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A study on the effects of the fractal characteristics of aggregates on the mechanical behavior of cemented sand and gravel

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ABSTRACT: Owing to complex aspects of cemented sand and gravel (CSG), such as included unscreened aggregates, CSG properties differ from those of ordinary concrete. Fractal theory is introduced to study the effects of aggregate characteristics on CSG properties, quantifying aggregate gradation and shape. Numerical simulation and analyses show that: (1) improved aggregate gradation decreases the gradation fractal dimension and increases the CSG peak stress and elastic modulus; (2) more irregularly shaped aggregates increase the shape fractal dimension and decrease the CSG peak stress and elastic modulus; (3) the relationship quantified between aggregate characteristics and CSG mechanical properties provides a theoretical basis for aggregate allocation in engineering design and construction. Mixing artificial aggregates can improve aggregate gradation but reduces CSG performance. Appropriately blending artificial and on-site aggregates achieves optimal CSG performance; in this study, this is attained using 20% artificial aggregates added under standard gradation.

KEYWORDS: Aggregate; Concrete; Mixture proportion; Modulus of elasticity; Mechanical properties.

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RESUMEN: *Estudio del efecto de las características fractales de los áridos sobre el comportamiento mecánico de arena y grava cementada*. La presencia de áridos no cribados en arena y grava cementadas (CSG) hacen que sus propiedades difieran de las del hormigón convencional. Se introduce la teoría fractal para estudiar los efectos de las características de los áridos en las propiedades de CSG, cuantificando la gradación y la forma de los áridos. La simulación numérica y el análisis muestran que: (1) la gradación mejorada de los áridos disminuye la dimensión fractal de la gradación y aumenta la tensión máxima y el módulo elástico de CSG; (2) áridos de formas más irregulares aumentan la dimensión fractal de la forma y disminuyen la tensión máxima y el módulo elástico de CSG; (3) la relación cuantificada entre las características de los áridos y las propiedades mecánicas de CSG proporcionan una base teórica para la asignación de los áridos en el diseño de ingeniería y en la construcción. La mezcla de los áridos artificiales puede mejorar la gradación de los áridos, pero reduce el rendimiento de CSG. Combinaciones adecuadas de áridos artificiales y naturales logran un rendimiento óptimo de CSG; en este estudio, esto se logra añadiendo un 20% de áridos artificiales con gradación estándar.

PALABRAS CLAVE: Áridos; Hormigón; Proporciones de mezcla; Módulo de elasticidad; Propiedades mecánicas.

1. INTRODUCTION

Cemented sand and gravel (CSG) is a cementitious material of a known strength formed by mixing, paving, vibrating, and rolling a small amount of cementing material together with unscreened and unwashed gravels at the project site (1). Responding to the United Nations' call for new, green building materials (2), CSG can be used in modern dam construction technology to pursue efficient, low-cost construction while protecting natural resources. This has become the development trend toward future dam construction technology. CSG dam technology has been applied worldwide; permanent CSG dams have been built in Japan, Turkey, Greece, France, and elsewhere. It has also been gradually extended and applied in temporary works and in parts of permanent works in China. CSG dams are usually applied in areas where riverbeds provide abundant sand gravels. In order to broaden its applicability to more dam types, artificial aggregates can be used to replace natural aggregates for projects in riverbeds lacking natural gravels. Compared with natural aggregates, artificial aggregates have much larger surface areas owing to their multiple corner angles and rough surfaces. The presence of unscreened aggregates in CSG complexifies its aggregate characteristics; moreover, CSG properties are different from those of ordinary concrete. Aggregate type, shape, and grading are all important factors influencing the mechanical behavior of concrete materials (3, 4). Therefore, in order to provide a theoretical basis for CSG use in engineering design, it is necessary to systematically study the relationship between aggregate characteristics and CSG properties.

In recent years, an increasing number of studies have focused on the relationship between aggregate shapes and the resulting macroscopic properties of composite materials. Huang (5) proposed from his experiments that the more sphere-like the shape of a coarse aggregate, the greater the compressive strength and elastic modulus of the resulting concrete. Guo (6) found through experiments that, with increasing fractions of irregular particles, the slump and concrete strength of C30 and C50 concrete decrease. In research performed by Sánchez–Roldán et al. (7), it was observed that recycled coarse aggregates (RCA) have less angular shapes compared to natural aggregates; this characteristic, together with better particle coupling, provides greater compactness to the whole mixture. In addition to the shapes of aggregates, the shapes of other components in concrete have also been investigated. Research conducted by Zhang et al. (8) showed that the improved geometry of ultra-high-molecular-weight polyethylene (UHMWPE) fibers can ensure their uniform distribution in a matrix, significantly enhancing the splitting tensile strength and residual compressive strength of the resulting concrete.

In terms of numerical simulation, Xiong and Xiao (9) determined that round aggregates reduce the stress concentration intensity inside concrete compared to irregular aggregates; this suggests that the resulting concrete strength is relatively high, which is consistent with experimental results. On the basis of numerical simulation, Wang (10) proposed that the average peak stress of the tensile strength of round aggregates is slightly higher than that of polygonal aggregates for the same volume fraction of aggregates and pores. Numerical modeling by Zheng et al. (11) implied that changes in aggregate shape cause stress concentrations that affect the strength of the concrete. Hou and Wang's numerical modeling (12) found that aggregate shape has little effect on the compression resistance of concrete. Although the above literature focuses on concrete, it is applicable only to standard gradation; the gradation characteristics of CSG with unscreened aggregates remain to be studied further.

Separately, fractal theory was introduced into the study of material structure, opening a new avenue for quantifying the relationship between material complexity and macroscopic properties. Yu (13) described the statistical properties of porous media based on fractal theory and fractal technology. Zhang and Jin (14) studied the application of fractal theory to concrete pore structures. Gao et al. (15) and Hu et al. (16) described and quantified the fractal characteristics of aggregate appearance and outlines using the method of fractal dimensions. Li et al. (17) adopted fractal dimensions to describe the particle shape and gradation of concrete aggregates.

Based on different gradation characteristics of natural sand gravels at the project site, this study uses numerical simulation to obtain the maximum density gradation attainable by adding artificial aggregates. Fractal theory is applied to characterize aggregate properties and to further explore the effects of aggregate fractal characteristics on CSG macroscopic and mesoscopic mechanical behavior. This provides a theoretical basis for mix proportion design in other engineering applications.

2. MATERIALS AND METHODS

2.1. Fractal Theory

Fractal geometry (18) was founded by the French-American mathematician, Benoit Mandelbrot. As an emerging science describing the irregularity and complexity of materials, it offers a new way to study the quantitative relationship between aggregate complexity and the mechanical properties of CSG.

2.1.1 Fractal Model Based on Aggregate Gradation

Aggregate gradation refers to the proportional relationship between the numbers of aggregate particles of different sizes. Traditional aggregates are divided into small stones (5–20 mm), medium stones (20–40 mm), large stones (40–80 mm) and super-large stones (80–150 mm) according to particle size. Such an irrational gradation indicates poor aggregate density, and reduces the performance of the composite material.

Based on the gradation method, a fractal model was established for aggregate gradation of CSG (19). The resulting fractal function for graded CSG aggregates is (Equation [1]):

$$P_r = \left(\frac{r^{3-D_g} - r_{min}^{3-D_g}}{r_{max}^{3-D_g} - r_{min}^{3-D_g}}\right) P_0 \qquad [1]$$

where r represents the size of a sieve pore for grading particles; r_{min} and r_{max} represent the smallest and largest particle sizes, respectively; D_g represents the fractal dimension of the aggregate size mass distribution; and P_0 represents the pass rate at the maximum nominal particle size. Because r_{min} is much smaller than r_{max}, Equation [1] can be simplified to Equation [2]:

$$P_r = \left(\frac{r}{r_{max}}\right)^{3-D_g} P_0 \qquad [2]$$

In accordance with the above formula, the fractal dimension D_g of the aggregate gradation can be obtained.

2.1.2 Fractal Model Based on Aggregate Shape

The section of an aggregate is rough and complex with obvious fractal characteristics; this can be represented by the box dimension. One of the most widely used fractal dimensions, its mathematical expression is as follows: supposing that is any non-empty bounded subset on R and N_δ is the minimum number of boxes of size δ that can cover the set F, the box dimension can be obtained through the following Equation [3] (14):

$$D_x = \lim_{\delta \to 0} \frac{\ln N_\delta(F)}{\ln(1/\delta)} \qquad [3]$$

where δ represents the unit measurement scale in a continuous distribution, i.e., a unit square used in the two-dimensional plane; N_δ represents the number of measurement scales, which is the number of small squares covering polygonal aggregates; and D_x represents the box dimension of an aggregate shape.

2.2. Random CSG Aggregate Model

2.2.1 Generation of Random Aggregates

In the generation of random aggregates, a group of random variables uniformly distributed on the interval [0, 1] were first generated by the Monte Carlo method (20-22). The probability density function with X was assumed to be as follows Equation [4]:

$$f(x) = \begin{cases} 1, x \in [0,1] \\ 0, x \notin [0,1] \end{cases} \qquad [4]$$

Random variables on any other intervals can be obtained from the transformation of random variables on the interval [0, 1]. For example, the uniformly distributed random variable Y on any interval [a, b] can be obtained by Y = a + (b – a) X. Thus, random variables that meet the uniform distribution on each interval were generated.

The position of aggregates within different particle size ranges in the test pieces was randomly determined using the Monte Carlo method. The number of aggregate particles was obtained from the gradation of concrete and the occupancy of aggregates was determined using the Fuller gradation theory based on the principle of maximum density.

According to the Walaraven Equation (23), a three-dimensional aggregate gradation curve can be transformed into a two-dimensional planar aggregate gradation curve. The cumulative distribution probability of aggregates with diameter D less than D_0 was calculated as follows Equation [5]:

$$P_c(D < D_0) = P_K\left[1.065(D_0/D_{max})^{\frac{1}{2}} - 0.053(D_0/D_{max})^4 - 0.012(D_0/D_{max})^6 - 0.0045(D_0/D_{max})^8 + 0.0025(D_0/D_{max})^{10}\right] \qquad [5]$$

where P_k represents the occupancy fraction of aggregates, for which a value of 70% was used in this study. In accordance with Equation [5], the number of aggregate particles at various levels of the cross section can be calculated.

2.2.2 Inversion of Mesoscopic Material Parameters

CSG test cubes of 100 mm × 100 mm × 100 mm were used in the experiment. Based on laboratory conditions, standard grade II aggregates were adopted with the mix proportions shown in Table 1.

Table 1. Mix proportions used in the uniaxial compression test.

Cement (kg/m³)	Flash (kg/m³)	Sand (kg/m³)	Water (kg/m³)	Aggregate (kg/m³)	Sand rate
70	20	434	90	1736	0.2

The test pieces were cured for 28 d for the uniaxial compression test. In the test, a universal testing machine and a displacement control method were used to obtain the stress–strain curve.

From a mesoscopic perspective, CSG can be seen as a three-phase composite material composed of sand gravel aggregates, a mortar matrix, and interfaces between the mortar matrix and the aggregates. In the two-dimensional plane, it was assumed that the natural sand gravel aggregates are round and the artificial sand gravel aggregates polygonal. In this study, by generating aggregate random circles and adhesive random circles with boundaries, the inner and outer circles were divided into quadrants. The number of corner points for each quadrant was determined, and the corner point coordinates were formed. Finally, the corner points were connected to generate polygons (24).

The constitutive relationship and failure criterion for mesoscopic component materials were selected simply. The constitutive model of each component adopted a linear elastic model while the failure criterion adopted the maximum stress criterion; that is, when the tensile stress in a material exceeds its maximum tensile strength, the material is assumed to crack.

In the finite element calculations, the material parameters of each component included the tensile strength, elastic modulus, and Poisson's ratio. Since the parameters of meso-component materials were difficult to measure, minimizing the difference between stress–strain curves obtained from experiments and numerical simulation was taken as the optimization goal to obtain the parameters by means of inversion (25-27). The comparison between numerical simulation results and lab uniaxial compression tests is shown in Figure 1.

Figure 1 shows that the peak stress in the experiment is slightly lower than that in the numerical simulation and the strain values are basically the same. Moreover, the correlation coefficient between the two curves is very high. After failure, the measured curve shows a descent stage while the simulation results show brittle failure with less of a decline. This is caused by the unreasonable description of the yield failure criterion used; however, the numerical simulation described the main mechanical properties quite well. The values of the mesoscopic parameters obtained from inversion are shown in Table 2.

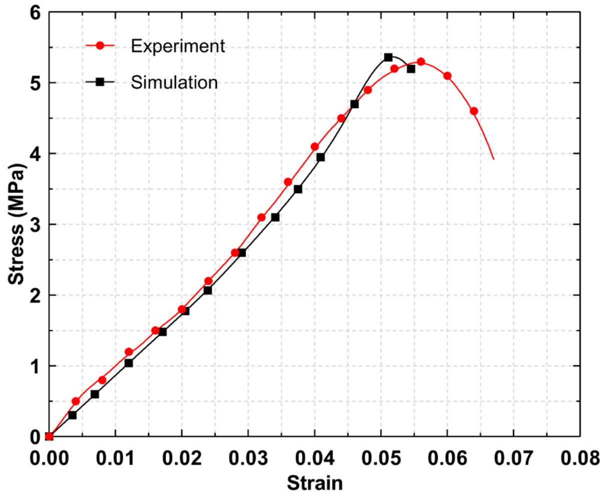

FIGURE 1. Parameter inversion results.

Aggregate shape has a remarkable impact on the interface (28, 29), but because the interface occupied a very small proportion of the CSG, the impact of aggregate characteristics on mesoscopic parameters was ignored in this study.

3. RESULTS

CSG aggregates usually come from the project site and have round or near-round shapes. In principle, they are used without screening, giving rise to a complex gradation. The research of Feng (1) showed that natural sand gravels at project sites have alternately distributed sand and gravel layers with uneven gradation (see Figure 2), causing a significant strength decrease in the resulting CSG. Figure 2 shows the gradation and Fuller curves of the 12 groups of on-site aggregates. The gradation of on-site aggregates deviates markedly from the standard Fuller gradation. Therefore, the gradation must be adjusted using artificial aggregates (30).

For projects lacking natural riverbed sand gravels, artificial aggregates can be used to replace natural aggregates. Artificial aggregates are generally shaped as irregular polygons. Their surfaces are relatively rough and irregular with more edges and corners than natural aggregates. Artificial gravel aggregates supplement natural gravel aggregates

TABLE 2. Mesoscopic component parameters.

Meso component	Elastic modulus (MPa)	Poisson's ratio	Tensile strength (MPa)
Aggregate	210	0.16	0.5
Cement mortar	65	0.20	0.5
Interface	32	0.16	0.4

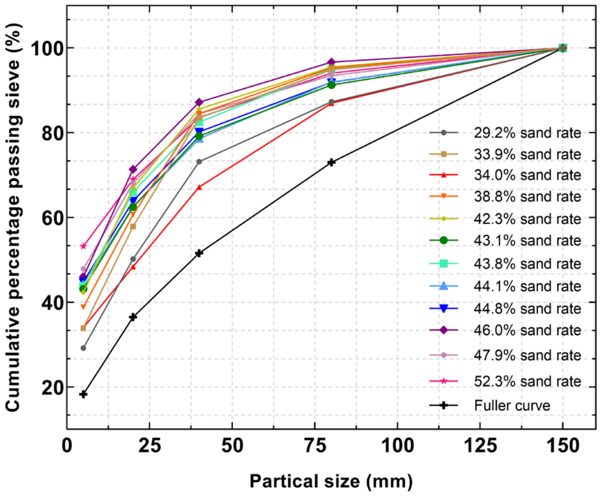

FIGURE 2. Gradation and Fuller curves of the 12 groups of aggregates (based on data in (1)).

at dam sites, allowing the aggregate gradation of CSG to be adjusted. In order to mix aggregates in a logical way, the aggregates' characteristics must be quantified. Owing to the complex gradations and shapes of aggregates, fractal theory was introduced in this work to quantify their characteristics.

3.1. Fractal Characteristics Based on Aggregate Gradation

The impact of aggregate gradation characteristics on CSG was compared with Fuller gradation, which was taken as the standard gradation (BZ) of aggregates and was combined with cemented sand and gravel site aggregates. The on-site gradations with sand rates of 29.2% and 38.8% were selected as control gradation 1 (DZ1) and control gradation 2 (DZ2), respectively. The cumulative percentage of particles passing the sieve is illustrated in Figure 2 and the cumulative screening rate is shown in Table 3.

TABLE 3. Cumulative distribution of grade II aggregates.

No.	Sieving particle size (mm)							
	40	35	30	25	20	15	10	5
BZ	100.0	94.0	87.0	79.0	71.0	61.0	50.0	35.0
DZ1	100.0	93.0	85.5	77.4	68.6	61.3	52.3	39.9
DZ2	100.0	93.8	87.2	79.9	71.8	65.4	57.4	45.9

Since the Fuller curve model was highly consistent with the power function curve, the cumulative aggregate distribution curve was transformed into the same form as Equation (2) to determine its fractal dimension. The aggregate standard gradation curve (BZ) is expressed as Equation [6]:

$$P_r = 15.568 \times r_i^{0.5049} \qquad [6]$$

According to the above formula and Equation [2], the fractal dimension of the standard gradation was 2.4951.

The fractal dimensions of the three gradations obtained are shown in Table 4. Figure 3 presents the fractal curves of the grading qualities obtained for the three aggregate grading curves listed in Table 3.

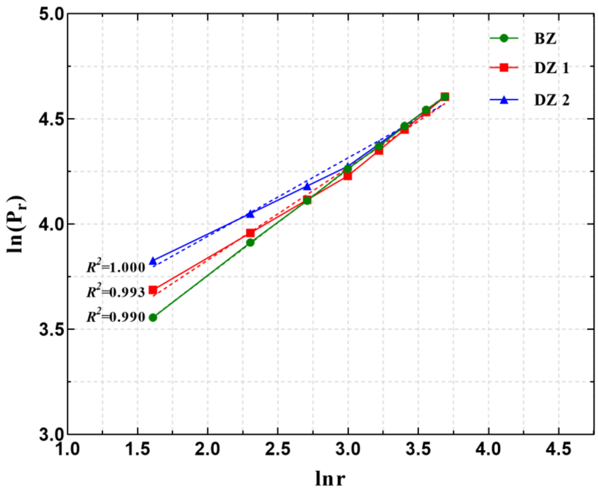

FIGURE 3. Mass fractal curves of gradations BZ, DZ1, and DZ2.

TABLE 4. Calculated fractal dimensions for the gradations BZ, DZ1, and DZ2.

No.	Slope K	Fractal dimension D_g	R^2
BZ	0.5049	2.4951	1.000
DZ1	0.4404	2.5596	0.993
DZ2	0.3730	2.6270	0.990

Table 4 and Figure 3 show that, as the cumulative aggregate screening rate approaches the standard value, the curve steepens and the fractal dimension decreases. That is, for aggregates with significant fractal characteristics within the same scale range, the larger the fractal dimension, the poorer the gradation; conversely, the smaller the fractal dimension, the better the gradation.

3.2. Fractal Characteristics Based on Aggregate Shape

Natural sand gravel aggregates are generally round and artificial aggregates are generally polygonal. In order to study the effect of the mix proportion of different shapes of sand gravel aggregates on the performance of CSG, the fractal characteristics of mixed aggregates were determined as listed in Table 5.

Table 5. Fractal characteristics of mixed aggregates.

No.	Aggregate proportion (%)	
	Round	Polygonal
LC1	0	100
LC2	20	80
LC3	40	60
LC4	60	40
LC5	80	100
LC6	100	0

Based on Equation [3], the mixing ratios (LC1, LC2, LC3, LC4, LC5) of the above-mentioned five different shapes of aggregates are calculated, and the fractal dimension regression calculation results are shown in Figure 4 and Table 6. Since there were no polygonal aggregates in LC6, it was not required to calculate its fractal dimension.

Table 6 summarizes the fractal dimension regression results and Figure 4 shows the fractal curves for different aggregate shapes.

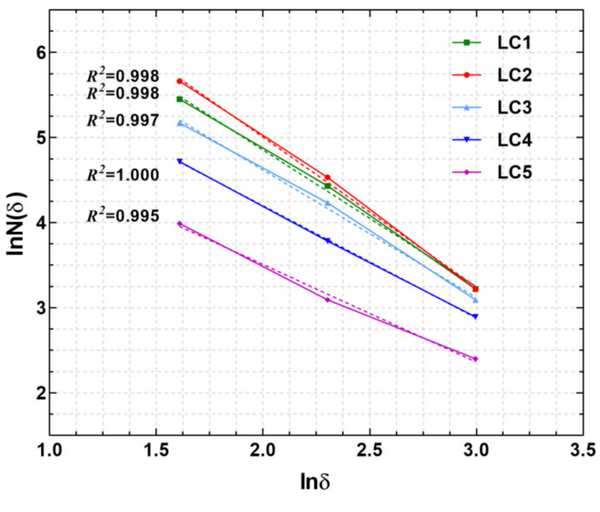

Figure 4. Fractal curves for different aggregate shapes.

According to Table 6 and Figure 4, as the proportion of polygonal (artificial) aggregates in CSG decreases, aggregate shape complexity and fractal dimension decrease. That is, within the same scale range, the larger the fractal dimension, the more polygonal the artificial aggregates; conversely, the smaller the fractal dimension, the less the polygonal the artificial aggregates.

Table 6. Calculation results of fractal dimension based on aggregate shape.

No.	Fractal dimension D_x	R^2
LC1	1.7630	0.998
LC2	1.6102	0.998
LC3	1.5000	0.997
LC4	1.3187	1.000
LC5	1.1477	0.995

4. DISCUSSION

Based on the results obtained, the following discussion examines the effects of aggregate characteristics on CSG mechanical behavior. In particular, the relationships between aggregate gradation and shape fractal dimensions and resulting CSG mechanical behavior are discussed.

4.1. Effect of Aggregate Gradation Fractal Dimension

The effect of aggregate gradation on the mechanical behavior of CSG was studied based on the three aggregate gradations described in 3.1: the standard gradation (BZ), control gradation 1 (DZ1), and control gradation 2 (DZ2). The random aggregate models in which all aggregates were artificial (LC1) are shown in Figure 5 for the three gradations, and the corresponding stress–strain curves obtained from numerical simulations are shown in Figure 6.

As the aggregate gradation approaches the standard gradation, the fractal dimension of the aggregate gradation decreases and the peak stress increases. Simultaneously, as the aggregate gradation improves, the tangent slope of the stress–strain curve increases; that is, the elastic modulus increases. This occurs because, as the aggregate gradation approaches the standard gradation, the aggregate quantity increases, improving the aggregate density; thus, both the strength and elastic modulus increase. This is consistent with experimental results in the literature (31) and validates the research method used in this study.

4.2. Effect of Aggregate Shape Fractal Dimension

The effect of aggregate shape on the mechanical behavior of CSG was analyzed in accordance with the relationship between fractal characteristics

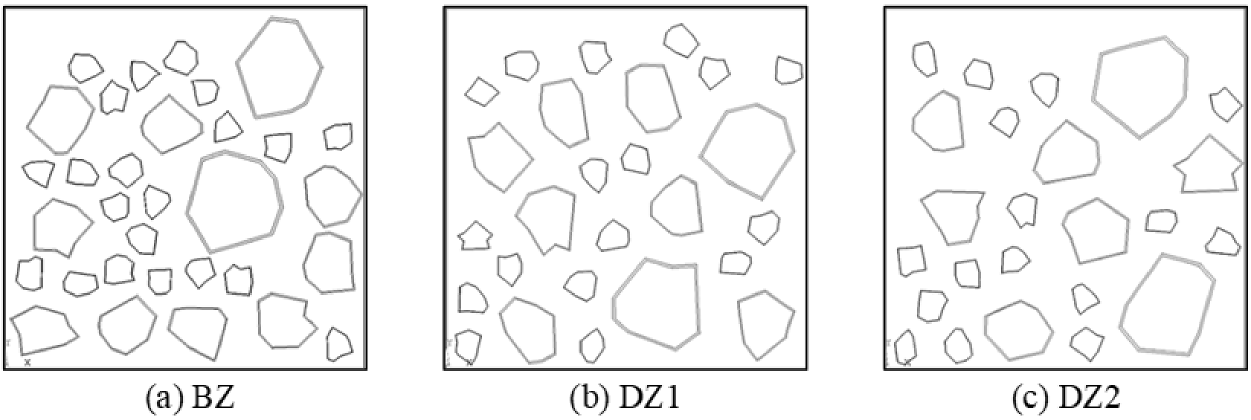

FIGURE 5. Random aggregate models considering different gradations with the same aggregate shapes.

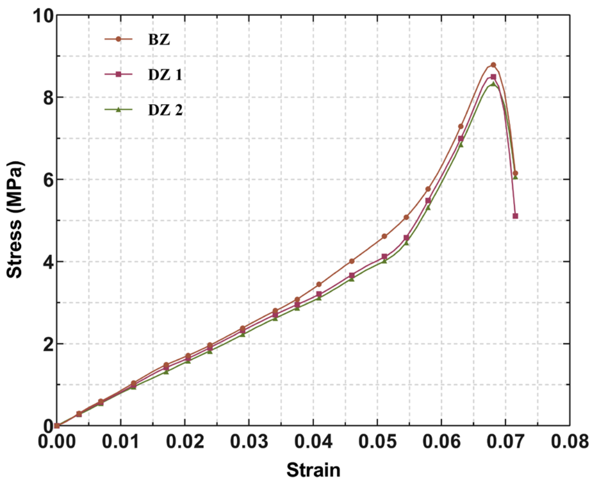

FIGURE 6. Stress–strain curves for different aggregate gradations.

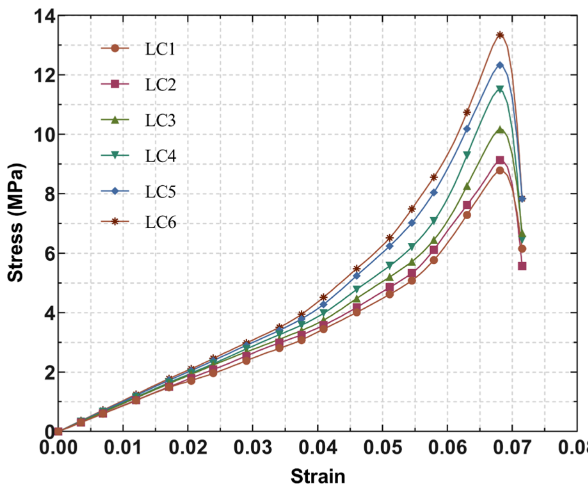

FIGURE 8. Stress–strain curves for different aggregate shapes.

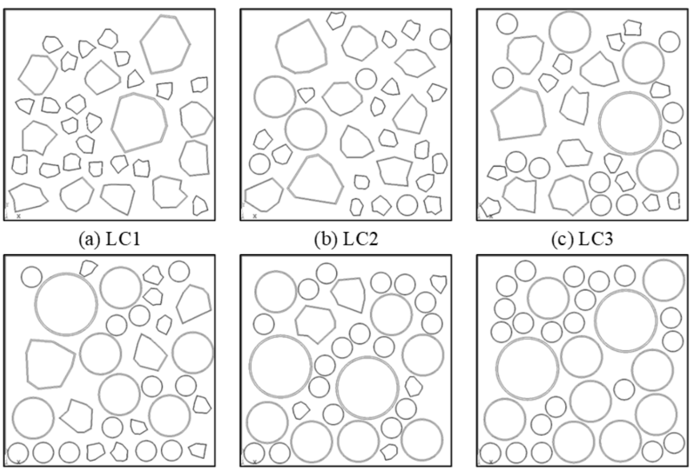

FIGURE 7. Random aggregate models considering different aggregate shapes with the same gradation.

and mechanical characteristic parameters. Figure 7 shows the models of different aggregate shapes under the standard gradation.

Figure 8 shows the stress–strain curves under uniaxial compression obtained for the models illustrated in Figure 7.

Figure 7 and Figure 8 show that, as the proportion of polygonal aggregates increases (i.e., as the aggregate shape fractal dimension increases), the peak stress and the tangent slope of the stress–strain curve both decrease: that is, the elastic modulus decreases. This is consistent with experimental results in literature (32-35). There are several possible explanations for this phenomenon: the influence of corner edges and of stress concentration.

Considering the impact of the corner edges, the area of the interfacial transition zone (ITZ) units around the polygonal aggregates is larger than that around the circular aggregates of the same volume. Under the

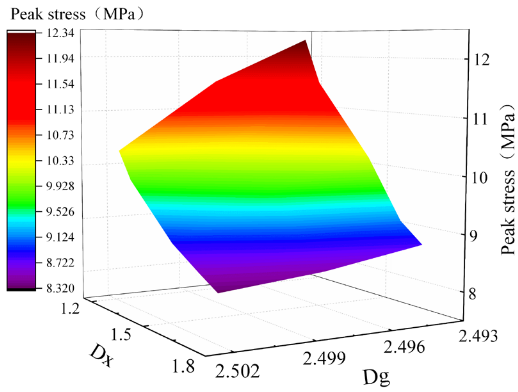

Figure 9. Peak stress corresponding to the shape (Dx) and gradation (Dg) fractal dimensions of different aggregates.

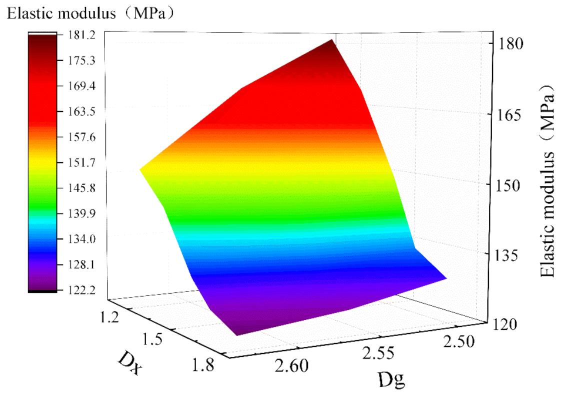

Figure 10. Elastic modulus corresponding to the shape (Dx) and gradation (Dg) fractal dimensions of different aggregates.

same stress, more ITZ units around the polygonal aggregates will show damage and fracture than around the circular aggregates. This conclusion is consistent with that in the reference works (9, 36, 37).

Considering the impact of stress concentration, the stress distribution around polygonal aggregates is more concentrated than that around the circular aggregates. Therefore, ITZ units around the polygonal aggregates are more prone to damage and fracture. Furthermore, under the standard gradation, when the aggregate shapes are all round (LC6), i.e., when all the aggregates are natural sand gravel aggregates, the highest peak stress and elastic modulus are achieved. However, since this study focuses on project sites lacking natural sand gravels, this condition is difficult to achieve and is not considered further.

Figure 9 and Figure 10 present diagrams of the relationship between the fractal characteristics and mechanical characteristic parameters.

According to Figure 9 and Figure 10, for the same aggregate gradation fractal dimension, the CSG peak stress and elastic modulus both increase as the aggregate shape fractal dimension decreases. Conversely, for the same aggregate shape fractal dimension, the CSG peak stress and elastic modulus both decrease with the increase of the aggregate gradation fractal dimension.

For use in CSG, artificial aggregates are mixed into natural aggregates sourced from riverbeds. Considering the complex resulting aggregate characteristics, aggregate gradation and shape were quantified using fractal dimensions in this research. On one hand, the results obtained show that mixing artificial aggregates standardizes the resulting gradations, and that the closer a gradation is to the standard gradation, the better its CSG mechanical properties. On the other hand, excessive artificial aggregate content may degrade CSG mechanical properties. For project sites lacking natural aggregates, artificial aggregates should be added appropriately to achieve the best performance. When 20% artificial aggregate content was added under the standard gradation considered in this study, the elastic modulus and peak stress reached their maximum values; this scenario was suitable for on-site mixing. The method used in this study to investigate the impact of complex aggregates on CSG mechanical properties through fractal theory and numerical simulation can provide a theoretical reference for other CSG projects.

5. CONCLUSIONS

In view of the complex characteristics of CSG aggregates, the concept of fractal dimensions was introduced to quantify aggregate gradation and shape. A two-dimensional random aggregate model of CSG was established, and mechanical properties of CSG under different aggregate gradation and shape fractal dimensions were studied through parameter inversion. The following conclusions were drawn:

1. The closer the aggregate gradation to the standard gradation, the smaller the fractal dimension of the aggregate gradation; as the proportion of polygonal aggregates increased, the aggregate shape fractal dimension increased.
2. According to uniaxial compression numerical testing, as the aggregate gradation fractal dimension decreased, both the peak stress and elastic modulus of CSG increased.
3. According to uniaxial compression numerical testing, as the aggregate shape fractal dimension increased, both the peak stress and elastic modulus of CSG decreased.
4. For mixing artificial aggregates with natural aggregates from riverbeds, a mix proportion for optimal mechanical properties was obtained; this could provide a theoretical basis for similar projects.

5. Due to the limited test methods available for this study, the mesoscopic numerical simulation technique in this work did not consider the effect of aggregate shape on interface performance; this topic requires further research in the future.

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