Research Article

Experiment on Size Effect and Fractal Characteristics of Waste Brick and Concrete Recycled Aggregate

Hongbo Li [ID],[1,2,3] **Hubiao Zhang,**[1] **Pengfei Yan** [ID],[1] **Yufei Tong,**[1] **Changyu Yan,**[1] **and Yongfa Ding**[1]

[1]*College of Civil and Hydraulic Engineering, Ningxia University, Yinchuan 750021, China*
[2]*Ningxia Research Center of Technology on Water-saving Irrigation and Water Resources Regulation, Yinchuan 750021, China*
[3]*Ningxia Center of Research on Earthquake Protection and Disaster Mitigation in Civil Engineering, Yinchuan 750021, China*

Correspondence should be addressed to Hongbo Li; 13469578416@nxu.edu.cn

Herein, the size effect of single-particle crushing of recycled brick and concrete recycled macadam under static load and the fractal characteristics of aggregate under impact load are investigated. The mechanical change law of recycled macadam after compaction crushing under static load is analyzed through single-particle load crushing and impact crushing tests with different particle groups. Furthermore, the fractal dimension D is introduced to study the effects of impact energy, particle size, and different materials on the fractal characteristics of the recycled macadam. Consequently, the material, shape, and particle size of a single-particle significantly affect the crushing strength under static loading, and there is an apparent size effect on the crushing strength. Moreover, the proportion of unbroken particles in the overall mass sieve increased with decreasing particle group order under impact loading. The proportion of unbroken particles in the 4.75–9.5-mm group constituted more than 60% of the total, indicating that its anticrushing ability was significant. In addition, the model relationship between fractal dimension D, non-uniformity coefficient, and curvature coefficient is established. When $1.887 \leq D \leq 2.631$, the gradation of recycled macadam is superior.

1. Introduction

In recent years, large amounts of construction waste is produced as the byproduct of the building industry (e.g., house repair, demolition, construction, and decoration) with the continuous improvement of living standards and rapid economic advancements and urbanization [1]. In contrast, the demand for sand and stone raw materials is surging owing to road construction, new town development, and municipal infrastructure construction [2–4]. According to China's overall building structure statistics, the proportion of brick concrete structures is the highest, and recycled brick and concrete recycled aggregate have become the most significant proportion of construction solid waste. Therefore, it is urgent to fully utilize recycled brick and concrete aggregate in China's road engineering. Recycled aggregate differs from natural sand and gravel because the recycled aggregate produces a greater crushing effect when subjected to low loading. Particle crushing leads to a change in the recycled aggregate gradation, affects the thickness and fineness proportion, alters the overall structure of recycled aggregate, and influences the recycled aggregate's strength and mechanical deformation properties [5–8].

Scholars have performed in-depth research on the change of particle gradation in the process of particle breakage and migration. Yu et al. [9] studied the law of particle migration and evolution in the process of granular rock and soil particle breakage. They performed one-dimensional compression tests of single-particle and multiparticle group mixtures under different stress and gradation. It was determined that the particle breakage and migration mode occurred repeatedly step by step and migrated according to the order of particle group. Thus, the particle gradation was continuous after breakage. Cai et al. [10] investigated the drainage shear test of

rockfill materials under different gradation, density, and confining pressure using large-scale triaxial apparatus. It is found that the density has minimal influence on the particle size distribution, but different gradation and confining pressure have a significant effect on the particle size distribution. Consequently, there is a specific linear relationship between particle breakage and confining pressure. The larger the particle, the more severe the breakage. Furthermore, Pei [11] examined the fractal dimension variation of recycled aggregate after impact load test crushing. The double logarithm fitting line was utilized to find that recycled aggregate has excellent self-similarity and conforms to fractal characteristics. Therefore, as the impact load and aggregate crush value increase, the fractal dimension increases. In addition, Wang et al. [12] established the natural logarithm nonlinear relationship between particle content and relative particle size and proposed the discontinuous grading curve equation. The results demonstrate that the relative crushing rate calculated by the grading equation of discontinuous graded coarse-grained soil is accurate. Sun et al. [13] studied the influence of rockfill particle shape on the size effect of rockfill crushing strength and found that the more irregular the particle shape, the smaller the Weibull modulus of particle crushing strength, and the more pronounced the influence on the size effect of strength. Dong et al. [14] introduced a new method to solve the gradation matrix transfer based on existing research and improved the original gradation transfer matrix by ignoring the particle breakage variation of different particle groups. The report established that various particle groups have varying limited crushing rates, considered the proportion of uncracked particles in the comprehensive screening, and verified the solution using a one-dimensional compression test. The findings provide a theoretical basis for further study of more complex situations. Moreover, Zhu et al. [15] derived the rockfill gradation equation based on the fractal theory, and the correlation coefficients were all above 0.95 after the empirical fitting, which was in good agreement. The relationship between C_u, C_c, and particle size fractal dimension D is established using coarse-grained soil gradation. It is first proposed that the fractal dimension of rockfill and transition material with large particle size is between 2.22 and 2.603 when the particle size fractal dimension of rockfill and transition material is between 2.22 and 2.63. Liu [16] studied andesite single-particle breaking strength in uniaxial compression and the "V" groove broken test. They analyzed the effect of particle shape on the andesite crushing strength. The study showed that the broken form of regular particles is solitary, and most particles exhibit tensile fracture, whereas the broken form of irregular particles is related to the number of contact points. Therefore, the broken form of single particles is different when the force mode and force point are different. Xiao-Quan et al. [17] conducted a single-particle crushing test on solid water rockfill under wet and dry conditions and simulated the triaxial wetting test with different particle sizes under constant confining pressure and stress using DEM. The study showed that the particle crushing strength decreased with the increase of particle size, consistent with the stress-strain curve simulated by DEM. Currently, most of these studies are based on qualitative research, such as

discrete element simulation of rockfill, coarse-grained soil, gravel stone, fractured natural gravel particles, and particle size distribution after crushing. However, the recycled brick and concrete building solid waste, including fractured recycled aggregate and particle size distribution after crushing and related research, are rarely reported and tested and lack support.

The crushing theory of crushed stone is mainly based on theoretical research. For example, the discrete element method simulates the particle crushing form and particle size distribution of rockfill, coarse-grained soil, gravel, and natural crushed stone. In contrast, there is less research on the particle crushing form and particle size distribution of recycled brick and concrete recycled crushed stone. In addition, there is a lack of relevant experimental research and technical support. Therefore, the crushing strength law of different particle groups of recycled brick and concrete recycled gravel is studied utilizing the single-particle crushing test under static load. Consequently, the relationship model between fractal dimension D and nonuniformity coefficient and curvature coefficient is established with the help of the fractal dimension. Furthermore, the fractal dimension D index is used to evaluate the grading of recycled aggregate, which provides a theoretical basis for the effective utilization of recycled aggregate.

2. Single-Particle Breakage Order Size Effect under Static Load

2.1. Testing Method. Recycled brick and concrete recycled aggregate with different particle sizes are selected for single-particle breakage testing to comprehensively study the particle crushing characteristics and strength changes of recycled brick and concrete recycled aggregate in this paper. The experiment is performed on the YAW4306 microcomputer controlled electrohydraulic servo universal testing machine of Ningxia University. The maximum measuring range of the instrument is 1000 kN, and the accuracy is 0.01 kN. Figure 1 presents the schematic of the instrument.

The test materials are recycled brick and concrete recycled aggregate from the Ningxia area. The results showed that the needle flake particle content of recycled brick is 31.4% and that of concrete recycled aggregate is 11.9%. According to the specification [18], the flat elongated particle content should not be more than 20% of the total particle content in highway pavement construction. Therefore, this paper primarily focuses on the application of recycled brick and concrete recycled aggregate in the future.

After a jaw crusher crushes the recycled aggregate, four groups of 9.5–16, 16–19, 19–26.5, and 26.5–31.5 mm are selected according to Test Procedures for Aggregates of Highway Engineering (JTG E42—2005) [19]; the feasibility of base filling material for simulated recycled brick and concrete recycled rubble, and the bulk and flake particles are evenly selected for examination, with 30 particles in each group. During loading, a single particle is placed horizontally in the middle of the loading plate of the universal testing
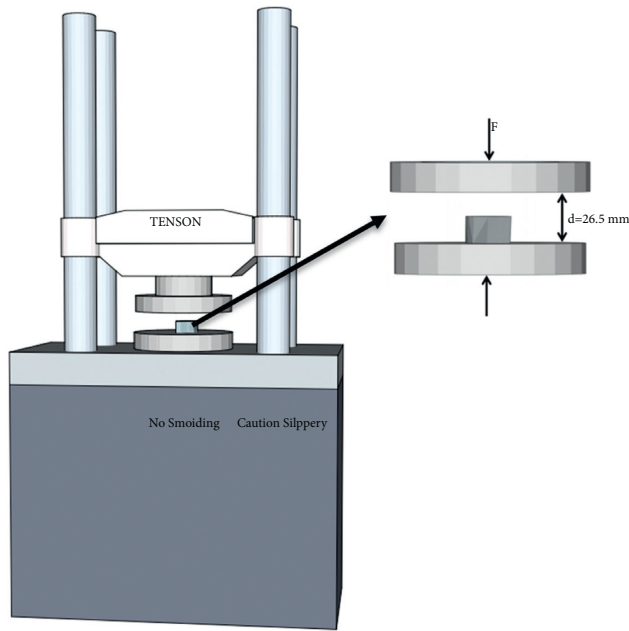
Figure 1: Test device.

machine according to different particle sizes, and the loading plate is raised at the rate of 1 mm/min, and the change of load-displacement curve of each particle during loading is recorded in real time. The particle is considered to be broken when there is an apparent main crack or a sudden drop in the load-displacement curve.

2.2. Analysis of Particle Crushing Size Effect

2.2.1. Analysis of Particle Crushing Mechanics Law. The load-displacement curves of recycled brick and concrete recycled aggregate are shown in Figures 2 and 3.

From the load-displacement curves of two different particles in Figures 2 and 3, it could be observed that the load-displacement curves of various particles vary because of the difference in particle shape, material, and gradation. There are several peaks in the process of particle failure, signifying that the particles have completed the crushing process stages. (1) In the compaction stage in the early phase of loading, the volume of particles decreases with the increase of load, and the particles are compacted because the original open structural plane and microcracks of recycled brick and concrete recycled aggregate particles gradually get close. Brittle failure occurs after the failure strength is reached, mainly caused by the contact between the particle and compressed surfaces. (2) The shape of recycled aggregate is irregular and angular. In the process of contact between loading plate and particles, single-point and multipoint contact is formed in addition to surface-to-surface contact. When the vertical load increases to a specific value, the curve suddenly drops, and a single-point failure occurs. If the particle has a single-point failure, its load-displacement curve has a peak value. When the contact form between the particle and the compression surface is a multipoint contact, the load-displacement decreases after the particle is broken at a single point, and then the load-displacement curve of other points continues to rise. Each peak value corresponds to a point breakage until the primary crack or macroscopic fracture that runs through the whole particle is produced. Single-point and multipoint failure mainly occur in recycled bricks because recycled bricks contain higher flat elongated particle content and irregular angular particles. Thus the load-displacement curve is more prominent and wavy.

2.2.2. Analysis of Particle Crushing Mode and Mechanism. Consequently, there are two modes of crushing failure of recycled aggregate: single fracture and multifracture modes. The crushing mode of recycled brick aggregate is the single crack mode, as shown in Figure 4, and the concrete recycled aggregate crushing mode is the single crack mode (Figure 5(a)) and multiple cracks (Figure 5(b)).

In the crushing process, the recycled brick aggregate produces a single crack that runs through the whole particle, leading to fracture. Consequently, the recycled brick has prominent brittle properties. (1) Due to the irregular shape of recycled brick particles, during axial compression, the indirect contact of recycled brick particles is easier to form higher stress concentration, yield first and produce particle crushing phenomenon, and form the main single crack crushing mode [20]. (2) The flat elongated particle content of the iste brick aggregate is 31.4%. Furthermore, when the particles are placed horizontally on the loading plate for axial compression, the particles and the compression surface are subjected to a multipoint force, resulting in an uneven force that is easy to break. Therefore, a single crack-breaking mode of the main body runs through the whole particle.

After crushing, the recycled aggregate of concrete produces two types of crushing characteristics shown in Figure 5: single crack and multicrack. The particle crushing mode mainly depends on the stress distribution inside the particle. When the single crack crushing mode occurs, it is mainly because the concrete recycled gravel is needle or flake, the shape is irregular, the stress is uneven, and the stress concentration at the tip is easy to occur, resulting in weak bending resistance, mainly in the single crack crushing mode [21]. The multicrack crushing mode is mainly due to a thick layer of cement mortar wrapped on the surface of concrete recycled gravel, which makes up for the micro-cracks in the aggregate and improves the concave convex degree of aggregate surface, so that the shape of concrete recycled gravel particles is quasispherical, the roundness is good, and there is stress concentration at the contact between particles and compression surface, Firstly, the particles are locally broken and gradually form an overall fracture with the progress of loading. The cracks are generated at the stress concentration and develop into multiple cracks. With the progress of loading, these cracks expand rapidly around, and then the cracks penetrate the whole particle, so as to make the particles break as a whole. The crushing feature is to form multiple cracks in the shape of mushrooms.
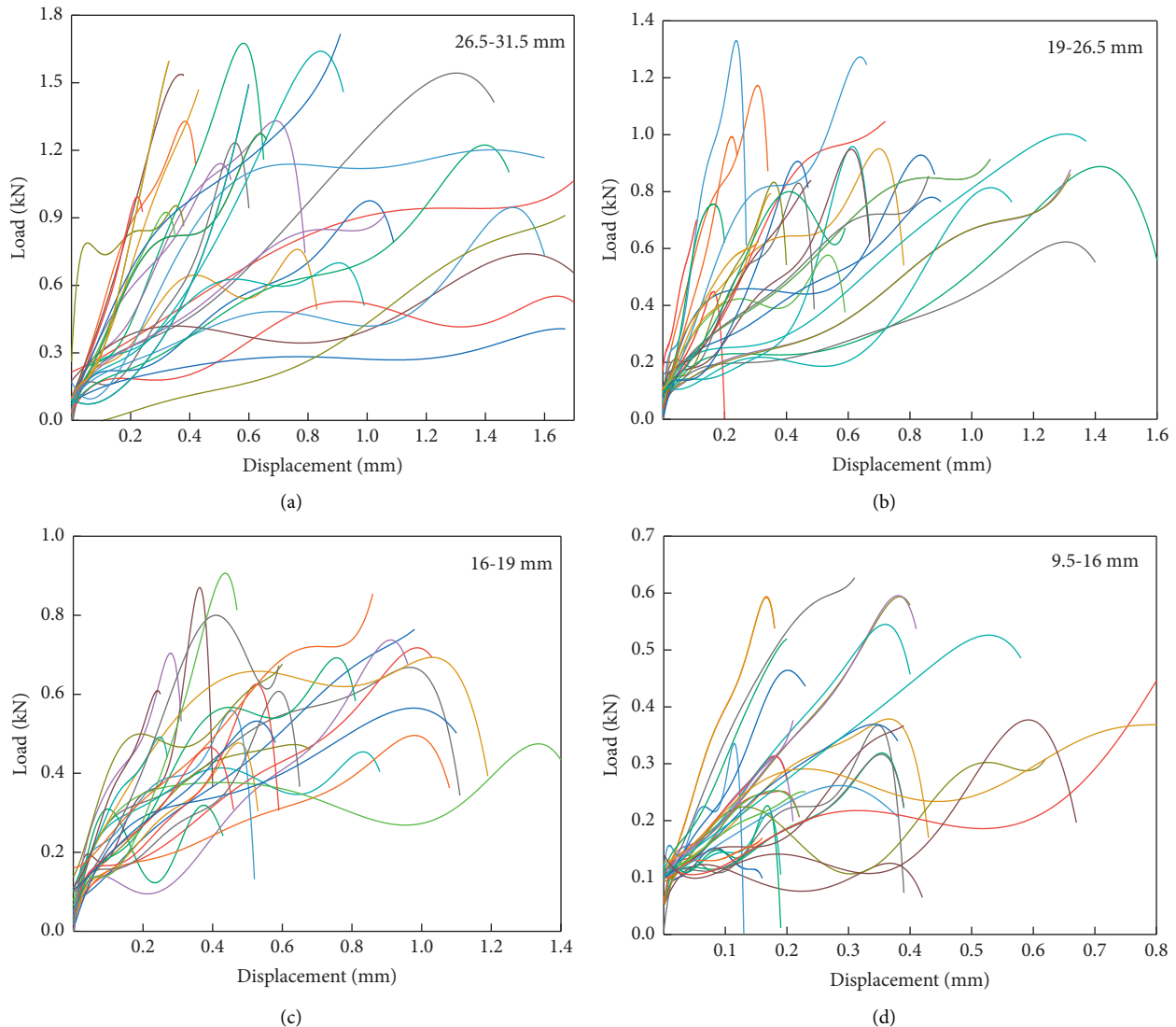
FIGURE 2: Load-displacement curves of recycled bricks with different particle sizes. (a) 26.5–31.5 mm. (b) 19–26.5 mm. (c) 16–19 mm. (d) 9.5–16 mm.

2.2.3. Statistical Analysis of Particle Strength. The distance between the upper and lower loading plates is adopted as the nominal particle size, and the peak value of the load-displacement curve divided by the square of the loading plate distance is used as the particle crushing strength [13]. Figure 6 draws the particle crushing strength and fitting curves of different particle size groups.

As displayed in Figure 6, with the decrease of particle size, the particle crushing strength of recycled brick increases from the initial 1.371 MPa to 2.916 MPa, and the particle crushing strength of recycled crushed stone of concrete increases from the initial 2.507 MPa to 3.998 MPa, so the particle crushing strength has a noticeable size effect in the crushing strength of two kinds of recycled aggregate particles. Furthermore, the particle crushing strength decreases with the increase of particle size, mainly owing to the following three aspects. (1) The surface of recycled aggregate is not smooth, and large particles are more prone to flexural

failure under static load. (2) Large particles had many initial defects (e.g., sharp corners, notches, voids, and grooves) and different microcrack distribution. Therefore, large particles are prone to local stress concentrations under static load, which leads to particle failure. (3) The recycled aggregate particles are uneven and prone to multipoint failure in the crushing process, so when the particle size is larger, the particles have been broken in the process of multipoint failure.

The particle crushing strength of recycled brick is lower than that of concrete aggregate; the main reason is that the mineral composition of recycled brick particles and concrete recycled crushed stone particles is different. According to the XRD detection spectra of the two materials in Figure 7, the mineral composition of concrete recycled crushed stone is mainly quartz and kaolinite, and the mineral composition of recycled brick particles is mainly mullite, cristobalite, and quartz. Due to the different mineral composition of the two
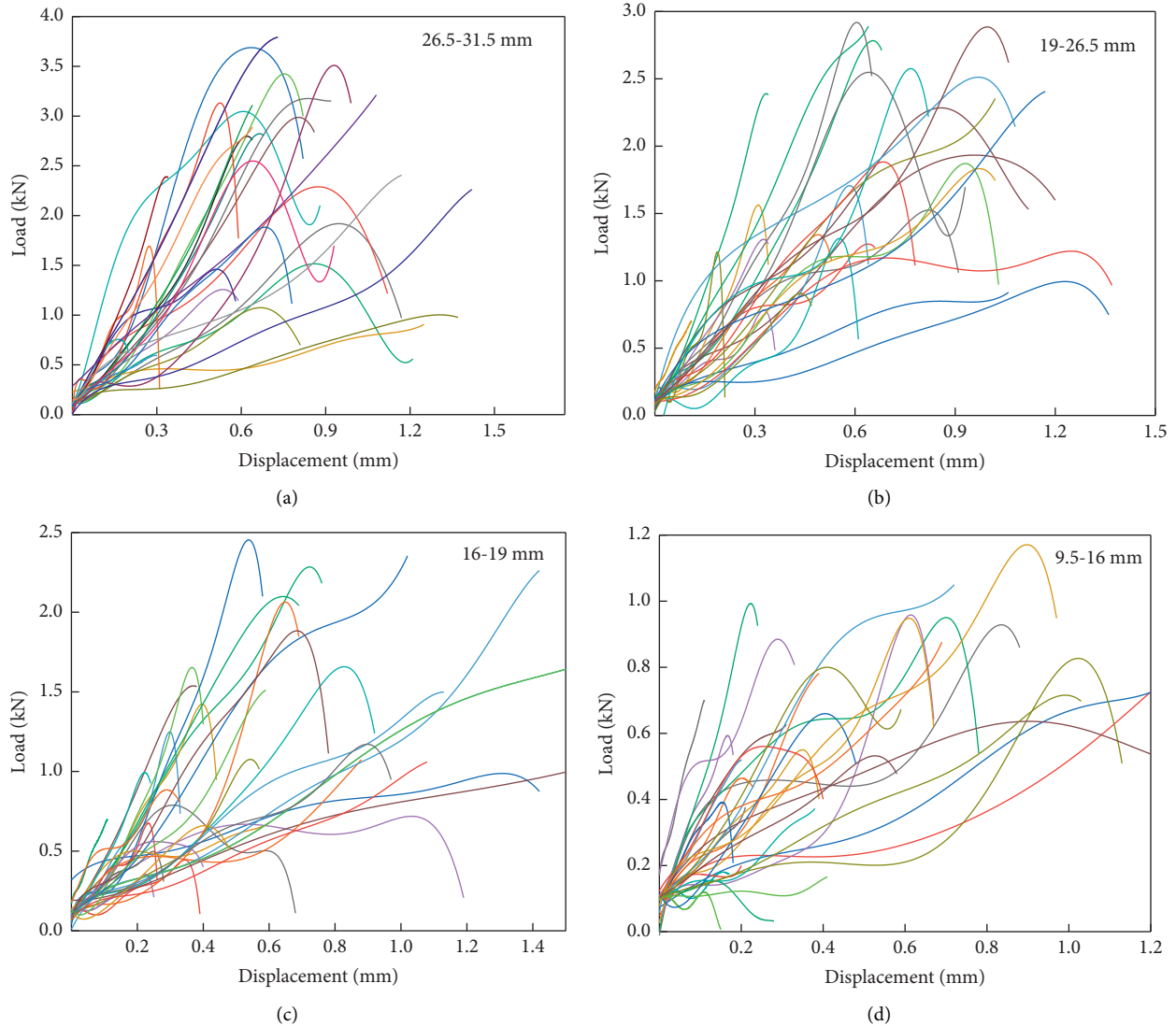
(a)

(b)

(c)

(d)

FIGURE 3: Load-displacement curve of recycled aggregate with different particle size. (a) 26.5–31.5 mm. (b) 19–26.5 mm. (c) 16–19 mm. (d) 9–16 mm.

materials, the particle strength of recycled brick is lower than that of recycled crushed stone of concrete; secondly, the content of needle-like particles in iste brick aggregate is about 2.6 times that of concrete recycled aggregate, and the shape of iste brick particles is irregular. In addition, cracks are more likely to occur during axial compression, so the crushing strength of recycled brick particles is lower than that of concrete recycled aggregate particles.

2.2.4. Particle Strength-Particle Size Fitting. According to the formula of compressive strength in the code [22], the representative values of single-particle strength of recycled brick and recycled concrete aggregate are calculated, respectively, and the calculated results are listed in Table 1.

It can be observed from Table 1 that the representative value of 95% guarantee rate strength of single-particle crushing is significantly affected by particle size and different materials. To clarify the relationship between single-particle crushing strength and particle size and material, the representative values of 95% guarantee rate of single-particle crushing strength of recycled bricks and concrete recycled aggregate of different materials are linearly fitted, and the fitting results are shown in Figure 8.

The 95% guarantee rate strength representative value of a recycled brick and concrete recycled aggregate is fitted, and the relationship between particle crushing strength and particle size is obtained, as shown in Figure 8 above. The correlation coefficient R^2 of the two kinds of recycled aggregate is more than 0.98, and the correlation is good. The fitting results show the relationship between single-particle crushing strength and particle size, and different materials. Consequently, the particle crushing has a particular size effect, which decreases with the increase of particle size, and the strength of the material itself is low. Therefore, the crushing strength of a single particle is also relatively low.

FIGURE 4: Crushing mode of recycled brick particles.

3. Fractal Characteristics of Aggregate Impact Crushing

3.1. Fractal Model. Fractal geometry is used for irregular, disordered, unsmooth, and nondifferentiable phenomena and behaviors in nature. The linear fractal is a widely used fractal with self-similarity. In 1977, Mandelbrot published his monograph fractal: form, opportunity, dimension, and created fractal theory [23–25].

According to the statistical fractal model, in the fractal aggregate of particles, the number of particles N and particle size di meet the following formula:

$$N(\geq d_i) = \frac{k}{d^D},\qquad(1)$$

where k is a constant.

According to the cubic relationship between the mass M and the number N of particles, it can be concluded that

$$\frac{M(r < d_i)}{M_T} = \frac{\left(d_i^{\,3-D} - d_{\min}^{\,3-D}\right)}{\left(d_{\max}^{\,3-D} - d_{\min}^{\,3-D}\right)},\qquad(2)$$

where R is the particle size, $M(r < d)$ is the mass content less than a specific particle size, M_T is the total mass of all particles, and $d_{\max}$ is the maximum particle size in the particle group.

The following formula is shown below, assuming the minimum particle size $d_{\min} = 0$:

$$\frac{M(r < d_i)}{M_T} = \left(\frac{d_i}{d_{\max}}\right)^{3-D}.\qquad(3)$$

Taking the logarithm on both sides of the above formula, we have

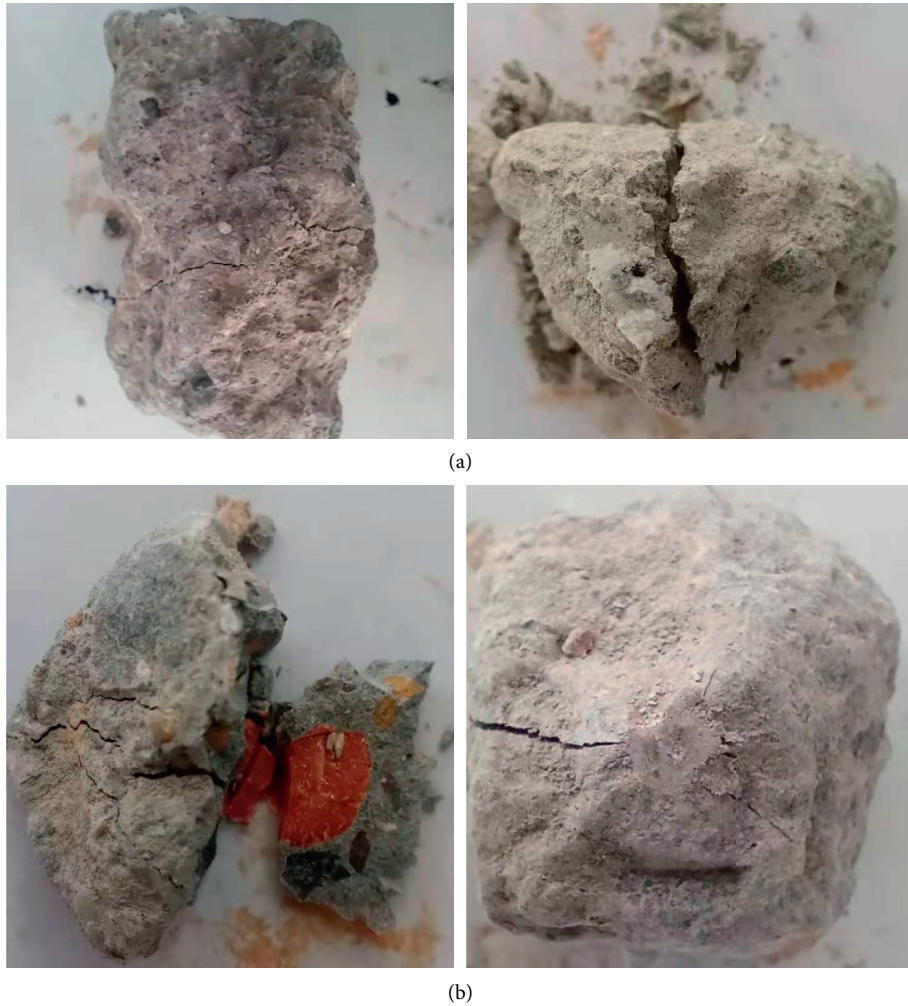$$\lg\left[\frac{M(r < d_i)}{M_T}\right] = (3 - D)\lg\left(\frac{d_i}{d_{\max}}\right),\qquad(4)$$

(a)

(b)

Figure 5: Crushing mode of recycled aggregate particles of concrete. (a) Single crack crushing. (b) Multicrack crushing.
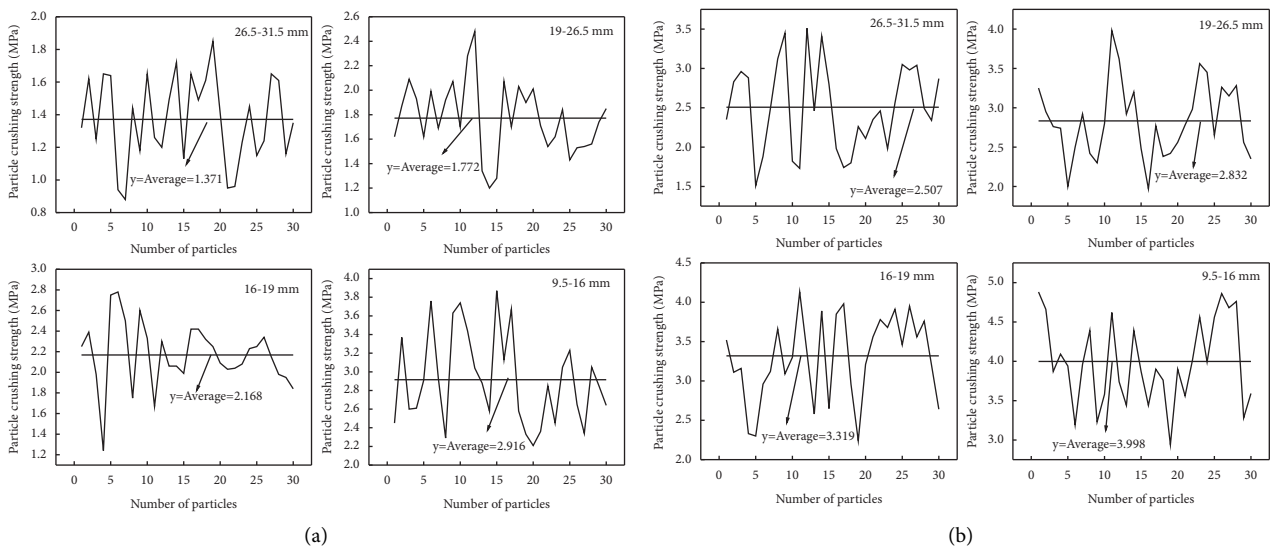

(a)

(b)

Figure 6: Crushing strength of different recycled aggregate particles. (a) Crushing strength of recycled bricks with different particle sizes. (b) Crushing strength of recycled aggregate particles of concrete with different particle sizes.
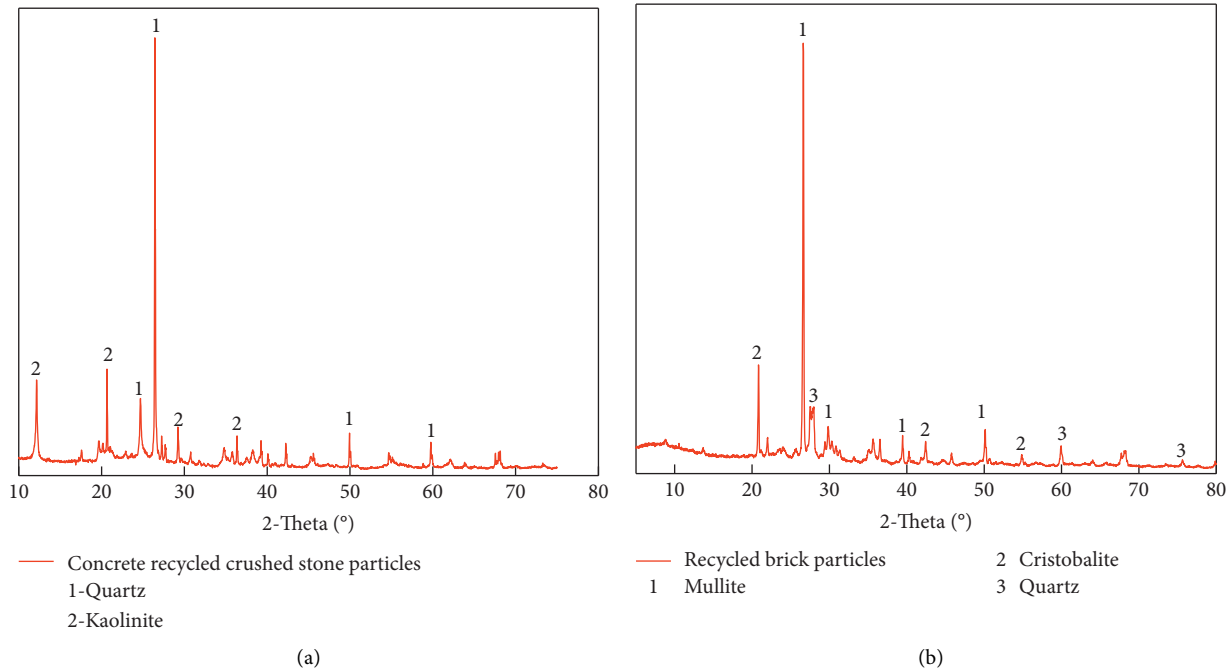
FIGURE 7: XRD patterns of different recycled aggregate particles. (a) Recycled brick particles. (b) Concrete recycled crushed stone particles.

TABLE 1: 95% guarantee rate representative value of crushing strength of single particle.

Aggregate type	Particle size (mm)	Maximum value (MPa)	Minimum value (MPa)	Average value (MPa)	Standard deviation (%)	Coefficient of variation (%)	95% representative value of single-particle strength
Recycled brick	9.5–16	3.93	1.81	2.916	86	29	1.49
	16–19	2.6	1.61	2.168	39	18	1.51
	19–26.5	2.48	1.62	1.772	37	21	1.15
	26.5–31.5	2.21	0.88	1.371	54	40	0.46
Recycled aggregate particles of concrete	9.5–16	4.88	2.94	3.998	79	19	2.69
	16–19	4.13	2.51	3.319	66	20	2.23
	19–26.5	3.98	1.97	2.832	82	29	1.47
	26.5–31.5	3.51	1.51	2.507	81	32	1.16

and taking lg (d_i/d_{max}) as abscissa and lg $[M (r < d_i)/M_T]$ as ordinate, the linear slope is $(3-D)$, and the fractal dimension D of each gradation is obtained. Thus, the smaller the fractal dimension D, the coarser the particle [26–28].

The fractal dimension D of particle breakage can characterize the superior gradation and particle size after crushing and reflect the particle size distribution after crushing. Herein, the fractal dimension D of particle breakage is used as an index to measure the degree of particle breakage, which is a quantitative standard.

3.2. Test Method. The hammer weight was 4.5 kg, the drop height of the hammer was 450 mm, the diameter of the compaction barrel was 152 mm, the self-made steel plate was 150 mm, and the thickness was 4 mm. During the test, the self-made steel plate is placed on the upper part of the aggregate to make the impact energy evenly distributed on the surface of the aggregate. The two materials were set with five different particle group gradations (i.e., 4.75–9.5,

9.5–16.5, 16.5–19, 19–26.5, and 26.5–31.5 mm) for compaction and crushing testing. The test gradation and the number of compaction are listed in Table 2, where 1–5 are set as single-grain gradation and 6 as multigrain gradation. The samples are all 700 g in mass and added into the compaction barrel in layers. According to the Test Specification for Inorganic Binding Stability Materials for Highway Engineering (JTG E51—2009) [29], the impact energy is set at 1.59, 3.18, 4.76, and 6.35 kJ, respectively.

3.3. Test Results and Analysis

3.3.1. Fragmentation Law of Grain Composition under Impact Load. Figure 9 shows the gradation of each particle group after compaction and crushing of recycled aggregate and concrete recycled crushed stone.

Based on Figure 9, the grading of different grain groups is continuous after impact crushing, and the grading of each grain group is gradually evolving, similar to the overall
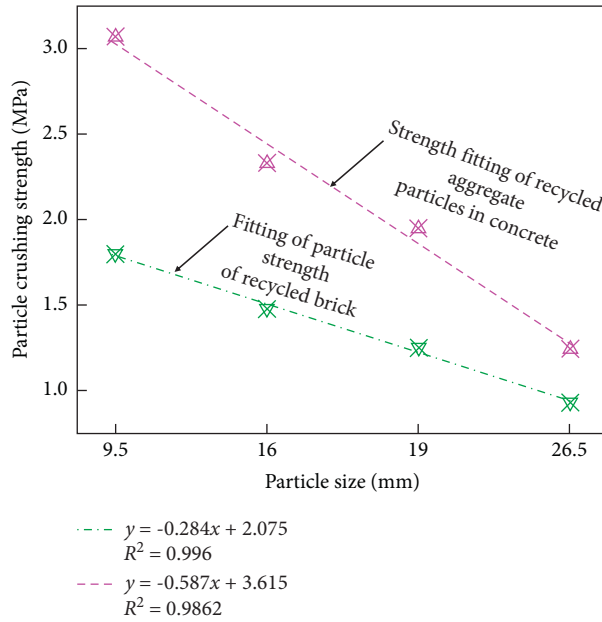
FIGURE 8: Fitting relation curve of single-particle strength representative value with 95% guarantee rate of different materials.

TABLE 2: Test sample grading and cumulative impact energy design.

Gradation number	The quality of each fraction and the total quality of the test material (g)					Total (g)	Impact energy (kJ)
	25–30 mm (ZT/T)	20–25 mm (ZN/S)	15–20 mm (ZS/N)	10–15 mm (zx/f)	5–10 mm (ZF/E)		
1	700					700	1.59, 3.18, 4.76, 6.35
2		700				700	1.59, 3.18, 4.76, 6.35
3			700			700	1.59, 3.18, 4.76, 6.35
4				700		700	1.59, 3.18, 4.76, 6.35
5					700	700	1.59, 3.18, 4.76, 6.35

grading. When the impact energy is minor, there are fewer small particles in the particle group, and they are distributed in a narrow area. However, with the increase of impact energy, more small particles are produced by crushing, making the particle size range gradually widen after crushing. As a result, the particle size decreases with the increase in applied load, indicating that particles have decreased in size during the crushing and migration process.

After the single graded grain group is fractured, it migrates and recombines to the smaller grain group according to the grain group order to form the multilevel grain group. To study the migration evolution and recombining law of the single-grain group under different impact loads, five different grain size groups are broken with the impact action, and the percentage content of each grain group is drawn into a histogram, as shown in Figure 10.

It can be seen from Figure 10 that after the same particle group is broken under different impact loads, a large number of aggregates are broken and decomposed, and the phenomenon of migration and recombination to the lower particle group occurs. Compared with concrete under impact loading, the unbroken particles of recycled macadam concrete are clearly larger than those of recycled brick, mainly due to the low strength of recycled brick itself and the

high needle flake content. In the single-particle size group of the same material, the proportion of unbroken particles in the whole sieve decreased in turn after impact crushing, and when the smallest particle size of the new secondary particles group was larger than that of 9.5 mm, the new particles decreased with the increase of impact energy. In contrast, when the minimum particle size of the new secondary particles is smaller than that of 4.75 mm, the new particles increase with the increase of impact energy. The results showed that the increase and decrease of new secondary particles showed a turning point when the particle size was 4.75–9.5 mm. The main reason was that the crushing resistance of large particles was weak, and the broken particles were more fully broken with the increase of impact load, and the large particles migrated to smaller particles according to the order of particle groups. Therefore, the proportion of unbroken particles in the whole sieve decreased when the particle size was larger than 9.5 mm and increased when it was smaller than 4.75 mm.

Various grain groups under impact loading are not fractured, and the grain percentage is different, as shown in Figure 10. According to the grain group order and the nonfractured grain group screening, there is an increase in the total quality, suggesting that aggregate crushing capacity is
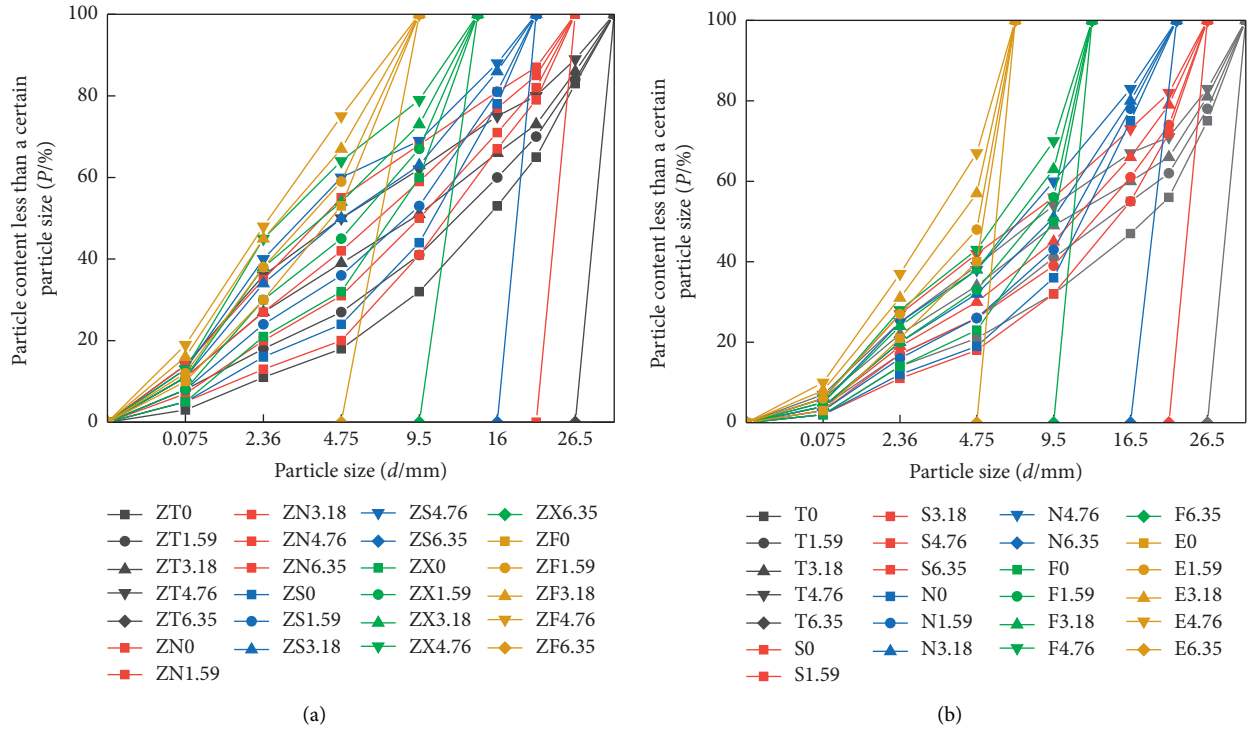
FIGURE 9: Gradation curve of each particle group under different cumulative energy. (a) Gradation curve of recycled brick. (b) Gradation curve of recycled concrete aggregate.

related to material properties as well as shape and is closely related to particle size. Moreover, the increment value of the new generation group grain percentage also varies. As the particle size decreases, the proportion of unbroken particles increases. For example, the proportion of unbroken particles in the overall screening is more than 60% in the 4.75–9.5 mm particle group, signifying that the crushing resistance of the 4.75–9.5 mm recycled aggregate is high. Therefore, an appropriate increase of 4.75–9.5 mm aggregate content can improve the compressive properties of these two materials in engineering applications. Consequently, the influence of particle recombination on strength in the process of particle crushing and migration should be considered in the proportioning design, and the large particle size should be appropriately increased to avoid the change of overall grading caused by particle crushing and recombination. Moreover, reducing the main stress frame affects the compressive strength of the aggregate and the construction quality.

3.3.2. Fractal Dimension under Different Cumulative Energy (Fractal Distribution Curve of Grain Size).

Impact tests were performed on different particle groups of recycled brick. According to the fractal dimension calculation process for impact crushing in Section 3.1, the logarithmic relationship between cumulative mass and particle size of each particle group under screening after impact crushing was computed and fitted to determine the fractal dimension of recycled bricks of various particle groups under different impact energies, and the fractal curve of particle size, as shown in Figure 11.

As shown in Figure 11, (1) under different impact energies, the correlation coefficient of recycled brick is between 0.9031 and 0.9977, demonstrating that the mass percentage of each particle group of recycled brick has statistical similarity after impact crushing. The particle size distribution is continuous, and the filling compactness between particles is strong, conforming to the fractal characteristics of crushing. Therefore, the fractal dimension can describe the aggregate formation and distribution of recycled brick after impact crushing. The fractal dimension of each particle group at different impact energy ranges from 2.4959 to 2.6836.

The relationship between the fractal dimension of each particle component and the impact energy is shown in Figure 12.

Figure 12 displays the same particle group, where the particle crushing becomes sufficient with the increase of impact energy. Furthermore, as the content of fine aggregate increases, the fractal dimension D of recycled brick crushing also increases. The fractal dimension of fragment group 26.5–31.5 mm is greater than the other components of fractal dimension, which is mainly due to the large irregular shape particles within renewable brick, more flakes and needles, fragility, and the rough surface. Under the more considerable impact energy, the intergranular wear increases, and the strength is minor and can less resist shear compression. Thus, the larger fractal dimension distribution is more substantial and fully fractured [30].
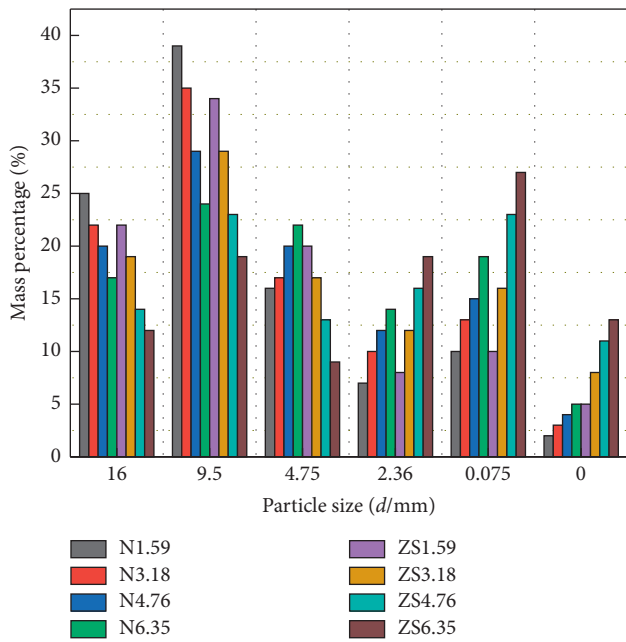
According to (4), double logarithm fitting is conducted for the recycled concrete gravel, and the fitting results are shown in Figure 13.
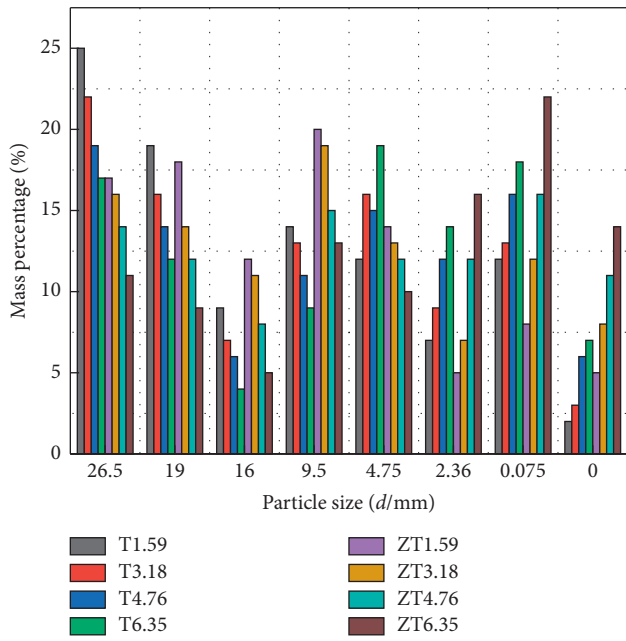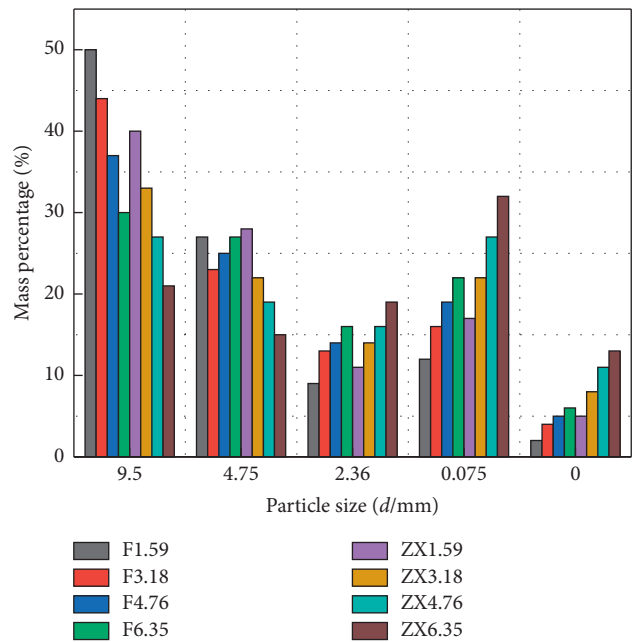
(a)
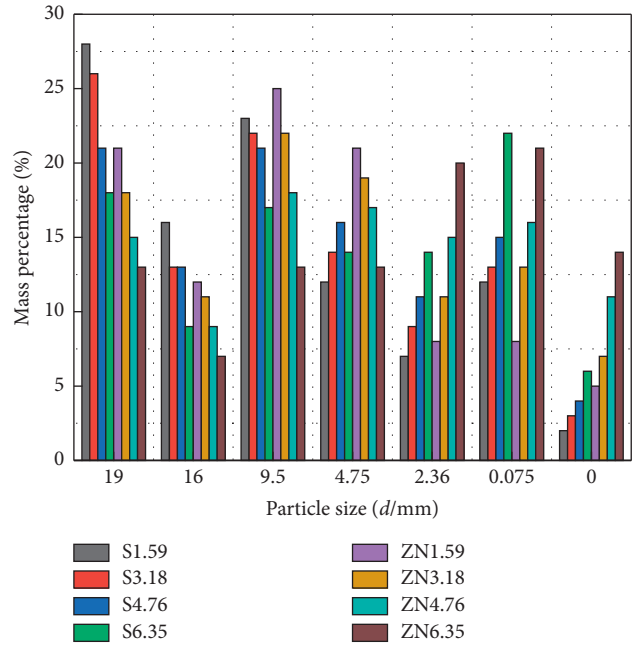
(b)

(c)

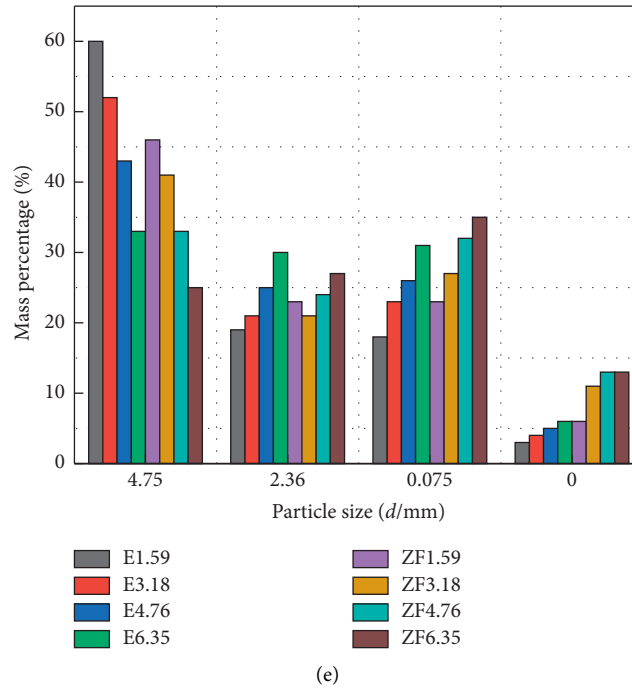(d)

Figure 10: Continued.

(e)

FIGURE 10: Weight percentage of crushed granule under different impact loads. (a) 26.5–31.5 mm mass percentage. (b) 19–26.5 mm mass percentage. (c) 16–19 mm mass percentage. (d) 9.5–16 mm mass percentage. (e) 4.75–9.5 mm mass percentage.
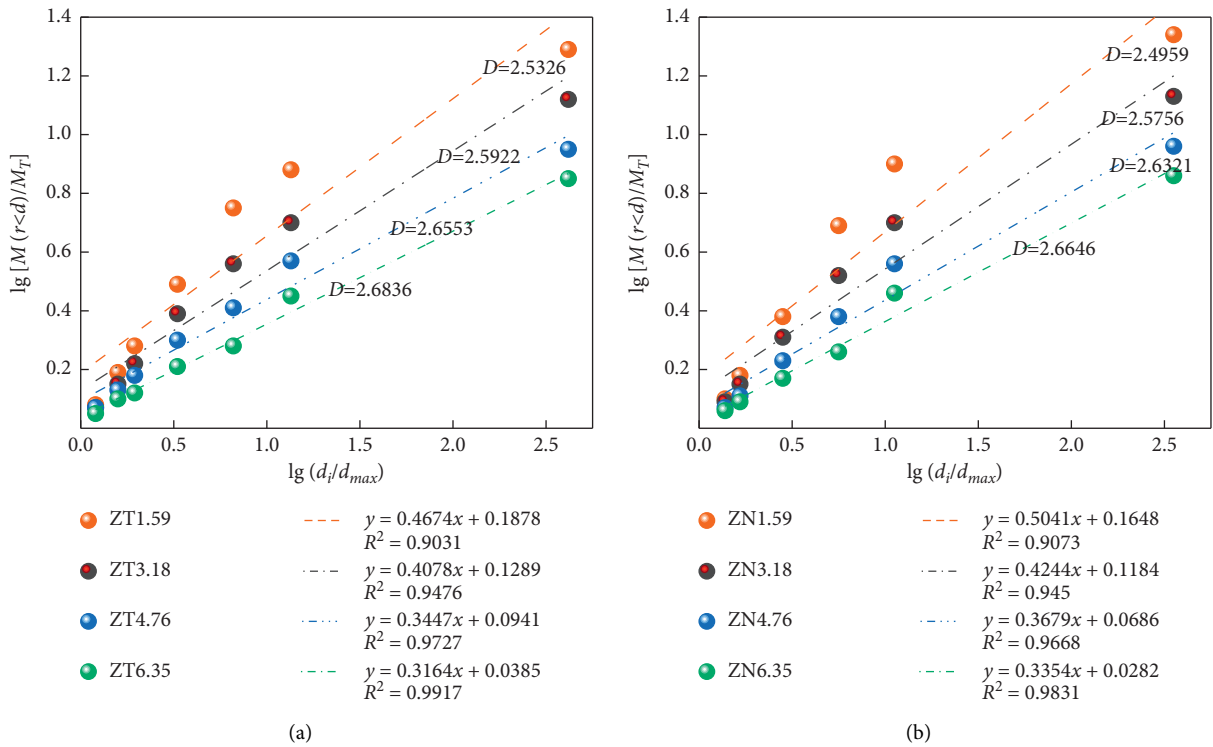

(a)

(b)

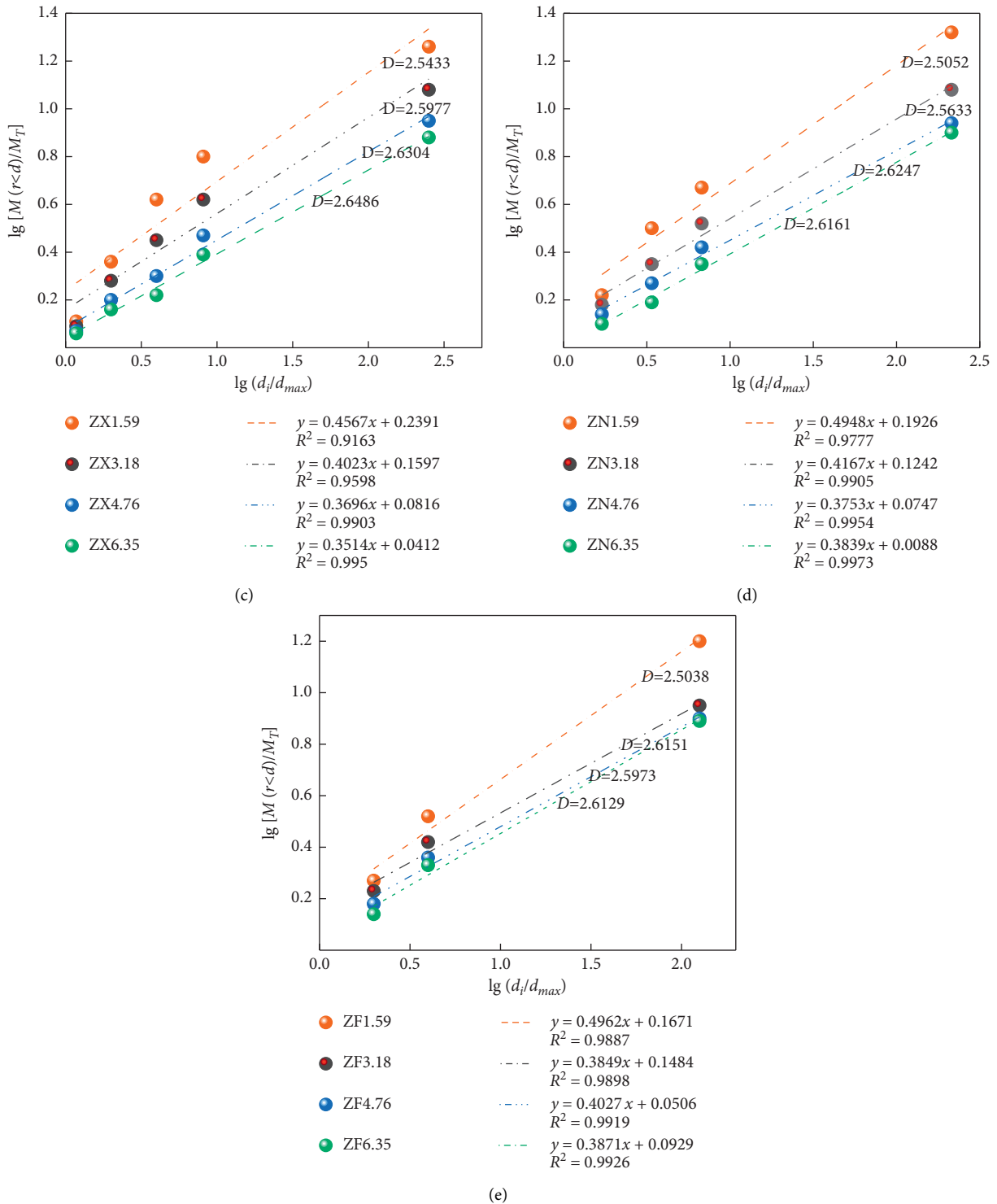FIGURE 11: Continued.

(c)

(d)

(e)

FIGURE 11: Fractal curve of reclaimed brick size. (a) 26.5–31.5 mm. (b) 19–26.5 mm. (c) 16–19 mm. (d) 9.5–16 mm. (e) 4.75–9.5 mm.

Figure 13 clearly demonstrates that the correlation coefficient R^2 of recycled concrete gravel after log-fitting is close to one, indicating that this aggregate has excellent self-similarity after crushing and conforms to the fractal geometric features. However, the fractal dimension varies under different impact effects. With the increase of impact load, the particle is broken more fully, and the large particle is broken into small particles

and moves down one level. Therefore, the fractal dimension also varies, and the difference of fractal dimension can objectively reflect the crushing degree of different particle groups. The fractal dimension of each particle component and different impact energies are compared as shown in Figure 14.

Figure 14 signifies similar grains under different impact energy groups, where the fractal fracture dimension increases
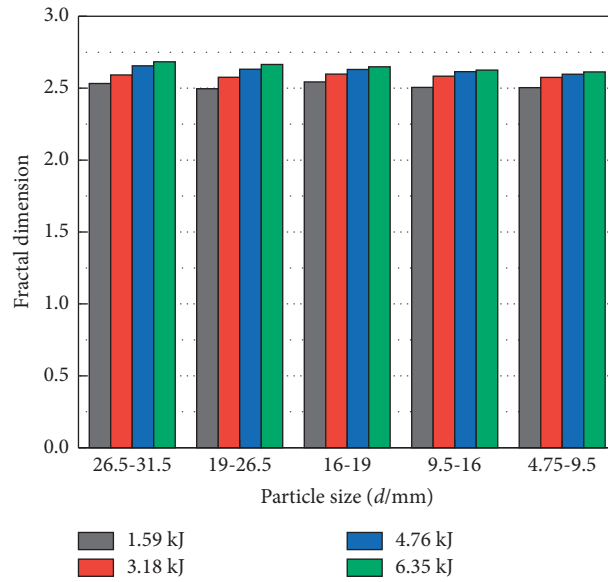
FIGURE 12: Comparison of parting dimensions of recycled bricks under different impact energy.
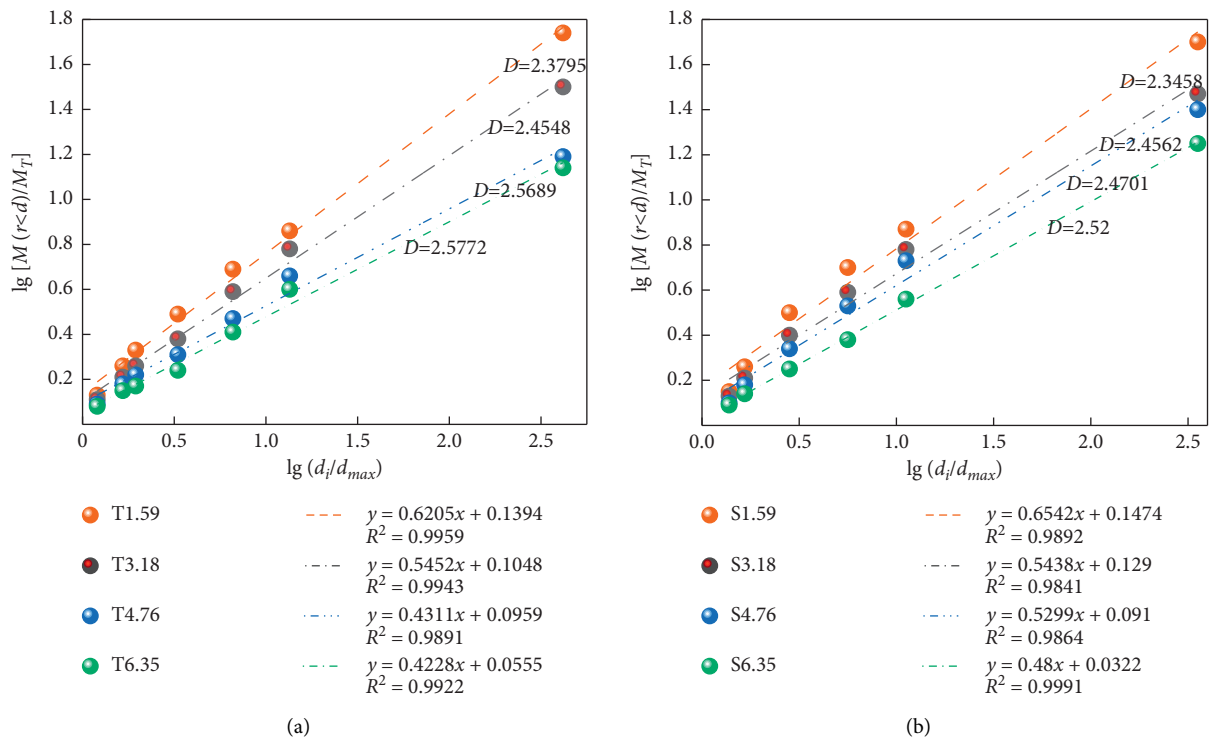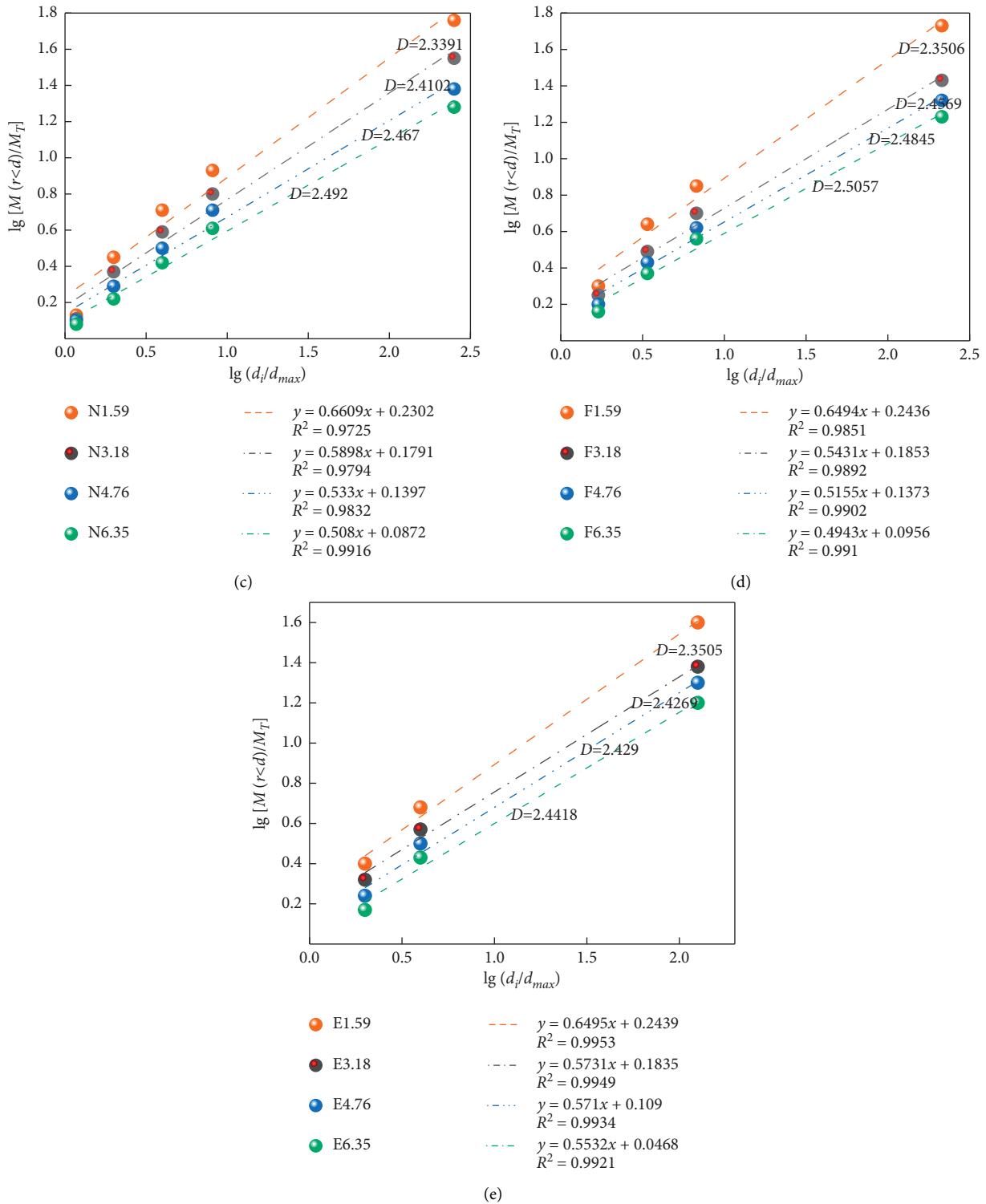

(a)

(b)

FIGURE 13: Continued.

(c)

(d)

(e)

FIGURE 13: Fractal curve of particle size of recycled aggregate of concrete. (a) 26.5–31.5 mm. (b) 19–26.5 mm. (c) 16–19 mm. (d) 9.5–16 mm. (e) 4.75–9.5 mm.

with the rise in impact loading. Consequently, the increase of impact loading causes the particles to squeeze together, and the effective contact pressure and particle crushing significantly rise, increasing the fractal dimension. Conversely, the increasing trend compared with the coarse particles less-

grain group is not apparent. Compared with recycled brick, the shape of the recycled concrete gravel is primarily circular, and its surface is smooth. Figures 12 and 14 present the D_C (fractal dimension of recycled concrete gravel) < D_B (fractal dimension of recycled brick), which

also indicates that the crushing resistance of the two materials varies. It can be observed that the size of fractal dimension is closely related to the material, shape, and particle size.

3.3.3. Fractal Evaluation Index of Aggregate. In coarse aggregate gradation and evaluation index, the commonly used uniformity coefficient C_u and curvature coefficient C_c, two indicators to evaluate the coarse aggregate gradation, are in good condition, for gradation composition with fractal characteristics of reclaimed brick and concrete rubble, which could be considered using fractal dimension D instead of uniformity coefficient of C_u and curvature coefficient C_c to reflect these two graded properties of recycled aggregate. According to the geotechnical code, the relationship between the nonuniformity coefficient C_u and the curvature coefficient C_c is as follows:

$$C_u = \frac{d_{60}}{d_{10}},$$
$$C_c = \frac{d_{30}^2}{(d_{10}d_{60})}. \tag{5}$$

In the formula, d_{60} is the limiting particle size, d_{30} is the average particle size, and d_{10} is the finite particle size, representing less than 60%, 30%, and 10% of the particle content, respectively.

Set the fractal distribution curve of particle size of recycled brick and recycled gravel of concrete as shown in Figure 15. According to (4), the slope of the line is (3-D):

$$k = (3 - D) = \lg \frac{(\lg 60 - \lg 10)}{(\lg d_{60} - \lg d_{10})}$$
$$= \log \frac{\lg 6}{\lg (d_{60}/d_{10})}. \tag{6}$$

The uniformity coefficient and fractal dimension of particle size are deduced as follows:

$$C_u = \frac{d_{60}}{d_{10}} = 6^{1/3-D}. \tag{7}$$

Similarly, $d_{30}/d_{10} = 3^{1/(3-D)}$, $d_{30}/d_{10} = (1/2)^{1/(3-D)}$, and the relationship between the curvature coefficient and the fractal dimension of particle size can be deduced as follows:

$$C_c = 3^{1/(3-D)} \times \left(\frac{1}{2}\right)^{1/(3-D)} = 0.5^{3-D}. \tag{8}$$

The size of the uniformity coefficient can reflect the distribution range of particle size, and the curvature coefficient can reflect the shape of the gradation curve. According to the geotechnical code, the gradation is good when the nonuniformity coefficient $C_u > 5$ and $C_c = 1$–3. Thus, it can be deduced that when coarse particle aggregate is well graded, the value range of particle size fractal dimension D: $1.887 \leq D \leq 2.631$.

As can be seen from (8), when the fractal dimension D of recycled brick and concrete recycled gravel meets $1.887 \leq D \leq 2.631$, it is considered that the grading of the two

recycled materials is good. Figures 7 and 8 demonstrate that when the particle size of recycled brick is between 16 and 31.5 mm and the impact energy is 0.81 kJ, the fractal dimension of recycled brick is greater than 2.63. In contrast, the results prove that when the aggregate impact energy is considerable, and the particle size is larger than 31.5 mm, the gradation of recycled brick is poor. The fractal dimension D of recycled concrete gravel ranges from 2.3391 to 2.5689, meeting the requirements of $1.887 \leq D \leq 2.631$, as displayed in Figure 8.

4. Discussion

According to the research on particle size effect under static load in Section 2, it is found that there is an obvious size effect on particle crushing strength; that is, the particle crushing strength decreases with the increase of particle size. As shown in Figure 6 in Section 2.2.3, when the particle size is 26.5–31.5 mm, the average crushing strengths of recycled brick particles and concrete recycled gravel particles are 1.371 MPa and 2.168 MPa, respectively, which decreases with the increase or decrease of particle size. The particle crushing strength of the two materials increased. When the particle size was 9.5–16 mm, the average crushing strength of recycled brick particles and concrete recycled gravel particles increased by 51.6% and 45.8%, respectively, and the crushing strength of brick was significantly lower than that of concrete recycled grave. According to the fractal characteristics of aggregate impact crushing in Section 3, after the same particle group is crushed under different impact loads, a large amount of aggregate is broken and decomposed, and there is a phenomenon of migration and reorganization to the lower particle group. Compared with concrete, the unbroken particles of concrete recycled gravel are significantly larger than those of recycled brick under impact. It is mainly due to the low strength of recycled brick and the high content of needle and flake. After impact crushing of single-particle size group of the same material, the proportion of unbroken particle group in the overall screening decreases successively. With the decrease of particle size, the proportion of unbroken particle content increases continuously, and it is concluded that the crushing resistance of 4.75–9.5 mm recycled aggregate is high.

Through the static load particle crushing test and impact crushing fractal characteristic test, it can be obtained that there is an obvious village size effect on the particle crushing strength and compressive performance; that is, the particle crushing strength and compressive performance decrease with the increase of particle size. The main reason is that the surface of recycled gravel with different particles is not smooth. There are many initial defects of large particles and different distribution states of microcracks. In addition, the particle crushing strength and crushing resistance of recycled brick are significantly lower than those of concrete recycled gravel, which is mainly due to the different mineral composition of recycled brick and concrete recycled gravel, the rougher surface, and the more internal pores of recycled brick compared with concrete recycled gravel. Therefore, in engineering application, the impact of particle
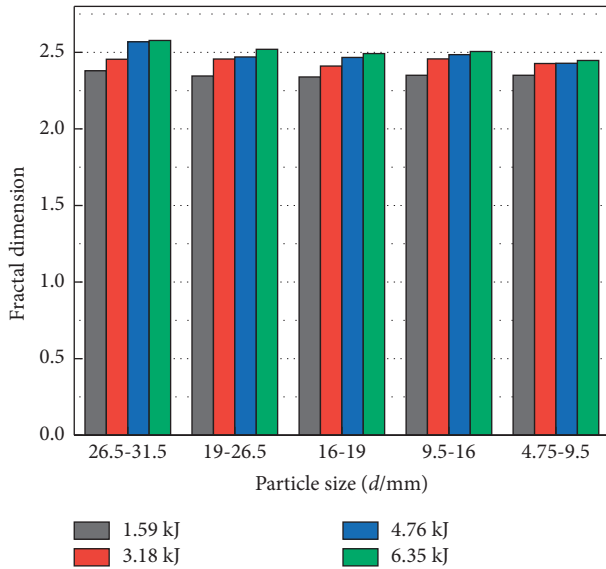
FIGURE 14: Comparison of parting dimensions of concrete recycled aggregate under different impact energy.

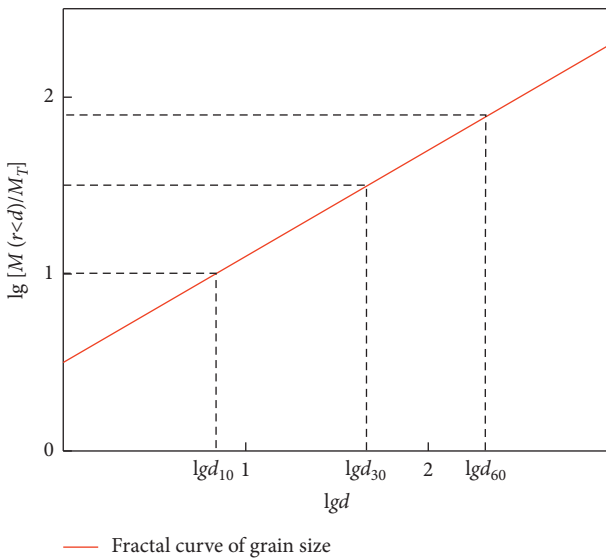—— Fractal curve of grain size

FIGURE 15: Particle size fractal distribution curve of recycled aggregate with fractal structure.

recombination on strength during particle crushing and migration should be considered, and the large particle size should be appropriately increased, so as to avoid the change of overall gradation caused by particle crushing and recombination and the reduction of main stress skeleton, so as to affect the compressive strength of aggregate and engineering construction quality.

5. Conclusion

(1) The order of the particle group and the proportion of the unbroken particle group in the overall screening increases successively, and when the particle size is 4.75–9.5 mm, the proportion of the unbroken

particle group in the overall screening is more than 60%, indicating that the recycled gravel with the particle size of 4.75–9.5 mm has good crushing resistance. Therefore, it is suggested to increase the particle size content of 4.75–9.5 mm in construction applications to improve the mechanical properties of recycled gravel.

(2) The fractal curve of the particle size of recycled brick and recycled gravel of concrete after impact crushing is a straight line, indicating that these two materials have strict self-similarity and meet the fractal characteristics. In addition, the particle size distribution is continuous, the filling between particles is dense, and the gradation characteristics are good.

(3) After replacing the uniformity coefficient C_u and the curvature coefficient C_c with the fractal dimension D, it was deduced that when the fractal dimension D of recycled brick and concrete recycled gravel met $1.887 \leq D \leq 2.631$, the two materials were well graded.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

References

[1] Z. Sun, B. Yang, B. Guan, and W. Huang, "Research progress on mechanical properties of recycled concrete," *Environmental Engineering*, vol. 38, no. 6, pp. 221–227, 2020.

[2] Y. Guo, S. Wan, and C. Wu, "Application of alkali-excited waste concrete road base materials in reconstruction project of Maqiao river road," *Journal of China and Foreign Highway*, vol. 39, no. 5, pp. 266–271, 2019.

[3] L. Xie, K. Wu, X. Cai, and W. Huang, "Study on permeability and mechanical properties of pervious concrete base material from construction waste," *Concrete*, vol. 12, pp. 173–175, 2017.

[4] L. Guo, S. Wan, H. Li, C. Wu, and Y. Xu, "Study on properties of cement stable reclaimed aggregate containing light brick," *New Building Materials*, vol. 48, no. 3, pp. 51–56, 2021.

[5] G. G. Giwangkara, A. Mohamed, and N. H. A. Khalid, "Recycled concrete aggregate as a road base material," *IOP Conference Series: Materials Science and Engineering*, vol. 527, no. 1, Article ID 012061, 2019.

[6] M. Meng, Z. Sun, C. Wang, and H. Xiang, "Size effect on mudstone strength during the freezingthawing cycle," *Environmental Geotechnics*, vol. 271, 2019.

[7] D. Ma, H. Duan, J. Liu, L. Xibing, and Z. Zilong, "The role of gangue on the mitigation of mining-induced hazards and environmental pollution: an experimental investigation," *The Science of the Total Environment*, vol. 664, pp. 436–448, 2019.

[8] O. Daniel, M. J. Khattak, M. Abader, and N. Heim, "Soil-geopolymer mixtures using recycled concrete aggregates for base and subbase layers," *MATEC Web of Conferences*, vol. 271, Article ID 02003, 2019.

[9] J. Yu, C. Shen, and S. Liu, "Breakage and migration of dyed gypsum particles under one-dimensional compression," *Chinese Journal of Rock Mechanics and Engineering*, vol. 39, no. 5, pp. 1071–1079, 2020.

[10] Z. Cai, X. Li, G. Fei, and Y. H. Huang, "Particle breakage rules of rockfill materials," *Chinese Journal of Geotechnical Engineering*, vol. 38, no. 5, pp. 923–929, 2016.

[11] Y. Pei, *Discussion on Interaction and Breaking Mechanism of Recycled Aggregate under Impact Load*, North University of China, Taiyuan, China, 2020.

[12] Q. Wang, Y. Xiang, B. Zhang, X. Wai, and H. Lin, "Study on establishing and application of gradation equation for coarse-grained soil," *Science Technology and Engineering*, vol. 20, no. 31, Article ID 12968, 2020.

[13] Z. Sun, G. Ma, W. Zhou, W. Y. Han, C. Yuan, and X. H. Bin, "Influence of particle shape on size effect of crushing strength of rockfill particles," *Rock and Soil Mechanics*, vol. 42, no. 2, pp. 430–438, 2021.

[14] Z. Dong, C. Dong, S. Zhang, and S. Daichao, "On the breakage transition matrix of granular soils," *Chinese Journal of Rock Mechanics and Engineering*, vol. 40, pp. 1–9, 2021.

[15] S. Zhu, S. Zheng, Z. Ning, and J. Wang, "Gradation design method for rockfill materials based on fractal theory," *Chinese Journal of Geotechnical Engineering*, vol. 39, no. 6, pp. 1151–1155, 2017.

[16] Y. Liu, *Experimental Study on Breakage Characteristics of Andesite Crushed Rock under Impact and Static Load*, Beijing Jiaotong University, Beijing, China, 2019.

[17] S. Xiao-Quan, S.-C. Chi, Y. Tao, and X. Zhou, "DEM simulation of the size effect on the wetting deformation of rockfill materials based on single-particle crushing tests," *Computers and Geotechnics*, vol. 123, Article ID 103429, 2020.

[18] Ministry of Transport, *Ministry of Transport, Prc.JTG/TF20 -- 2015*, China Communications Press Co., Ltd., Beijing, China, 2015.

[19] The Ministry of Communications of the People's Republic of China, *JTG E42-2005, Test Specification for Highway Engineering*, People's Transportation Press, Beijing, China, 2005.

[20] C. Tian, X. Lan, and X. Liu, "Study on mechanical properties of calcium sand compression and fragmentation considering topography features and grading effects," *Engineering Geology Journal*, vol. 40, no. S1, pp. 503–510, 2021.

[21] M. Zhou, Y. Wen, and G. Deng, "Three-dimensional discrete element simulation of single-particle splitting test," *Geotechnical mechanics*, vol. 40, no. S1, pp. 503–510, 2019.

[22] Ministry of Communications of the People's Republic of China, *JTG E51-2009, Test Procedures for Inorganic Binder Stabilized Materials in Highway Engineering*, People's Transportation Press, Beijing, China, 2009.

[23] H. Li and F. Wang, "Fractal theory and its development," *The Study of Dialectics of Nature*, no. 11, pp. 20–23, 1992.

[24] Z. Chen, G. Li, K. Wei, L. Wu, and Y. Zhu, "Study on ultimate state and probability of breakage for rockfill materials with-fractal graduation," *Chinese Journal of Geotechnical Engineering*, pp. 1–10, 2021.

[25] J. Sheng, X. Liu, and R. Zhu, "Fractal theory and frfractal characteristics of rock broken," *Journal.of Wuhan Yejin University.of Science & Technology (Natural Science Edition)*, no. 1, pp. 8–10, 1999.

[26] K. Du-Min, Z.-L. Long, R.-Q. Guo, P.-Y. Yu, and X. J. Wang, "Numerical investigation of the cushion and size effects during single-particle crushing via DEM," *Acta Mechanica Solida Sinica*, vol. 33, pp. 851–863, 2020.

[27] S. Bian, G. Li, and Z. Mi, "Application of fractal theory in rockfill rheology," *Hydro-Science and Engineering*, vol. 6, pp. 60–68, 2017.

[28] G. Cai, J. Guo, L. Chen, and Z. Lu, "Numerical simulation test and crushing experiment of multi-stage particle models with deferent shape," *China Powder Science and Technology*, vol. 25, no. 3, pp. 65–71, 2019.

[29] Ministry of Transportation of Prc, *Test Specification for Inorganic Binder Stability Materials for JTG E51-2009, Highway Engineering*, People's Transportation Press, Beijing, China, 2009.

[30] D. Foti and L. Michela, "New mortar mixes with chemically depolymerized waste PET aggregates," *Advances in Materials Science and Engineering*, vol. 2020, Article ID 8424936, 9 pages, 2020.