing circular sieves than the one passing square sieves. After a trial-and-error calculation process with  $C$  of 0.87, an approximate agreement was reached between the corrected gradation and mechanical sieving gradation of same aggregates, as shown in Fig. 8, which is the same as the conclusion of Mora [14] ( $C$  was between 0.81 and 0.89).

The accuracy of gradation predicted under the condition of spherical aggregate assumption was also investigated quantitatively in this study. The relative error of aggregates' passing percentage is defined as:

$$E_k = \frac{|P_{M,k} - P_{S,k}|}{P_{M,k}} \times 100\% \quad (6)$$

$$E = \frac{1}{n} \sum_{k=1}^n E_k$$

where,  $E_k$  = relative error of passing percentage for rank  $k$ ,  
 $P_{M,k}$  = passing percentage of mechanical sieving for rank  $k$ ,  
 $P_{S,k}$  = passing percentage of spherical aggregate assumption for rank  $k$ ,

$E$  = average error, and

$n$  = number of total ranks.

Table 2 shows the result of errors for spherical aggregate assumption before and after correction using the method discussed.

It can be seen in Fig. 8 and Table 2 that before the correction, the error caused by spherical aggregate assumption is significant with the average and maximum errors of 15.41 and 20.67%, respectively. However after correction, the calculation error is reduced with the average and maximum error of 3.52 and 5.00%, respectively. Therefore after the correction, gradations determined under the spherical aggregate assumption and by the mechanical sieving have a reasonably good match. So, using digital image processing to calculate the gradation of aggregates can reach a reasonably high accuracy of 95%, which will meet the general engineering requirement.

## Conclusions

As the summary of this technical note, the following conclusions can be made:

1. A new method to estimate the gradation of asphalt mixtures is proposed in this technical note. In this new method, industrial CT is used to acquire slice images of aggregates to be studied and these images are combined according to a probability statistics approach to estimate the corresponding 3D volumetric gradation from the 2D sectional gradations.
2. The new method proposed in this note takes the assumption that the aggregate is a sphere, which leads to the discrepancy or error between calculation results and measured results. By introducing correction factor  $C$ , the error becomes less than 5%, which can meet the general engineering requirement.
3. Because of the restriction of image processing accuracy, only the gradation of coarse aggregates was investigated in this study and further research efforts should be given to determine the gradation of fine aggregates. In general, as a nondestructive test technique, this method will have wide application potentials as the accuracy of image processing improves.

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