Intelligent numerical computation method and quantitative study on morphological characteristics of multi-scale aggregate

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Abstract. Use Image-Pro Plus software, high-precision inductive sensor TR200, electron microscope and ENVI image processing system to quantitatively study aggregate morphology from three scales: macro, meso, and micro, and obtain 17 quantitative indicators of morphological characteristics, compared with the occupancy rate of the aggregate broken surface and the roughness of the aggregate surface. The results show that the 17 morphological characteristics indexes are feasible for multi-scale quantification of aggregate morphology. Macro-morphological characteristics directly indicate the angularity and needle-like shape of materials, micro-morphological characteristics directly indicate the roughness of materials surface, and micro-morphological characteristics directly indicate the micro-morphological characteristics of materials. The quantitative indexes of aggregate morphology at micro-scale and micro-scale are improved, and the results are helpful to reveal the morphological characteristics of aggregate comprehensively.

Keywords: Coarse aggregate, Morphological characteristics, Angularity, Roughness, Digital image processing.

1. Introduction

Macroscopic morphological characteristics refer to macroscopic visible morphological characteristics such as angular and needle-like aggregate. The research methods include image processing [2, 3], CT scanning [4, 5], analyzer measurement [6, 7], mathematical modeling [8, 9, 10], etc. Meso-morphological characteristics refer to the micro-morphological characteristics such as the depth and width of gullies on aggregate surface and the roughness of surface texture. The research methods are mainly characterized indirectly by contour measurement method [11, 12] and mathematical modeling method [13, 14]. Micro-morphological characteristics refer to the surface morphological characteristics of aggregate in the micro range [15, 16]. The research methods are image analysis [17, 18] and electron microscope scanning [19, 20]. A large number of scholars have studied the macro-morphology of coarse aggregate [1], but few have studied the micro-morphology and micro-morphology of aggregate by direct characteriz...
ation method. In this paper, the morphological characteristics of aggregate are systematically studied from macro, micro and micro scales.

2. Study on macro morphological characteristics of aggregate
The macroscopic morphological characteristics of aggregate refer to the morphological characteristics of aggregate in the range of 500μm-100mm, which are mainly angular and needle-like of aggregate. Four aggregates of pebbles with a particle size of 9.5 mm-13.2 mm, broken pebbles I, broken pebbles II, and basalt were selected for the experiment. The proportion of gravel on the broken surface was measured for 4 kinds of aggregates, and the summary results are shown in Table 1.

| Occupancy rate (%) | Pebble | Broken pebble I | Broken pebble II | Basalt |
|--------------------|--------|-----------------|------------------|--------|
| P₁                 | 0      | 99.67           | 100              | 100    |
| P₂                 | 0      | 57.15           | 92.03            | 100    |

Note: P₁ is the occupancy rate of aggregates containing one or more crushed surfaces. P₂ is the occupancy rate of aggregates containing 2 or more broken surfaces.

64 pieces of each of the 4 kinds of aggregates are selected, and the images are collected by the camera, as shown in Fig. 1.

![Aggregate image collection](image.png)

**Fig 1.** Aggregate image collection.

Image-Pro Plus software is used to denoise the color of the aggregate image, and then the aggregate element is picked up, and the aggregate rendering interface. The extracted parameters mainly include Area parameters, Perimeter, Perimeter(convex), Perimeter(ellipse), Box(X), Box(Y), Feret (max), Feret (mean), Feret (min), etc.

According to the principle of plane projection, an inductance depth meter is used to measure the aggregate thickness-to-width ratio ζ. Use the box plot to calculate the aggregate thickness-to-width ratio ζ, as shown in Fig. 2.
According to the equivalent ellipse theory, the convexity $p$, roundness $r$ and axiality $a_s$ are used to quantify the two-dimensional morphological characteristics of aggregate, and the slice $S_d$, sphericity $D_s$ and morphological factor $S_f$ are used to quantify the three-dimensional morphological characteristics of aggregate. The calculation formula is shown in Table 2.

**Table 2.** The calculation formula of macro-morphological characteristic indicators.

| Macro morphological index | Calculation formula | Macro morphological index | Calculation formula |
|---------------------------|---------------------|---------------------------|---------------------|
| $A_s$                     | $\frac{Box - Y - Box - X}{Box - Y}$ | $R$ | $\frac{Perimeter^2 - 4\pi Area}{Perimeter^2}$ |
| $P$                       | $\frac{Perimeter_{convex} - Perimeter_{ellipse}}{Perimeter_{ellipse}}$ | $D_s$ | $1 - \frac{4\pi A \cdot \zeta}{Perimeter^2}$ |
| $S_d$                     | $\frac{Feret_{max}}{\zeta \cdot Feret_{min}} - 1$ | $S_f$ | $1 - \frac{\zeta \cdot Feret_{min}}{\sqrt{Feret_{min} \cdot Feret_{max}}}$ |

The macro-morphological characteristic indexes of four aggregates of cobblestone, broken cobblestone I, broken cobblestone II, and basalt are shown in Fig. 3.
Fig 3. 3D bar graph of aggregate morphological feature data.

Statistics of the macroscopic morphological characteristic indexes of 4 kinds of aggregates, the mean value and the coefficient of variation are obtained, as shown in Table 3.

Table 3. Index data of aggregate macroscopic morphological characteristics.

| Aggregate type         | Statistic | P     | As    | R     | Sd    | Ds    | Sf     |
|------------------------|-----------|-------|-------|-------|-------|-------|--------|
| Pebble                 | AVG       | 0.0052| 0.2843| 0.0857| 0.6032| 0.1584| 0.2339 |
|                        | C.V       | 1.298 | 0.414 | 0.505 | 0.466 | 0.381 | 0.320  |
| Broken pebble I        | AVG       | 0.0283| 0.2730| 0.1387| 0.7796| 0.2669| 0.2990 |
|                        | C.V       | 0.788 | 0.4556| 0.433 | 0.451 | 0.344 | 0.310  |
| Broken pebble II       | AVG       | 0.0503| 0.2168| 0.1883| 0.8044| 0.3247| 0.3089 |
|                        | C.V       | 0.4795| 0.5508| 0.2835| 0.4476| 0.3067| 0.3354 |
| Basalt                 | AVG       | 0.0526| 0.2070| 0.1754| 0.6440| 0.2802| 0.2654 |
|                        | C.V       | 0.3981| 0.5329| 0.3151| 0.3860| 0.2374| 0.2426 |

3. Study on meso morphological characteristics of aggregate

Meso-morphological characteristics of aggregate refer to the surface morphology characteristics of aggregate in the range of 1μm-500μm, mainly the roughness of aggregate surface.

The high-precision inductive sensor tr200 is used to detect the smooth surface of pebbles, the broken surface of broken pebbles and the gully depth and texture width of basalt surface in 3D space, as shown in Fig. 4.
The aggregate roughness index adopts: AveRage value of arithmetic deviation ra of meso-outline depth on aggregate surface, peak height Ry of maximum outline, height Rz of outline unevenness at ten o'clock, maximum peak value Rp of outline and average value RSm of outline width. Schematic diagram of aggregate surface meso-morphology characteristic index is shown in Fig. 5.

![Schematic diagram of aggregate profile curve.](image)

The calculation formulas of Ra and RSm are shown in formula 1 and formula 2:

\[
Ra = \frac{1}{L} \int_{x_0}^{x_1} f(x)dx 
\]

(1)

\[
RSm = \frac{1}{m} \sum_{i=1}^{m} Xsi 
\]

(2)

Three aggregate surfaces, namely smooth surface of cobblestone, broken surface of broken cobblestone, and surface of basalt, were selected for the determination of mesomorphological indicators. The statistical data is shown in Table 4.

| Roughness parameter (μm)          | Statistic       | Ra   | Ry   | Rz   | Rp   | RSm  |
|-----------------------------------|-----------------|------|------|------|------|------|
| Pebble glossy surface             | Mean value      | 1.514| 9.246| 8.221| 3.193| 39   |
|                                   | Coefficient of variation | 0.220| 0.309| 0.292| 0.194| 0.225|
| Broken surface of cobblestone     | Mean value      | 5.235| 31.671| 27.609| 11.035| 81   |
|                                   | Coefficient of variation | 0.073| 0.177| 0.179| 0.140| 0.624|
| Basalt                            | Mean value      | 5.702| 34.934| 28.279| 12.196| 46   |
|                                   | Coefficient of variation | 0.361| 0.404| 0.462| 0.387| 0.464|
The box plot is used to calculate the aggregate morphological feature indicators, as shown in Fig. 6.

![Box plot of characteristic parameters of aggregate morphology.](image)

**Fig 6.** Box plot of characteristic parameters of aggregate morphology.

4. **Study on micro morphological characteristics of aggregate**

The microscopic morphology of aggregate refers to the surface morphology of aggregate in the range of 0.1μ m-1μ m.

Samples of pebbles, broken pebbles and basalt were scanned by SIGMA 300 scanning electron microscope. Collect microscopic pictures of 100-10000 times, as shown in Fig. 7.

![Microscopic image of aggregate.](image)

**Fig 7.** The microscopic image of aggregate.
The ENVI system is used to analyze the gray value of the scanning electron microscope image, and the aggregate scanning electron microscope image (excluding the annotation part at the bottom of the image) is selected as the training area. The whole scanning electron microscope image is stretched and denoised, and the maximum likelihood classification method is used for supervised classification.

According to the Bayesian formula, the discriminant function is obtained:

$$g_i(x) = \ln[p(\omega_i)] - \frac{1}{2} \ln \sum \omega_i - \frac{1}{2}(x-u_i)' \sum_i^{-1}(x-u_i)$$

(3)

In the formula, I=1, 2... $N_c$ is the selected serial number in the image, and there are a total of $N_c$ color difference classifications. K is the number of bands selected in the experiment. $u_i$ is the mean vector of each category in the electron microscope image. The covariance and mean of training samples are used to replace $\sum \omega_i$ and $u_i$.

Typical peaks, gullies and slopes in the scanning electron microscope are selected as samples for training, and the occupied areas of peaks, gullies and slopes in the scanning electron microscope are obtained, as shown in Fig. 8.

![Fig 8. Feature extraction results of scanning electron microscope images.](image_url)

Extraction of peaks, gullies and slope occupancy in scanning electron microscope images. The results are summarized in Table 5.

| Surface type               | Microscopic parameters | 100 times | 500 times | 1000 times | 2000 times | 5000 times | 10000 times |
|---------------------------|------------------------|-----------|-----------|------------|------------|------------|-------------|
| Pebble glossy surface     | Crest                  | 3.17      | 17.74     | 16.01      | 15.59      | 15.30      | 17.08       |
|                           | Gully                  | 7.12      | 7.25      | 12.51      | 3.51       | 3.68       | 3.08        |
|                           | Dome                   | 89.71     | 75.01     | 71.48      | 80.90      | 81.03      | 79.84       |
| Broken surface of cobblestone | Crest                | 12.31     | 7.76      | 8.03       | 7.80       | 7.23       | 12.07       |
|                           | Gully                  | 22.21     | 1.55      | 4.73       | 8.76       | 3.44       | 6.44        |
|                           | Dome                   | 65.49     | 90.69     | 87.25      | 83.43      | 89.32      | 81.49       |
| Basalt                    | Crest                  | 18.51     | 17.46     | 17.09      | 20.24      | 19.78      | 17.15       |
|                           | Gully                  | 3.52      | 4.25      | 5.16       | 6.31       | 9.61       | 5.83        |
|                           | Dome                   | 77.97     | 78.29     | 77.75      | 73.45      | 70.61      | 77.02       |
The common occupancy rate of peaks and gullies in aggregate surface morphology is defined as $Q$ ($\%$) of micro texture, which represents the morphological characteristics of aggregate surface at micro scale. The statistical results are shown in Fig. 9.

![Fig 9. Micro-texture occupancy rate statistics.](image)

5. Verification of aggregate morphological characteristics index

5.1. Verification of macro morphological characteristics

P and R of cobblestone, broken cobblestone I and broken cobblestone II increased in turn, while S decreased in turn, which indicated that the angularity of the three aggregates increased in turn. Sd and Ds increased in turn, which indicated that the needle fineness of the three aggregates increased in turn. P, r, A and Ds of basalt are similar to broken cobblestone II, which indicates that the two aggregates of basalt and broken cobblestone II are similar in angularity and needle shape. Sf is a comprehensive characterization of aggregate macro-morphology. The larger Sf is, the more obvious the angular and needle-like properties of aggregate are. It is consistent with the measured results of gravel percentage on the broken surface of four kinds of aggregates.

The verification results show that six macroscopic morphological characteristics, such as convexity p, axiality as, roundness r, slice Sd, sphericity Ds and morphological factor Sf, can fully characterize the morphological characteristics of aggregate at macro scale.

5.2. Verification of meso morphological characteristics

The average values of Ra, Ry, Rz, and Rp of the smooth surface of cobblestone, broken surface of cobblestone, and basalt surface increase sequentially. It directly shows that the depth of the surface profile of the three aggregates, the degree of peak convexity, and the degree of unevenness of wave peaks all increase in sequence. On the surface of cobblestone, broken cobblestone and basalt, the mean RSm of cobblestone glossy surface is 39μm, the mean RSm of basalt is 46μm and the mean RSm of cobblestone broken surface is 81 μm. The results show that the width of glossy surface gully of cobblestone is the smallest and the width of gully of broken cobblestone is the largest on the surface of three aggregates, which is consistent with the scanning image of electron microscope.

The verification results show that the five meso-morphological characteristics indexes ra, Ry, Rz, Rp and RSm can accurately characterize the morphological characteristics of aggregate at meso-scale.

5.3. Verification of micro morphological characteristics

Q is an index of surface micro-morphology characteristics of surface aggregate. According to the analysis, the Q of cobblestone glossy surface is the lowest when it is enlarged by 100 times, and it tends to be stable when it is enlarged by 500 times to 10000 times. Q is the largest when the broken surface...
of cobblestone is enlarged by 100 times, and decreases gradually with the increase of magnification and tends to be stable. On the surface of basalt, Q tends to be stable with the increase of electron microscope magnification. It is directly indicated that the cobblestone glossy surface is smooth under low magnification, and the microscopic morphology of aggregate becomes more complex with the increase of electron microscope magnification. The morphology of cobblestone fracture surface is complex under low magnification, and gradually becomes smooth with the increase of electron microscope magnification. The micro-morphology of basalt surface is complex, and its micro-morphology changes little with the increase of electron microscope magnification.

The verification results show that the data characterization of aggregate micro-morphological characteristics index is consistent with the micro-image morphological characteristics, and Q can accurately quantify the micro-level morphological characteristics of aggregate.

6. Conclusions

1. Macro-scale: the macro-morphology of aggregate is quantitatively analyzed from two dimensions and three dimensions, and six macro-morphological characteristics indicators can fully characterize the morphological characteristics of aggregate at macro-scale.

2. Meso-scale: meso-morphological quantitative indicators Ra, Ry, Rz, Rp and RSm can accurately quantify aggregate surface roughness.

3. Micro-scale: 6 micro-aggregate morphological characteristics indicators, which can accurately quantify the micro-morphological characteristics of the aggregate surface under a high-power electron microscope.

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