Research Article

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Fractal characteristic of recycled aggregate and its influence on physical property of recycled aggregate concrete

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Abstract: Fractal dimension is introduced to describe the complicated characteristics of recycled aggregate and their influence on properties of recycled concrete as an integrated indicator. The fractal dimensions of both particle outline and distribution of recycled aggregate have obvious self-similarity and fractal characteristics. The order of the bulk density, water absorption, and crushing index of recycled aggregate in particle group state is clearly and directly related to the fractal dimension of boundary line. Additionally, the fractal dimension of the distribution of recycled coarse aggregate in concrete decreases in order of natural aggregate, Type I, Type II, and Type III recycled coarse aggregate; smaller distribution dimension value represents more concentrated distribution of aggregate, and 7 and 28 days compressive strength of the corresponding recycled concrete increases. The fractal dimension method is an effective process to assess comprehensive performances of recycled aggregate

and helpful to establish a quantitative evaluation criterion for its wide applications.

Keywords: fractal dimension, recycled aggregate and concrete, box-counting dimension and quantitative evaluation

1 Introduction

In recent years, due to the increasing industrialization and urbanization, abundant wastes are created when buildings are demolished after reaching their service life or due to the urban renewal, and the amount of building waste has climbed to more than 3.5 billion tons per year in China. The various and complicated building wastes may directly or indirectly pollute the air and soil if not properly treated, which causes many environmental problems [1–5]. In fact, recycled aggregate concrete is produced with partial or full recycled aggregate and has attracted considerable attention in the past decade, since it meets the concept of sustainable development [6–15].

The rational and effective utilization of building wastes is done by processing them into recycled aggregate by cleaning, crushing, and sieving, as shown in Figure 1(a). In one hand, recycled aggregate is mainly derived from waste concrete; concrete with various strength grades may lead to great difference in performance of recycled aggregate, for instance, low strength concrete waste can be milled into high-quality recycled aggregate. Due to the various resources and strengths of removed concrete, the quality and performance of recycled aggregate are relatively diversified [13,14]. In other hand, recycled aggregate particles are surface-attached with plenty of hardened cement paste, and many micro-cracks emerge during the crushing processing, causing multiple interfacial transition zones (ITZs) in recycled concrete. The ITZs between old aggregate and old cement paste and between old paste and new cement paste in recycled concrete are fully recognized and substantially reported based on the structure image of recycled aggregate

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Figure 1: Recycled aggregate (a) and multiple ITZ illustration of recycled coarse aggregate (b).

and recycled aggregate concrete [16–21]. As shown in Figure 1(b), the ITZs between old aggregate and old paste, old aggregate and new paste, and the old paste and new paste together form multiple weak interface areas. These above lead to larger porosity, larger water absorption, higher crushing index, and smaller bulk density with respect to natural aggregate [22–24]. Therefore, it differs from natural aggregate as regards several inconvenient and complicated technical indexes of recycled aggregate including fineness modulus, grading, water absorption, particle shape, roughness, strength, and water demand ratio, which are currently required in Chinese national codes “Recycled fine aggregate for concrete and mortar” (GB/T25176-2010) and “Recycled coarse aggregate for concrete” (GB/T25177-2010).

In comparison with normal concrete, lower quality recycled aggregate concrete needs more water, which in turn leads to lower compressive strength and modulus, more shrinkage, higher chloride ion permeability coefficient, quicker carbonization and lower freezing-thawing resistance, and the application of low-quality recycled aggregate is normally limited in low strength concrete structure or components [17,18]. Therefore, it is necessary to establish a quantitative evaluation method between the characteristics of recycled aggregate and the performance of recycled aggregate concrete serving for commercial utilization.

Currently, the fineness modulus, grading, water absorption, particle shape, roughness, strength ratio, and water demand ratio are the main technical indexes of recycled aggregate as adopted by GB/T25176-2010 code. However, these indexes are not capable to completely reflect the characteristics and their influences on the properties of recycled aggregate concrete.

To distinguish the classification of different recycled aggregates and confirm their application range, it is important to establish an integrated index concerning these complicated technical indexes and their influences on properties of the corresponding recycled concrete. Additionally, as a multiphase material, the complicated microstructure of concrete is mostly chaos; the normal Euclidean dimension hasn’t enough capability to describe the uncertainty and irregularity of concrete structure [25]. It’s also urgent to introduce a precise and comprehensive quantitative analysis method to evaluate the performance of recycled aggregate and its influences on the corresponding recycled aggregate concrete.

Fractal dimension is the main concept of fractal geometry, which is capable to describe the chaos and the full-filling degree of a space and is a linking bridge between microscale and macroscale of structure. The concept of fractal dimension was introduced by Tyler *et al.* into nature science to represent the complicated graphics and processes in 1980s [26]. Since then, it was hereafter used to classify and measure the ability of system filling space and its randomness [27,28]. Since Diamond documented the fractal character of aggregate distribution [29], the fractal dimension has become acceleratingly popular in concrete microstructure research as a useful tool in recent years [30–43].

In fact, the microstructures of concrete including porosity, hydration products, aggregate distribution, and cracking are also assumed to be fractal characteristics [31]. The normal concrete structure can be considered as chaotic due to the uncertainties of irregular raw materials and cement hydration products. Therefore, the fractal research on concrete becomes a hot issue in the last few

years. The aggregate size effect evaluation and optimized gradation was achieved by means of fractal dimension controlling [32]. Based on the understanding of the cement paste and pore shape, the Menger sponge model was used to simulate the pore distribution and to establish the connection between cement paste and porosity [32]. The coarse aggregate's influences on workability and strength of recycled aggregate concrete were studied by means of fractal theory [33]. Guo and Sun classified the aggregate gradation dimension and deduced the influence of aggregate gradation dimensions on mechanism of concrete [34]. The surface cracking of recycled concrete beam was discovered to have a fractal characteristic; the fractal dimension of cracking showed a linear relationship with the shear force [35]. The relation between carbonization depth with the fractal dimension of crack and pore was discovered as well; carbonization depth of concrete increased with the reduction of fractal dimension [36]. Zeng et al. employed surface fractal dimension as an indicator to characterize the microstructure of cement-based porous materials [37,38]. The effect of surface fractal dimension on hydration, shrinkage, thermal conductivity, pore structure of concrete with incorporating silica fume, waste fiber, and organic additives is further discussed [39–53].

As is known, recycled aggregate is derived from waste concrete; thus, cement pastes of various thicknesses and strengths are attached on the surface of aggregate [17–20,54–56]. In consideration of the preparation process, the quality of recycled aggregate is decided by its surface attachments; it is hereby important to evaluate the surface property and quality [2–7]. Subsequently, the shape and distribution of recycled aggregate are rather similar with pore within recycled aggregate concrete; the recycled aggregate particle shape may also theoretically present fractal [31]. However, it is yet barely reported.

In this paper, digital image processing and fractal dimension analysis are proposed to describe the randomness, irregularity, and self-similarity characteristics of recycled aggregate and evaluate its quality instead of using complicated technical indicators as national code mentioned; furthermore, the influence of its fractal dimension value on the physical property of the corresponding recycled aggregate concrete is also investigated.

2 Applications of fractal geometry in a particle system

For a geometric form with certain dimension, its size (K) can be represented in equation (1) [54].

$$K = \lim_{r \rightarrow 0} N \times r^D \quad (1)$$

where D is the Hausdorff fractal dimension, N is the number of measurements, and r is the measurement unit.

Thus, N can be derived by the following equation (2),

$$N \propto r^{-D} (r \rightarrow 0) \quad (2)$$

And D can be in turn obtained from equation (3) after taking logarithm,

$$D = \lim_{r \rightarrow 0} \frac{\ln N(r)}{\ln \frac{1}{r}} \quad (3)$$

Additionally, there are some other kinds of fractal dimensions method including similarity, box, correlation, capacity, spectral dimension method, etc. Especially, box dimension method is simple and efficient, in which a box with size r is used to measure the 2D fractal set. Thus, there is different $N(r)$ with different r ; the fractal model of particle size is hereby established.

Particle size distribution is typically represented by total particle mass distribution in certain size spacing; it has also fractal characteristics which can be acquired by the following equation (4),

$$y_n(r) \propto -r^{-D} \quad (4)$$

The differential equation of equation (4) can be derived as following equation (5),

$$d_{y_m(r)} \propto r^{2-D} d_r \quad (5)$$

The integral of the above formula is shown in equation (6),

$$y_m(r) \propto r^{3-D} \quad (6)$$

Figure 2: Double logarithmic fitting of theoretical DSP fractal dimension calculation.

Table 1: Performance indicators of recycled sand and natural sand

Sand type	Performance items			
	Bulk density (kg·m ⁻³)	Dust content (%)	Water absorption (%)	Fineness modulus
Natural	1,570	0.1	—	3.65
Artificial	1,497	0.5	10.5	3.13
Type I recycled	1,554	0.1	3.5	2.7
Type II recycled	1,307	1.9	12.7	3.17
Type III recycled	1,253	2.5	22.7	3.10

where, $y_n(r)$ is the amount of particle smaller than size r , and D is the fractal dimension of particle size distribution, $y_m(r)$ is the mass amount of particle smaller than size r divided by total mass amount of system particles. There is a linear correlation between $y_m(r)$ and r in logarithmic coordinates; hence, the fractal dimension “ D ” can be calculated by means of the slope of the linear fitting.

In addition, the most compact accumulation of a particle system can be derived from the densified parking theory (DSP), as shown in the following equation (7),

$$U_{(d)} = 100 \left(\frac{d}{d_L} \right)^n \quad (7)$$

where n is the distribution model, d is the nominal diameter of a particle.

From Andresen formula, the ideal densified parking model (Horsfield model) can be set up [25], and its particle gradation fractal dimension is hereby calculated by a least square fitting in double logarithmic coordinates as shown in Figure 2; the slope of the linear fitting 3- D is 1.94, and the fractal dimension D is 1.06.

3 Fractal dimension calculation of recycled fine aggregate

The recycled sand is produced and classified according to GB/T25176-2010 code, and their technical indicators are listed in Table 1.

Table 2: Sieve residue percentage of Type II recycled sand

Sieve size (mm)	Divided sieve residue (%)	Accumulated sieve residue (%)
5.000	12.598	12.598
2.500	32.174	44.772
1.250	19.356	64.128
0.630	16.458	80.586
0.315	13.188	93.774
0.160	4.592	98.366
<0.16	1.502	
Total	99.868	

3.1 Gradation dimension calculation of recycled sand

As discussed in Section 2, the most compact accumulation of a particle system has its fractal characteristic, and then sand gradation may also have its own fractal characteristic. Therefore, Type II recycled sand and natural sand are sieved with a set of sieves to test their fractal dimension, and their sieve residue percentages are measured according to GB/T14684-2001 code, as shown in Tables 2 and 3, respectively.

Afterwards, according to equations (1)–(3), the fractal curve is drawn by conducting a conversion of sieve size as “ r ” and sieve residue as $N(r)$; the fractal dimension of Type II recycled sand is calculated by a least square fitting in double logarithmic coordinates, as shown in Figure 3(a), where D is 2.15, and the correlation coefficient R is 0.90493.

Similarly, Figure 3(b) shows the fractal dimension of natural sand by a least square fitting in double logarithmic coordinates. The gradient k of linear regression is 0.7784 and the corresponded D is hence calculated to be 2.22, which is slightly larger than that of Type II recycled sand.

It is worth noting that, in our lab, Type II recycled sand is normally processed by particle reshaped method, which is achieved by using high speed (linear velocity $>80 \text{ m} \cdot \text{s}^{-1}$) repeating joint impact and considerable frictions between aggregates. In this case, the surface shape

Table 3: Sieve residue percentage of natural sand

Sieve size (mm)	Divided sieve residue (%)	Accumulated (%)
5.000	15.656	15.656
2.500	28.484	44.14
1.250	16.206	60.346
0.630	16.298	76.644
0.315	15.026	91.67
0.160	5.578	97.248
<0.16	2.344	
Total	99.592

Figure 3: Double logarithmic fitting of Type II recycled sand (a), of natural sand (b).

is more important than its gradation for recycled aggregate because its surface shape has an influence on the packing efficiency.

3.2 Surface outline fractal dimension of recycled sand in single particle state

Recycled and natural sand samples are settled and taken images with image processing software. After separating target particles and eliminating background, the outline of sand can be accurately drawn as shown in Figure 4(a). Afterwards, the images are overlaid with step grid, as shown in Figure 4(b). Then, the number of grids covered on the sand image is counted as the “ $N(r)$ ” in equation (1).

Figure 4: Outline of Type III recycled sand (a) and grid coverage on sand image (b).

And a set of “ $N(r)$ ” can be obtained when various scales are assigned. Following a least square fitting in double logarithmic coordinates, as shown in Figures 5 and 6, the fractal dimension “ D ” of sands can be calculated, as listed in Table 4.

From Table 4, the D of single sand particle outline decreases in the order of Type I > Type III > Type II > natural sand. It shows disordering character because the single particle can’t embody the general features of experimental sand.

3.3 Surface outline dimension of recycled sand in particle group state

The single sand has been proved to have randomness and contingency. It is more realistic to take the sand group as the sample to discuss its fractal character. As shown in Figures 7 and 8, the similar process was executed as Section 3.2; the curve was drawn by taking sieve size as “ r ” and sieve residue as $N(r)$.

Figure 5: Double logarithmic fitting of natural sand (a) and Type I recycled sand (b).

Following a least square fitting in double logarithmic coordinates, as shown in Figures 9 and 10, the fractal dimension “ D ” of sands can be calculated, as listed in Table 5. Their correlation coefficients are all larger than 0.99, which indicates that the outline of sand group embodies significant self-similarity and fractal characteristic. Thus, the D is technically capable to be the numerical evaluation indicator for the recycled sand; the physical relation between D and aggregate quality will be discussed as below.

3.4 Relationship between fractal dimension and aggregate quality

It's known that there attaches cement paste on the surface of recycled aggregate; theoretically, it has rougher particle surface and larger dimension value than that of

Figure 6: Double logarithmic fitting of Type III (a) and Type II (b) recycled sand.

natural aggregate [25]. The larger dimension value indicates a more complicated outline and irregular shape, and the dimension values of particle shape of single sand are supposed to be in sequence of natural sand > Type I > Type II > Type III recycled aggregate. Nevertheless, from Table 4, the fractal dimension of particle shape of single sand is in order of Type I > Type III > Type II >

Table 4: Fractal dimension of sand outline in single particle state

Sand type	Artificial	Type III recycled	Type II recycled	Type I recycled
Fractal dimension	1.33	1.38	1.356	1.43

Figure 7: Outline of sand in particle group state.

Figure 8: Grid coverage on sand group outline.

natural sand. It is probably because randomness and contingency of single sand particle impair data accuracy.

As seen from Table 5, the outline dimension order of recycled sand in particle group state is Type III > Type II > natural sand > Type I recycled sand. Based on the requirements of GB/T25176-2010 code, the bulk density decreases in the order of Type I, Type II, and Type III recycled sand; the water absorption and dust content

Figure 9: Double logarithmic fitting of natural sand group (a) and Type I recycled sand group (b).

both increase in order of Type I, Type II, and Type III recycled sand. They are clearly and directly related to boundary line dimension of the recycled sand in particle group state in Table 5. Therefore, the boundary line dimension is capable to be a characteristic parameter representing comprehensive performance of recycled sand in particle group state.

Additionally, it is reported that the properties of high-quality recycled aggregate (Type I) including dense density, water absorption rate, crushing index value, and acicular particle content are comparable with those of nature aggregate [24]; Type I recycled sand and natural sand are practically used to prepare concrete mixing any proportion. It's worth to point out that natural sand has equal fractal dimension with Type II recycled sand in the present research. It means that they have similar particle shapes and comparable quality indicators.

Figure 10: Double logarithmic fitting of Type III (a) and Type II recycled sand in particle group state (b).

4 Dimension calculation of recycled coarse aggregate

Type I, II, III recycled coarse aggregates and natural coarse aggregate are used in this research. The bulk density and crushing index are listed in Table 6; the recycled coarse aggregates are identified and classified according to GB/T25177-2010 code; thus, Type I recycled coarse aggregate has the best quality, whereas Type III has the worst one.

4.1 Fractal dimension of recycled coarse aggregate in particle group state

The particle size influences the geometric condition of the coarse aggregate in particle group state with boundary contour line, which in turn affects the fractal dimension value and its relevant randomness and irregularity. Therefore, 100 g individual coarse aggregate with the maximum nominal size of 10–16 mm is taken as the experimental sample and images are taken as shown in Figure 11, and the grid with various side lengths is covered on the aggregate in particle group state with boundary contour line, depicted in Figure 12.

As shown in Figures 13 and 14, the similar process is executed as above, the curve is drawn by taking sieve size as “ r ” and sieve residue as $N(r)$. And the fractal dimension “ D ” is calculated by means of a least square fitting in double logarithmic coordinates, as listed in Table 7.

From Table 6, the fractal dimension of four kinds of coarse aggregates in particle group outline increases in turn of Type III recycled aggregate, Type II recycled aggregate, Type I recycled aggregate, and natural coarse

Table 5: Fractal dimension of sand outline in particle group state

Type	Artificial-sand	Type III recycled sand	Type II recycled sand	Type I recycled sand
Fractal dimension	1.694	1.743	1.700	1.44

Table 6: Performance indicators of coarse recycled aggregate

Aggregate type	Natural	Type I recycled	Type II recycled	Type III recycled
Bulk density ($\text{kg}\cdot\text{m}^{-3}$)	1382.6	1317.8	1239.6	1266.1
Crushing index (%)	10.3	12.4	16.3	18.9

Figure 11: Boundary contour line of aggregate particle group.

aggregate. According to Chinese national code, Type III recycled has the worst surface quality. It hereby indicates that the higher fractal dimension represents rougher surface and lower quality of recycled coarse aggregate. Fractal dimension of coarse aggregate in particle group state with boundary line is capable to evaluate the quality of aggregate; yet, it still can't represent the real distribution of aggregate.

Figure 12: Grid coverage of aggregate in particle group state boundary line.

4.2 Fractal dimension of recycled coarse aggregate distribution

Distribution of aggregate inside the concrete is an important factor that influences the slurry workability, cured mechanical property, and even the durability of concrete. It varies because of the difference of aggregate particle shape, gradation, mixing method, and cast method in the real concrete production. Therefore, the distribution of aggregate is not possible to be numerically calculated and directly compared; hereafter, it can't be used to quantitatively evaluate the quality of recycled aggregate concrete.

Here, a slice was taken by cutting of recycled aggregate concrete after 28 days standard curing; the aggregate distribution in this concrete slice was shown in Figure 15. Following the method as recorded in Section 3.2, the particle boundary line of real dispersed aggregates

Figure 13: Double logarithmic fitting of natural coarse aggregate (a) and Type II (b) recycled aggregate.

Figure 14: Double logarithmic fitting of Type II (a) and Type III (b) recycled coarse aggregate.

was taken by means of image processing, as shown in Figure 16. Following the same procedure, the particle boundary line and fractal dimension D were obtained by means of box-counting method, as shown in Figures 17 and 18, and the corresponding results were listed in Table 8.

From Table 7, the distribution fractal dimension decreases in order of natural aggregate, Type I, Type II, and Type III recycled coarse aggregate.

Table 7: Fractal dimension of boundary line of coarse aggregate particle group

Aggregate type	Natural	Type I recycled	Type II recycled	Type III recycled
Fractal dimension	1.48075	1.49005	1.51824	1.56259

Figure 15: Cutting slice of recycled concrete.

4.3 Relation between fractal dimension and aggregate quality

The normal and recycled concretes were produced based on the mix proportion listed in Table 9. The slump and strength were tested to discuss the relation between concrete qualities and aggregate performance. And the corresponding results related to boundary line dimension, distribution dimension, crushing index of aggregate in

Figure 16: Particle boundary line in real concrete slice.

Figure 17: Double logarithmic fitting of natural aggregate (a) and Type I recycled aggregate (b).

particle group state and the slump, and 7 and 28 days strength of concrete were listed in Table 10.

4.3.1 Relationship between fractal dimension and recycled coarse aggregate properties

From Table 10, the boundary line dimension of aggregate in particle group state increases from 1.49 of Type I up to 1.56 of type III recycled aggregate; similarly, the crushing index increases from 12.4 to 18.9%. It's introduced above that the recycled aggregate particles are attached by hardened cement paste residue on their surface, and many micro-cracks are formed during the crushing processing. Hence, more attachment leads to worse aggregate strength, and hereby higher crushing index. Thus, the higher boundary line dimension in particle group state represents lower quality of varied aggregate. Furthermore, natural aggregate is supposed to have best quality, and it has the smallest boundary line dimension of aggregate in particle group state.

Figure 18: Double logarithmic fitting of Type II (a) and Type III recycled coarse aggregate (b).

Theoretically, the fractal dimension is employed to describe the characteristics of randomness, irregularity, and self-similarity. It is probably suggested that larger boundary line dimension value in particle group state

Table 8: Fractal dimension of recycled coarse aggregate distribution

Sand type	Natural	Type I recycled	Type II recycled	Type III recycled
Fractal dimension	1.68997	1.65048	1.62911	1.50656

Table 9: Mix proportion of recycled concrete (unit: $\text{kg}\cdot\text{m}^{-3}$)

Water	Cement	Sand	Coarse aggregate
245	461	678	936

Table 10: Performance indicators of varied sands

Aggregate type	Boundary line dimension in particle group	Aggregate distribution dimension	Crushing index (%)	Slump (mm)	Strength (7 days) (MPa)	Strength (28 days) (MPa)
Natural gravel	1.48075	1.68997	10.3	110	27.80	37.50
Type I	1.49005	1.65048	12.4	76	21.37	24.40
Type II	1.51824	1.62911	16.3	47	17.43	22.91
Type III	1.56259	1.50656	18.9	41	15.40	19.00

represents rougher and more irregular particle surface, and better quality of recycled coarse aggregate has more regular and tighter surface attached with cement paste. The aggregate distribution dimension of recycled aggregate decreases from 1.65 of Type I down to 1.51 of Type III. It indicates that the aggregate with lower quality has more chaos and irregularity of distribution.

4.3.2 Relationship between fractal dimension and performance of recycled aggregate concrete

From Table 10, as the boundary line dimension in particle group state increases, the concrete slump decreases in order of natural aggregate, Type I, Type II, and Type III recycled coarse aggregate. It is mostly because some micro-cracks are produced in the attached paste interface during the crushing process of recycled aggregate, which accordingly leads to higher water absorption [36]. Thus, the boundary line dimension in particle group state is an effective mathematical tool to evaluate the surface quality of recycled aggregate.

Similarly, concrete strength at 7 and 28 days increases with the boundary line dimension of coarse aggregate in particle group state. It is probably because the boundary line dimension in particle group state represents the surface roughness; rougher surface indicates more amount of attached paste, weaker interfacial zone, and hereby results in worse quality of aggregate.

On the contrary, the distribution of fractal dimension decreases in order of natural aggregate, Type I, Type II, and Type III recycled coarse aggregate. It differs from that of particle surface dimension because the distribution of fractal dimension simply describes the dispersal state; larger distribution dimension value indicates even and uniform distribution of aggregate and the smaller distribution dimension represents more concentrated distribution of aggregate. Consequently, both 7 and 28 days compressive strengths of concrete increase with the distribution dimension values of aggregate.

5 Conclusions and prospects

- (1) Fractal dimensions of recycled sand in both single particle and particle group state have apparent self-similarity and fractal characteristics. It is effective to assess the complex performance indexes of recycled aggregate and the correlated recycled aggregate concrete by means of fractal method.
- (2) The order of the performances including bulk density, water absorption, and dust content is clearly and directly related to boundary line dimension of recycled sand in particle group state. The boundary line dimension in particle group state is capable to be a unified description parameter for comprehensive performance of recycled sand.
- (3) The higher boundary line dimension represents lower quality for various aggregates in particle group state; it increases from 1.49 of Type I up to 1.56 of Type III recycled aggregate. Higher boundary line dimension value of aggregate in particle group state represents rougher and more irregular particle surface of aggregate.
- (4) The distribution dimension decreases in order of Type I > Type II > Type III recycled coarse aggregate; it decreases from 1.65 of Type I down to 1.51 of Type III. It indicates that the distribution is more concentrated for low-quality recycled aggregate. Therefore, 7 and 28 days compressive strength of concrete increases with the distribution dimension values of coarse aggregate.

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