EFFECTS OF COARSE AGGREGATE MORPHOLOGY ON PERFORMANCE OF CEMENT-BASED MATERIALS UNDER CYCLIC LOADINGS

S.J. Lee\textsuperscript{1}, C. Lee\textsuperscript{2}, M. Shin\textsuperscript{3}, and S. Bhattacharya\textsuperscript{4}

ABSTRACT

This paper investigates the effects of coarse aggregate morphology on mechanical properties of cement-based materials. In order to ensure structural integrity and prolong the serviceability of aging infrastructure against man-made/natural hazards including earthquake, the civil engineering community has been trying to improve the mechanical properties of cement-based materials, e.g. high performance concrete, confined concrete, with enhanced predictive capability of the behavior. However, there is still a gap to fill in the body of knowledge; the effects of aggregate morphology on the performance of cement-based materials. The influences of the particle size distribution and the maximum nominal size of aggregates have been studied in depth. However, the effects of aggregate morphology have not been clearly understood, since research efforts have been hindered or the success has been limited due to high uncertainties in characterizing the 3D aggregate morphology and their distribution. The concrete industry has witnessed the importance of understanding the grain-scale aggregate morphology to estimate the macroscopic mechanical performance. For example, the use of highly angular aggregate results in a higher strength of concrete due to enhanced interlocking. The challenges for systematic study and questions on mechanical properties such as modulus, residual strain influenced by the morphology still remain to be better answered. This study introduces a systematic approach that quantifies 1) the 3D aggregate morphology and their distribution using a set of global form and local angularity values, and 2) its relations to the mechanical properties of cement-based materials under cyclic loadings. Two different sets of coarse aggregates are prepared: a) crushed and b) river (round) aggregates of which angularity can be clearly distinguished in terms of the morphology indices herein. A digital image analysis of each aggregate morphology is performed. Cylinders with two different sets of the aggregates are prepared and tested under cyclic loadings.

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Effects of Coarse Aggregate Morphology on Performance of Cement-Based Materials under Cyclic Loadings

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ABSTRACT

This paper investigates the effects of coarse aggregate morphology on mechanical properties of cement-based materials. In order to ensure structural integrity and prolong the serviceability of aging infrastructure against man-made/natural hazards including earthquake, the civil engineering community has been trying to improve the mechanical properties of cement-based materials, e.g. high performance concrete, confined concrete, with enhanced predictive capability of the behavior. However, there is still a gap to fill in the body of knowledge; the effects of aggregate morphology on the performance of cement-based materials. The influences of the particle size distribution and the maximum nominal size of aggregates have been studied in depth. However, the effects of aggregate morphology have not been clearly understood, since research efforts have been hindered or the success has been limited due to high uncertainties in characterizing the 3D aggregate morphology and their distribution. The concrete industry has witnessed the importance of understanding the grain-scale aggregate morphology to estimate the macroscopic mechanical performance. For example, the use of highly angular aggregate results in a higher strength of concrete due to enhanced interlocking. The challenges for systematic study and questions on mechanical properties such as modulus, residual strain influenced by the morphology still remain to be better answered. This study introduces a systematic approach that quantifies 1) the 3D aggregate morphology and their distribution using a set of global form and local angularity values, and 2) its relations to the mechanical properties of cement-based materials under cyclic loadings. Two different sets of coarse aggregates are prepared: a) crushed and b) river (round) aggregates of which angularity can be clearly distinguished in terms of the morphology indices herein. A digital image analysis of each aggregate morphology is performed. Cylinders with two different sets of the aggregates are prepared and tested under cyclic loadings.

Introduction

Aggregates typically constitute the largest volume of concrete (higher than 60%), which therefore, must be carefully selected due to its critical impact to structural performance and sustainability of concrete structures. Size and morphology are known as the two most important grain scale indices of aggregates for construction materials. The performances of a cement-based material such as compressive strength, tensile strength, fracture toughness, hysteresis behavior, and workability are highly dependent on both size and morphology of aggregates [1, 2].

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The ‘size distribution’ of aggregates is well defined in current guidelines and standard specifications [3]. However, there is no well-defined metrics/standards to describe ‘morphology distribution.’ This lack of systematic procedure/protocol to quantify the range and proportions (i.e., distribution) of 3D particle morphology has significantly hindered to optimize mixture design and enhance the predictive capabilities in the mechanical behavior of cement-based materials with aggregates.

The objective of this study is to provide a systematic approach that can robustly quantify the 3D aggregate morphology, their distribution and relations to the macroscopic performances of cemented aggregate-based materials. The aggregate morphology distribution is collectively defined on the set of 3D aggregate morphology index values individually identified using an image-based characterization technique. Two types of coarse aggregates, 1) river (round) and 2) crushed aggregates, are used for demonstrating the morphology distributions of two aggregates having discernible differences. Small scale laboratory tests are conducted on concrete cylinders to investigate the effects of the aggregate morphology on mechanical performances of cylinders.

**Imaging-based Morphology Characterization**

Over the past two decades, high-resolution imaging techniques have been widely adopted in the research community to capture the geometry of aggregate particles using photogrammetry [4], e.g., E-UIAIA [5]. Significant enhancement has been made to provide high accuracy in the imaging-based morphology characterization. However, the imaging equipment has been commonly developed for use in a laboratory setting, so the setups are typically unwieldy for in-situ evaluation of the morphological properties. Recently, mobile imaging techniques leveraging smartphones or other mobile devices have become more accessible and affordable. These advances in mobile platforms and applications enabled to obtain high enough resolution images of aggregates in the field as well as the lab, which significantly enhanced the practical aspects of in-situ characterization of aggregate morphology [6].

**Characterization of Particle Morphology**

Individual particle morphology is typically characterized using three morphological factors at three different scales: ‘global form’ (at a large scale), ‘local angularity’ (at an intermediate scale), and ‘surface texture’ (at a small scale) as shown in Fig. 1. A variety of morphology indices have been developed to quantify global form and local angularity based on the particle images as a set of scalar values such as Shape factor and Angularity factor [7] and Sphericity and Roundness [8]. On the other hand, the surface texture has been mechanically characterized in terms of surface friction coefficient, because the characterization of small-scale morphology requires an ultra-high resolution often at the petroscopic-scale and it is also computationally expensive.

However, a well-defined approach remains to be developed at ‘individual particle scale’ to robustly describe the 3D morphology, because morphology indices developed in research communities are mostly 2D, as is a photo image. The realistic particle morphology may be captured in 3D by modeling the geometry using Fourier descriptor [9], which is complicated for practical use. Therefore, a 2D particle image is typically leveraged for the morphology analysis to evaluate the two major morphological factors (i.e., global form and local angularity). A range of the morphological indices can be obtained when multiple photos are taken of one particle.
At least three 2D photos of particle are required from three orthogonal axes, and the mean ($\mu$) from the 2D images has been used to represent the overall 3D morphology [5]. However, this approach may lose valuable information representing the 3D particle morphology. For example, an oblong ellipsoid-like 3D particle could be projected as either a circle or an ellipse depending on different projection planes. Therefore, a high standard deviation ($\sigma$) can be obtained on the analyzed global form, representing the morphological irregularity, which can be in turn considered for the robust 3D characterization, but has not been adopted in the research communities.

In addition, a rigorous approach needs to be developed at ‘aggregate scale’ to robustly describe the aggregate morphology distribution. A mean value is taken for the set of evaluated ‘individual particle scale’ morphology of the sampled particles, and has been often used to represent the overall morphology at the ‘aggregate scale’ without information regarding the morphology distribution [11]. Some studies [12] showed the morphology distribution could be described in a similar manner to the size distribution. This approach plots the quantity of particles as cumulative percentage on a spectrum for each morphological factor, for which the morphology distribution is separately identified. Therefore, a method that can ‘holistically’ describe the distribution over the multiple morphological factors remains to be developed.

This study perceives these as two missing puzzle pieces for engineers to seamlessly connect the morphological information at ‘individual particle scale’ through ‘aggregate scale’ to the mechanical performances of concrete materials at an ‘engineering scale.’

**Characterization of Particle Morphology Distribution Leveraging ‘Morphology Space’**

This research introduces a ‘morphology space’ where $x$-axis represents ‘global form’, while $y$-axis represents ‘local angularity’ to simultaneously describe the 3D morphology at ‘individual particle scale’ and at ‘aggregate scale.’ The $z$-axis may represent ‘surface texture’ that can be mechanically characterized, but this study only focuses on ‘global form’ and ‘local angularity’ that can be identified from image-based analysis and leaves room for further investigation and continuation of the research for texture angularity.

**3D Morphology at ‘individual particle scale’**

It is generally perceived in the engineering practice that three orthogonal particle images can represent the overall 3D morphology. However, three orthogonal images may be insufficient to provide reasonable fidelity in morphology analysis, e.g., three orthogonal images of prolate
(elongated) and oblate (flattened) spheroids are morphologically same. Therefore, this study adopts five particle images including the three orthogonal images and two more images obtained from random orientations. The mean (μ) and standard deviation (σ) of morphological index value of global form and local angularity are then respectively evaluated to describe the overall 3D morphology of an individual particle. The sphericity (x) and roundness (y) are adopted to quantify the global form and local angularity in this study. Among the most common five definitions of sphericity, this study adopts the ‘width-to-length ratio sphericity’ that was reported as the best estimation of the global form and also independent of the roundness [13]. Both sphericity (x) and roundness (y) theoretically range between 0.0 and 1.0. A higher sphericity indicates the global form is a more equidimensional shape. A higher roundness indicates a lower angularity. The definitions are shown below:

\[ x = \frac{d_2}{d_1} \]  

(1)

where \( d_1 \) and \( d_2 \) are particle length and width.

\[ y = \frac{\sum r_i/N}{r_{max-in}} \]  

(2)

where \( \sum r_i/N \) is the average radius of corner circles and \( r_{max-in} \) is the radius of inscribed circle.

An example of the mean values and standard deviations computed from the morphology analysis on five images of one particle is shown in Fig. 2. These set of values are then used to define a bivariate ellipse on the proposed ‘morphology space’ as shown in Fig. 3. The underlying technique of this method is fitting the set of \( x \) and \( y \) with bivariate normal distribution of which parameters are a mean vector and covariance matrix. Note that covariance is set to be zero, since sphericity and roundness are fundamentally independent of each other due to their different base length scales. In statistical context, the bivariate ellipse shown in Fig.3, is translated by the contour line in which 95.4% (approximately 95%) of samples are included under the assumption of zero covariance between two variables.

<table>
<thead>
<tr>
<th></th>
<th>Mean (μ)</th>
<th>Std. dev. (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.494</td>
<td>0.853</td>
</tr>
<tr>
<td></td>
<td>0.883</td>
<td>0.533</td>
</tr>
<tr>
<td></td>
<td>0.937</td>
<td>0.740</td>
</tr>
<tr>
<td>y</td>
<td>0.400</td>
<td>0.371</td>
</tr>
<tr>
<td></td>
<td>0.452</td>
<td>0.352</td>
</tr>
<tr>
<td></td>
<td>0.371</td>
<td>0.390</td>
</tr>
</tbody>
</table>

Figure 2. Sphericity and roundness obtained from a single particle.

**Morphology distribution at ‘aggregate scale’**

Once the ‘individual particle scale’ bivariate ellipses are plotted in the morphology space for all sampled particles, the group of ellipses then collectively represent the morphology distribution at ‘aggregate scale’. The same statistical approach can be made to the group of ‘individual particle scale’ bivariate ellipses to describe ‘aggregate scale’ bivariate ellipse for the given aggregate as shown in Fig. 5. The ‘aggregate scale’ bivariate ellipse may have some covariance unlike the ‘individual particle scale’ bivariate ellipse, even if the resulting covariance is negligible, shown in Fig. 5.
Figure 3. Morphology space: The center of each ‘individual particle scale’ bivariate ellipse represents a set of mean values \((\mu_x, \mu_y)\) of evaluated global form and local angularity, while lengths along the X and Y axis \((2\sigma_x, 2\sigma_y)\) represents 95.4% intervals of bivariate normal distribution with zero covariance.

**Experimental Study**

**Preparation of Aggregate Samples**

This research uses both crushed and river (round) aggregates of size #5 per ASTM C33 [14], i.e. passing aggregate through 25 mm (1 in.) ranges from 90 to 100% by mass. From bulk crushed and river aggregates, the samples that pass 12.5 mm (1/2 in.) sieve and retained at 9.5 mm (3/8 in.) sieve are collected to minimize the variance of nominal size of aggregates, thus the effect of size distribution is factored out in this study. The washed aggregates are stored in the dry oven with 110 °C during 24 hours.

**Characterization of Aggregate Morphology Distribution by Image Analysis**

Image analysis is proceeded in five steps to characterize the aggregate morphology distribution, which is outlined in Fig. 4.

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image acquisition</td>
<td>Foreground segmentation</td>
<td>Image binarization</td>
<td>Image vectorization</td>
<td>Morphology computation</td>
</tr>
</tbody>
</table>

Figure 4. Five-step image analysis procedure.

**Step 1 - Image acquisition:** Thirty particles are randomly selected from each group of the crushed and river aggregates. Five photos are taken on each particle, thus a total of 150 images on each group of sampled aggregates. Particles are placed on a grid paper whose cell size is 7 mm × 7 mm (i.e., the diagonal length is ~ 10 mm) such that the particle size can be optically estimated. The particle photos are taken using iPhone 7+ (12 mega pixel camera with 1.5 micron per pixel).
Step 2 - Foreground segmentation: This step adopts the GrabCut algorithm [15] to segment the foreground particle image from the background that is implemented in OpenCV library [16]. This semi-automatic algorithm performs a ‘hard’ segmentation using an iterative graph cut. Energy defined in an objective function is minimized through the iterative segmentations. The final output is a segmented particle image with black background.

Step 3 - Image binarization: This study adopts a sphericity/roundness computation code developed by Zheng and Hryciw [13], which requires a black and white binary image for the morphology analysis. Therefore, the segmented image is then converted to a binary image by changing the color of pixels inside the foreground particle image to white. An in-house code is developed for the image binarization.

Step 4 - Image vectorization: The obtained binary image after Step 3 is a raster graphics with the pixels on the particle outline appear as a grid of low-resolution squares. This may impact the roundness computation if the code does ‘overfitting’ in evaluating the local angularity. Therefore, the binary image is vectorized to minimize the impact that orients from the graphical noise. This study adopts an open source vectorization code, Potrace [17], to capture the best-fitting particle outline. The vectorized image is then converted back to a high-resolution bitmap for use in the morphology analysis. The high-resolution bitmap is normalized to 1000 pixels per circumscribed circle diameter (PCD) as recommended by Zheng and Hryciw [13].

Step 5 – Morphology computation: The high-resolution images are leveraged to analyze the morphology, which is plotted on the morphology space. Fig. 5 shows the morphology distribution of each aggregate represented with a group of ‘individual particle scale’ bivariate ellipses. The figure also shows geometric details of ‘aggregate scale’ bivariate ellipses developed for each type of aggregates. The center of ‘aggregate scale’ bivariate ellipses of river aggregate is located upper-left to that of crushed aggregate, meaning: (a) the sphericity of river aggregate is lower than that of crushed aggregate by 0.04, which indicates the river particles are less equidimensional (i.e., more elongated); (b) river aggregate has an overall higher roundness by 0.16, thus lower angularity, despite of some outliers located below the crushed aggregate. The difference of angularity (0.16) is more significant than that of sphericity (0.04). The size of ‘aggregate scale’ bivariate ellipse of river aggregate is larger than that of crushed aggregate (larger inner area of the ellipse), meaning the morphology of river aggregate is more irregular. These traits of the morphology distribution are possibly attributed by the nature of the aggregates’ origin, as river aggregate is naturally occurring while crushed aggregate is generated by a crusher. Although the covariance between sphericity and roundness is set to be zero at ‘individual particle scale’, the computed covariance values of ‘aggregate scale’ bivariate ellipses at ‘aggregate scale’ are -0.001 and 0.0009 as manifested by the rotation in the figure.

![Figure 5. Morphology distributions of crushed and river aggregates](image-url)
Preparation of Concrete Cylinder Specimen

The aggregates are mixed with cement paste to cast eight 76.2 mm × 154.2 mm (3 in. × 6 in.) cylinders. The mixture proportions for unit volume of mortars are designed to have 20% more paste volume relative to aggregate volume as summarized in Table 1. Fine aggregate, whose nominal size is smaller than 4.75 mm, is excluded in the mixture to avoid interference of morphology effects produced by fine aggregates. The prepared specimens are cured in a temperature-controlled chamber until designated test ages at 23 °C.

Table 1. Mixture Proportion (per m³ mortar).

<table>
<thead>
<tr>
<th>Component</th>
<th>Crushedᵃ</th>
<th>Riverᵃ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cementᵇ (kg)</td>
<td>634</td>
<td></td>
</tr>
<tr>
<td>Water (kg)</td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>W/C</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Coarse Aggregateᶜ,ᵈ (kg)</td>
<td>1090</td>
<td>1121</td>
</tr>
<tr>
<td>Volume ratio of Paste to Aggregate</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

Note:  
ᵃ. Both mortars are estimated to have 5% of air.  
b. Specific gravity of cement is estimated to be 3.15.  
c. Specific Gravity: 2.53 (Crushed) and 2.60 (River) per ASTM C127.  
d. Absorption: 1.4% (Crushed) and 1.1% (River) per ASTM C127.

Mechanical Test Setup

With the previously described mixture designs including two different sets of the aggregates, a total of eight cylinders are prepared for the splitting tensile strength test (2 cylinders), compressive strength test (2 cylinders), and cyclic compression test (4 cylinders). Fig. 6 shows prepared samples before the tests, where a 1,112 kN (250,000 lb) hydraulic compression machine is used. A loading rate of about 0.7 MPa/min (100 psi/min) is adopted for the splitting tensile strength, and about 0.14 MPa/sec (20 psi/sec) for the compressive strength and cyclic tests. All the tests were conducted at 28 days.

Figure 6. Test samples; (a) Splitting tensile strength test; (b) Compressive strength test; (c) Cyclic compression test.
Test Results and Discussions

The test results of the average strengths (see Table 2) demonstrates the morphology-dependent performances. It is worthwhile to note that the unit weight of cylinders is about 2310 kg/m³, and no statistical difference is observed across cylinders with different aggregate types. The split test show that the obtained splitting tensile strength of the specimens with the crushed aggregate is higher than that of the cylinders with the river aggregate by 60%. The compression tests also show that the average compressive strength of specimens with the crushed aggregate is 80% higher than that with the river aggregate. These results are in agreement with previous researches [1, 18].

Table 2. Average Splitting and Compressive Strengths for Cylinders.

<table>
<thead>
<tr>
<th>Aggregate Types</th>
<th>Splitting Tensile Strength (MPa)</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>River</td>
<td>1.23</td>
<td>10.7</td>
</tr>
<tr>
<td>Crushed</td>
<td>1.93</td>
<td>19.7</td>
</tr>
</tbody>
</table>

Figure 7 shows the cross-section of the specimens with the two aggregates after the splitting tensile strength test. As shown in the figure, in the specimen with the river aggregate (a) the failure plane is mostly formed at the interface of the aggregate particles and cement paste, resulting in an uneven surface in the split face. On the other hand, the specimen with the crushed aggregate (b) exhibited the failure plan passing through some of the particles, which resulted in a relatively even surface. This observation corroborates the crushed aggregate provides better solid bond interface than the river aggregate due to stronger interlocking between the binding matrix through larger aggregate surface areas, considering the sphere geometrically has the smallest surface-area-to-volume ratio.

![Figure 7](image1.png)

(a) (b)

Figure 7. Cross-section of the tested specimens after the splitting tensile strength test; (a) River aggregate; (b) Crushed aggregate.

However, the more angular aggregates are, the higher stress concentrations at sharp corners are expected. Furthermore, the morphological angularity theoretically increases with the particle surface area per given volume, thus develops inherently a larger interphase region with the binding matrix. The interphase region is generally susceptible to damage, and commonly referred to as ‘weak links’ in cement-based materials. Therefore, the cylinders with the crushed aggregates are expected to exhibit more micro-cracks at the interfacial transition zone. In order to evaluate the negative effects of the particle angularity, the cylinders with both type of aggregates were cyclically loaded. Figure 8 shows the stress-strain curve of one of each tested cylinders, as an example. The cylinders were incrementally loaded with the following loading protocol: (1) loaded up to 40~50% of the compressive strength, and then unloaded; (2) reloaded up to 60~70%, and
unloaded; (3) reloaded to 80~90%, and unloaded; (4) finally reloaded to the failure. Despite of the higher compressive strength of the cylinders with the crushed aggregate, the cylinders with the river aggregate exhibits superior resilience in the stage of elastic behavior. For example, after the first cycle, the residual strain of the cylinder with the river aggregate is 50 $\mu$, while that of the cylinder with the crushed aggregate is 325 $\mu$ (see Figure 8). The cylinder with the river aggregate remains in the elastic region even after loaded up to 45% of the compressive strength, but the cylinder with the crushed aggregate begins to experience noticeable permanent damage even under less than 40% of the compressive strength applied. Therefore, the use of the crushed aggregate would not be always beneficial to performances of structures in case that relatively low-level strain or strength cyclic loadings are expected. The river aggregates led to better structural performance by delaying early micro-crack initiations, whose morphology is identified by significantly higher roundness than the crushed aggregate with the relatively similar sphericity (see Fig. 5).

**Figure 8.** Responses under cyclic loading; (a) Stress-strain curve of cylinders with crushed aggregate (CR) and river aggregate (RI), and (b) stress-strain curve of the tested cylinders normalized by the peak compressive strength.

### Conclusions

This study aims to provide a systematic approach that can robustly characterize the aggregate morphology distribution that is important as much as the size distribution due to the significant influences on the macroscopic performances of concrete. A morphology space is introduced to quantitatively describe the morphology distribution at individual particle and aggregate scales. Although further studies must be executed for determining the number of particles from a group, this study demonstrates the efficacy of this approach by correlating the evaluated 3D morphology distribution to mechanical behavior of cement-based materials observed in the laboratory tests. The proposed characterization method is practical leveraging smartphone-based image analysis, which is portable, accessible and affordable, while maintaining a high fidelity in the morphology analysis. This study clearly corroborates the importance of robust characterization of aggregate morphology distribution across the scales, and also positive and negative effects of particle angularity on the structural performance of cement-based materials at peak stress and under cyclic loading.
Acknowledgements

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