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Innovation of aggregate angularity characterization using gradient approach based upon the traditional and modified Sobel operation

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HIGHLIGHTS

- Real particles and computer generated particles were generated by image processing.
- Six different kernel sizes and two different pixel numbers method were used.
- The sensitivity of image resolution on the approach was analyzed.
- The 7 × 7 sized kernel with the 2-pixel method mimics the angularity index.

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ABSTRACT

This study aims to employ the modified Sobel-Feldman operation to quantify aggregate angularity using the gradient approach, which has been used in previous studies. In detail, the modified Sobel-Feldman operation lies in expanding the conventional kernel size of the operation from 3 × 3 to 5 × 5, and up to 13 × 13 using the average gradient vectors of two neighboring pixels (2-pixel) instead of one single pixel (1-pixel) to calculate the angularity index. To achieve this goal, image processing was conducted to obtain the outlines of aggregate images. The gradient vectors of the surface pixels were obtained using the conventional and modified Sobel-Feldman operation. Then the angularity index (AI) of aggregates were calculated based on the change in gradient vectors of neighboring pixels with a rotational angle of 10°. The angularity index calculated using the conventional and modified Sobel-Feldman operations were compared. The sensitivity of the approach to image resolution was also discussed in this study. The profile images of both real aggregates and computer generated aggregate models were used for this investigation. The results show that the conventional Sobel-Feldman operation results have a higher Angularity Index than that of larger sized kernels. The AI values calculated from the 2-pixel method were more stable compared to those using the 1-pixel method. The modified Sobel-Feldman operation has lower sensitivity to image resolution than the conventional operation. Overall, the gradient approach using the 7 × 7 sized Sobel-Feldman operation with the 2-pixel method is the best way to calculate the angularity index. The findings of this study can potentially be adopted by commercial angularity index measurement apparatuses such as the aggregate imaging system (AIMS).

1. Background

1.1. AI characterization

It is widely accepted that aggregate characteristics have a big impact on the performance of asphalt pavement [1,2]. Aggregate characteristics consist of angularity, surface texture, and aggregate shape. Angularity has a relationship with the sharpness of the aggregate particles [3].

Digital imaging techniques [4] have the advantage of quicker results, a decrease in technician subjectivity, and the capability to analyze samples with large data. Most imaging systems use video camera, such as the Aggregate Imaging System (AIMS [5]), and the University of Illinois Aggregate Image Analyzer (UIAIA [6]); some adopt the laser technique [7], and some utilize X-ray computerized tomography to obtain 3D images [8].

In the past decade, using imaging techniques [9–13] as well as correlating their characteristics to pavement performance has been

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the trend to quantify aggregate morphological characteristics. Also, Wnek [14] investigated the aggregate properties' influence on railroad ballast performance.

Researchers utilized the image analysis method from different aspects to define or quantify the aggregate angularity. Masad et al. [15] proposed a particle angularity model, which used an equivalent ellipse as the ideal particles to compare a real particle in the same direction. The ellipse is used to minimize the difference in angularity caused by different forms. Angularity index is expressed as follows:

$$AI = \sum_{\theta=0}^{\theta=355} \frac{|R_{P\theta} - R_{EE\theta}|}{R_{EE\theta}} \tag{1}$$

where $R_{P\theta}$ is the radius of the particle at a directional angle θ,

$R_{EE\theta}$ is the radius of an equivalent ellipse at a directional angle θ.

Rao et al. [16] developed an angularity index with an image analysis system (the University of Illinois Aggregate Image Analyzer, UIAIA). The angularity is obtained from three views (top, side and front view). Then, the final angularity index is computed by taking a weighted average of all three views.

$$Angularity = \sum_{e=0}^{170} e \times P(e) \tag{2}$$

where e is the starting angle for each 10-degree class interval,

$P(e)$ is the probability of change in angle β and has a value in the range e to $(e + 10)$.

The "Angularity Index" of a particle is then calculated by the mean of angularity values from the three different views, as given in the following equation:

$$AI = \frac{\sum_{i=1}^{3} Angularity(i) \times Area(i)}{\sum_{i=1}^{3} Area(i)} \tag{3}$$

where i is values from 1 to 3 from top, front, and side views.

Wang (2005) [17] took advantage of Fourier analysis to evaluate aggregate shape, angularity and texture. The profile of the aggregate was converted into a mathematical equation, and the ranges of frequency define the aggregate morphology.

Tafesse [18] developed a new method to calculate angularity, named the Smoothing Angularity Index (SAI). The SAI algorithm could be used in the field and has the advantage of simple image acquisition setups [19,20]. Firstly, two consecutive smoothing curves are plotted along the edge of the particle image. Then the perpendicular lengths between the two curves were used to calculate the amplitudes. Finally, the standard deviation of the amplitude is set as the particle angularity:

$$SAI = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(d_i - \bar{d})^2 a} \tag{4}$$

where d_i is the distance between the two smoothing curves at the i-th point,

$\bar{d}$ is the mean of the distance between the two curves and n is the number of perpendicular parts between the two smoothing curves.

Wang [21] compared different aggregate image analysis systems to evaluate morphological characteristics of aggregate. It is shown that either AIMS II or the FTI system is recommended to evaluate the angularity of aggregates.

Some researchers focus on developing the correlation between aggregate morphology and pavement performance. Bennert [22] investigated the correlation between the angularity of coarse aggregate and rutting depth in New York State. However, the result of the APA test did not relate well with the measured angularity of coarse aggregate. Souza [23] evaluated aggregate angularity on the rutting performance and fatigue resistance by experimental tests and microstructural finite-element simulations. More binder was needed as the angularity increased. In this way, the cracking resistance of mixtures is positive with the angularity of aggregate. Singh [24] took advantage of aggregate shape indices to estimate the dynamic modulus of asphalt mixtures. Mollanouri [25] simulated the mechanical behavior of particles with different angularities using the discrete element method.

In this study, the images of aggregates were taken with digital cameras. Through a series of image processing, the edge of the particle was acquired. Then, the edges were processed with a gradient method, herein the Sobel-Feldman operation was used. The calculated gradient directions were used to compute the angularity index (AI) of the particle. At the same time, to find the optimum parameter for this method, different factors were discussed.

1.2. Sobel-Feldman operation

The Sobel-Feldman operator includes two operations: the smoothing perpendicular to the derivative direction and the simple central difference in the derivative direction [26]. The perpendicular smoothing can be acquired from Pascal's Triangle. Particularly, the expression of the two operations are:

$$h(-1) = 1,\ h(0) = 2,\ h(1) = 1$$

$$h'(-1) = -1,\ h'(0) = 0,\ h'(1) = 1, \tag{5}$$

In a 2D Sobel-Feldman operation, the gradient matrix in the x- and y-directions are expressed as:

$$\begin{cases} k_x(x,y) = h(x)h'(y) \\ k_y(x,y) = h'(x)h(y) \end{cases} x,y \in \{0,-1,1\} \tag{6}$$

The convolution kernels in the x- and y-directions are calculated as:

$$kx = \begin{bmatrix} h(-1)h'(-1) & h(-1)h'(0) & h(-1)h'(1) \\ h(0)h'(-1) & h(0)h'(0) & h(0)h'(1) \\ h(1)h'(-1) & h(1)h'(0) & h(1)h'(1) \end{bmatrix} = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}$$
$$ky = \begin{bmatrix} h'(-1)h(-1) & h'(-1)h(0) & h'(-1)h(1) \\ h'(0)h(-1) & h'(0)h(0) & h'(0)h(1) \\ h'(1)h(-1) & h'(1)h(0) & h'(1)h(1) \end{bmatrix} = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} \tag{7}$$

$$Gx = kx * A \tag{8}$$

$$Gy = ky * A \tag{9}$$

$$G = \sqrt{(Gx^2 + Gy^2)} \tag{10}$$

$$\theta = \arctan\left(\frac{Gy}{Gx}\right) \tag{11}$$

where A = the input image;

Gx, Gy = the output image of x- and y- components;

kx, ky = the kernels in x- and y-directions.

G = the output image;

θ = the gradient direction;

$*$ = the 2D convolution operation.

For every 10 degrees from the particle center, as illustrated in Fig. 3(a), the point (pixel) on the edge is selected. Then the gradient direction of that point (pixel) is calculated. Moreover the difference in the gradient direction between adjacent points are calculated. Finally, the angularity index (AI) is acquired by summation.