



Effect of grinding time on the particle characteristics of glass powder



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ABSTRACT

Based on laser particle size analysis and activity index test results, the effect of grinding time on particle characteristics of glass powder is systematically investigated with the aid of the Divas–Aliavden grinding kinetic equation, RRB (Rosin–Rammler–Bennet) and Swrebec distribution model, fractal theory and gray correlational analysis in this paper. The results show that the grinding efficiency of glass powder with large particle size tends to decrease with the increase of grinding time, and draws near to zero after 120 min. Both the equivalent particle size and specific surface area (SSA) of glass powder show a good linear relation to logarithm or double logarithm of grinding time. Both RRB and Swrebec function model can adequately describe the particle size distribution (PSD) of glass powder ground for different times, and according to the RRB distribution model, both the characteristic particle size and the distribution index of glass powder show a downward trend with grinding time, which indicates that the grinding process cannot only levigate glass powder, but also widen its PSD. The PSD of glass powder shows obvious fractal features, and its fractal dimension also has an increasing tendency with grinding time. In addition, the activity index of glass powder increases with grinding time. Depending on the gray correlational analysis, the mass fraction of particles ranging 0–3 μm has a maximum positive effect on its activity index at early age while particles ranging 3–10 μm contribute most at later stage. As a result, 90 min is chosen as the optimal grinding time for glass powder in consideration of economical and technical benefits.

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1. Introduction

With the development of industrialization and urbanization, a huge quantity of waste glass emerges. Data from the United Nations shows that waste glass has occupied 7% of global solid waste [1]. In developed countries such as Europe and America, the quantity of waste glass made up 4%–8% of the total municipal refuse and America itself produced approximately 12.8 billion tons of waste glass in the year of 2005, of which only 21% has been recycled and the rest are roughly addressed by landfill [2]. Moreover, glass is not bio-degradable. Thus, in the process of landfill, not only are the resources tremendously squandered, but also the environment is badly polluted.

Glass powder, being amorphous and containing relatively large quantities of silicon and calcium, could theoretically be pozzolanic and even be cementitious when it is finely ground [3]. In addition, some researchers have pointed out that glass powder with certain fineness is

beneficial to the control of Alkali-silica reaction (ASR) when used as supplementary cementitious materials in concrete [4]. Therefore, the reasonable utilization of glass powder in concrete not only offers a potential for waste glasses recycling but also improves the concrete properties.

However, the finer the glass powder, the longer time it takes to grind, which will definitely increase energy consumption and cost. Furthermore, if glass powder with relatively high fineness continues to be ground, particle agglomeration or “secondary particle” may occur, which may on the contrary decrease its SSA and might weaken its performance in concrete. Besides the particle size characteristics such as fineness and equivalent particle size, grinding time also has a great effect on PSD features as well as activity index of powder materials, which would highly influence the effectiveness and efficiency of the utilization of glass powder in concrete [4–5]. Therefore, it is important to seek out the optimal grinding time for glass powder from economical and technical perspective.

It is assumed that the sieve residue of ground materials with a certain size is R . Apparently, the value of sieve residue R of ground glass powder will gradually reduce with the increase of grinding time. Divas and Fanrenwald have put forward that the reduction rate of sieve residue with a certain particle size ($-dR/dt$) is proportional to the sieve

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Table 1

Chemical composition of glass powder/mass, %.

SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	MgO	Cr ₂ O ₃	MnO	TiO ₂
69.17	10.52	2.94	1.47	12.13	1.26	1.16	0.22	0.03	0.06

residue value (R) at one moment during the grinding process [6]. The equation is as follows,

$$\frac{dR}{dt} = -K_t R \quad (1)$$

Where, K_t is the grinding rate constant.

Eq. (1) has been revised by Aliavden, and the kinetic equation used to describe the grinding process of materials is obtained as the following equation,

$$R = R_0 e^{-K_t t^M} \quad (2)$$

Where, R_0 is the initial sieve residue of ground materials with certain particle size; M is the time index and determined by the property of ground material and its grinding conditions. The kinetic equation can be finalized once the two parameters K_t and M are determined [7].

Many researchers have investigated the grinding kinetic equation, especially the effect of grinding process on the grinding parameter K_t [8–10]. Results show that K_t is closely related to the grinding efficiency of ground materials with certain size apart from its property and grinding conditions, and it decreases along with the decrease of grinding efficiency [11–12]. In addition, a great deal of work on the effect of grinding time on the particle characteristics of other powder materials including fly ash, slag, steel slag, etc., have also been done. However, such issues mentioned above have never been systematically discussed on glass powder before.

In this paper, the PSD of glass powder ground for different times are measured by laser particle size analyzer, based on which the parameters of grinding kinetic equations are determined and the effect of grinding time on the particle characteristics is investigated.

2. Experimental

In order to obtain glass powder, the waste beer bottles are collected, cleaned, sun-cured, smashed, and ground for different times, i.e., 10 (A), 30 (B), 60 (C), 90 (D) and 120 (E) min respectively, in a small insulative ball mill of SM 500 × 500 mm, produced by Daoxu machinery factory in Shangyu. The ball mill has a speed of 48 r/min, with the loading capacity of 5 kg sample. The beer bottles

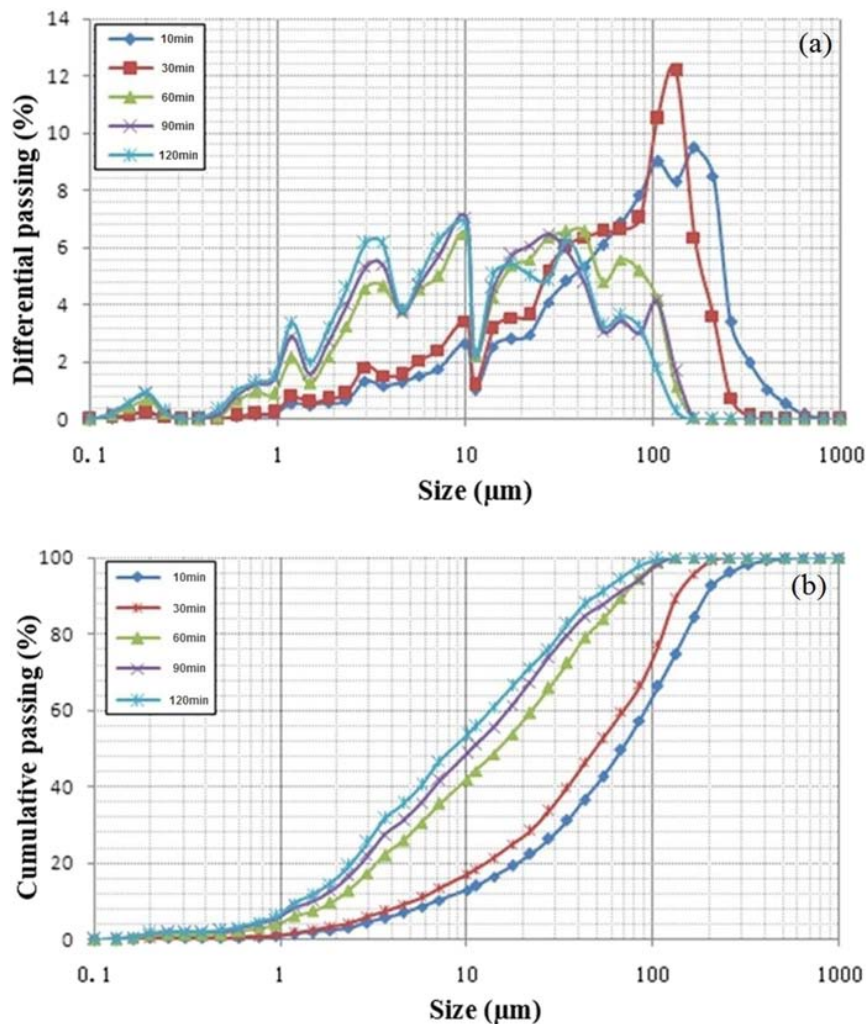


Fig. 1. Particle size distribution curves of glass powder: (a) differential curve, (b) integral curve.

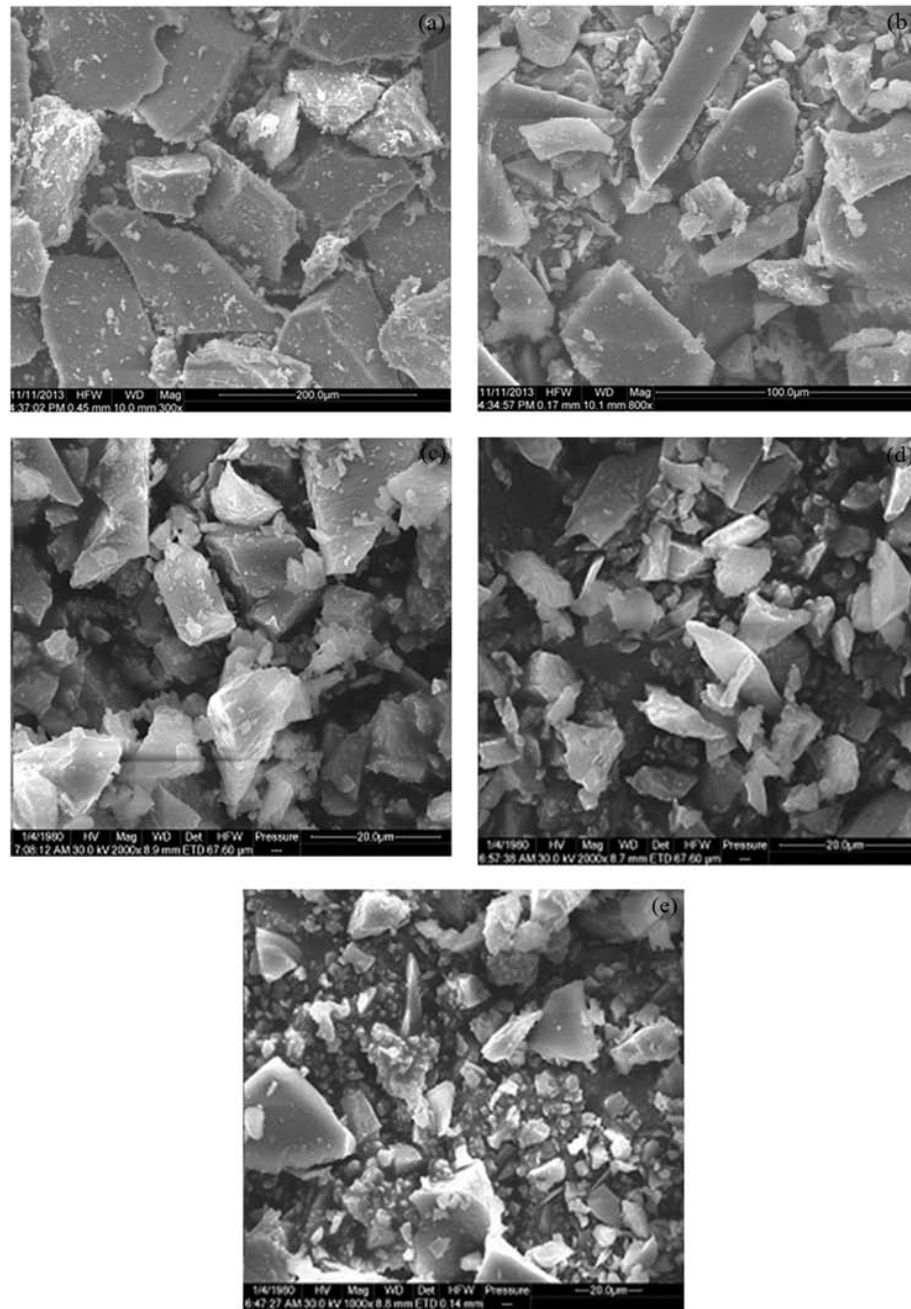


Fig. 2. Particle morphology of glass powder: (a) A(10 min), (b) B(30 min), (c) C(60 min), (d) D (90 min), and (e) E (120 min).

are made from soda-lime glass, which is the most widely used for manufacturing containers, float and sheets, and accounts for over 80% by weight of all the glass [3].

Table 2
Sieve residues of six representative size of glass powder/mass, %.

Grinding time/min	105.78 μm	53.91 μm	43.07 μm	10.00 μm	4.56 μm	0.95 μm
10	33.54	57.25	63.36	87	92.94	99.06
30	16.63	43.34	50.37	81.49	90.00	98.75
60	1.23	16.19	20.99	57.96	74.02	95.93
90	1.69	12.29	15.38	51.24	68.81	94.39
120	0.30	8.90	12.18	46.37	64.48	93.77

The chemical composition of glass powder is listed in Table 1. The glass powder used in the paper contains a great deal of SiO_2 , Al_2O_3 and CaO , and meets the requirement of the ASTM C 618-15 Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete.

The PSD of glass powder is measured by a laser particle size analyzer (Master sizer 2000), produced by English Malvern Plant, ranging from 0.1 to 1000.0 μm . The equivalent particle size and specific surface area of glass powder and cement are calculated by software carried in the laser particle size analyzer. The particle morphology of glass powder has also been investigated by using a scanning electron microscopy (JSM-5610LV, Japan). The strength activity index of glass powder ground for different times is tested according to Chinese standard GB/T 18046-2008.

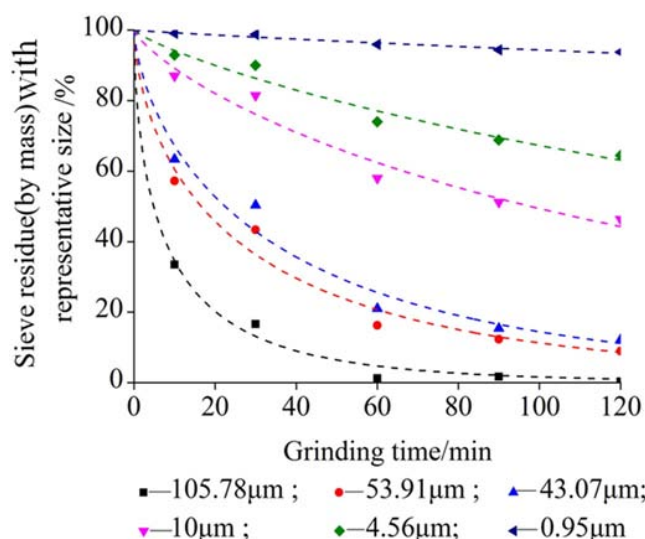


Fig. 3. Fitting curves for relationships between particle sieve residues (by mass) with six representative sizes and grinding time.

Table 3

Parameters of grinding kinetic equation for six representative size.

Parameters	105.78 μm	53.91 μm	43.07 μm	10.00 μm	4.56 μm	0.95 μm
K_t	0.27281	0.11519	0.08175	0.01868	0.00901	0.00100
M	0.59034	0.63902	0.68719	0.78860	0.82153	0.88166
R^2	0.996	0.984	0.980	0.969	0.968	0.960

3. Results and discussions

3.1. PSD and particle morphology of glass powder

Figs. 1 and 2 show respectively the PSD curves and the particle morphology of glass powder ground for different times.

From Fig. 1, the particle size of glass powder decreases with the increase of grinding time. Most of glass powder particles ground for 120 min are not more than 50 μm. From Fig. 2, relatively smooth surface of glass powder particles is observed, with their morphology shape mainly exhibiting angular, block, clastic, and granular, which is distinct from that of fly ash which is mostly spherical. With increasing grinding time, fine particles with granular and clastic morphology increase while coarse particles with angular and block morphology decrease, leading to the sphericity of entire PSD being improved, which may contribute to higher packing density and reducing the porosity of hardened composite pastes.

3.2. Kinetic equations of glass powder ground for different times

In order to validate if the grinding kinetics of glass powder ground for different times conform to the grinding kinetic equation and establish the equations, six representative sieve sizes (105.78, 53.91, 43.07, 10.00, 4.56 and 0.95 μm) are selected according to the PSD curves of

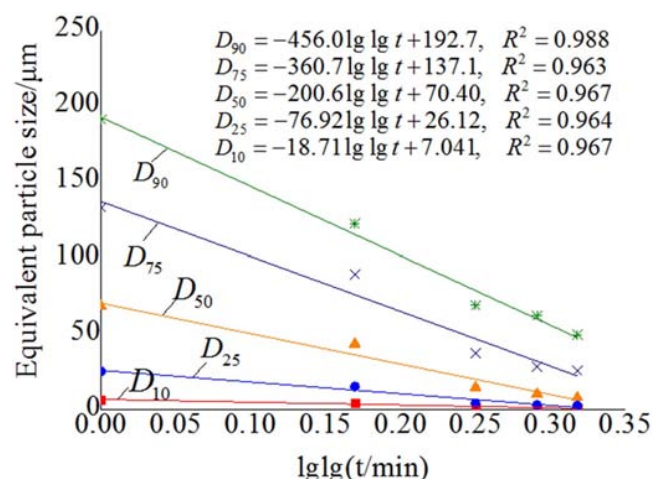


Fig. 4. Relationships between equivalent particle size of glass powder and double logarithm of grinding time.

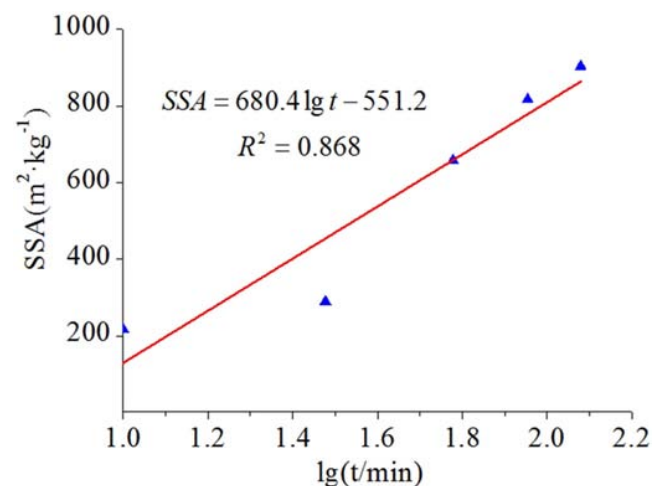


Fig. 5. Relationships between SSA of glass powder and logarithm of grinding time.

glass powder (Fig. 1), and the sieve residues (by mass) of particles with specific representative size at different grinding times are counted respectively and listed in Table 2.

Relationship between particle sieve residues with six representative size and grinding time is fitted according to Formula (2). The fitting curves and relevant parameters are shown in Fig. 3 and Table 3 respectively.

From Fig. 3, fairly good fitting curves, together with high values of correlation coefficient, are obtained from fitting of experimental results. It is shown that Formula (2) can well describe the grinding process of glass powder. All curves show a downward trend with grinding time: the larger the representative size, the sharper the downward trend. In

Table 4

Specific surface areas and equivalent particle size of glass powder.

Material	Grinding time/min	SSA/(m²/kg)	D10/μm	D25/μm	D50/μm	D75/μm	D90/μm
Glass powder	10	217	6.83	25.61	68.29	133.18	191.25
	30	289	4.56	15.46	43.61	89.59	122.58
	60	658	1.90	4.32	14.94	37.35	69.16
	90	817	1.45	3.28	10.64	28.54	62.17
	120	903	1.22	2.86	8.20	26.12	49.52
Cement	–	437	2.37	4.75	13.60	28.02	40.36

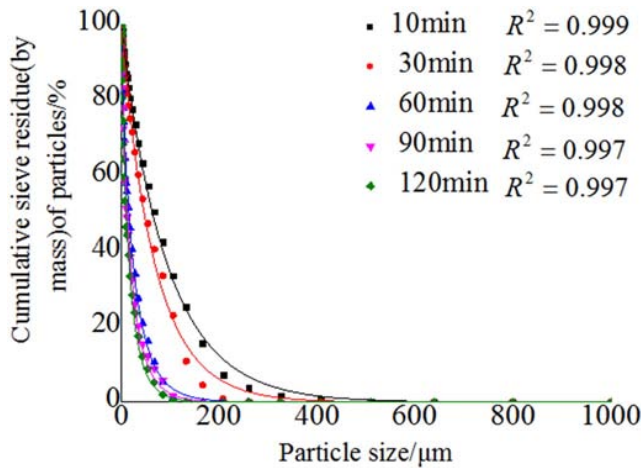


Fig. 6. Fitting curves for cumulative particle size distribution of glass powder.

other words, the coarse particles have a higher grinding efficiency than fine particles during the grinding process of glass powder, which is well illustrated by the decreasing of K_f at Table 3.

As regard to glass powder with large particle size, the grinding efficiency is fairly high initially and decreases with increasing grinding time, and draws near to zero after 120 min. The results can be explained as follows: in the initial stages of the grinding process, particles are crushed mainly by means of volume crushing, leading to high grinding efficiency. With the increase of grinding time and the decrease of particle size, the toughness of glass powder has been improved while the volume crushing effect based on collision and extrusion has been weakened, hence resulting in a low grinding efficiency at later stages. As grinding process continues, agglomeration effect occurs around particles with cushions or “secondary particle” formed, which may severely impede the further development of crushing process for glass particles. As a result, grinding efficiency finally decreases near to zero.

3.3. Effect of grinding time on equivalent particle size and SSA

In this study, the equivalent particle size of glass powder is defined as a corresponding particle size value when the cumulative particle size distribution percentage reaches a certain value. For instance, D_{25} refers to the corresponding particle size when the cumulative PSD percentage reaches 25%, which physically means that the quantity of particles with size below D_{25} makes up 25% of the total mass.

The SSA and the equivalent particle sizes (D_{10} , D_{25} , D_{50} , D_{75} , and D_{90}) of glass powder ground for different times are listed in Table 4, which indicates clearly that the equivalent particle size descends while SSA increases gradually with increasing grinding time. After ground 120 min, the equivalent particle size of glass powder is basically smaller than that of cement and its SSA is twice as high as that of cement, showing that the glass powder ground for 120 min has high fineness level. Additionally, the equivalent particle size D_{90} of glass powder after ground 120 min is 49.5 μm , indicating that particle size of most

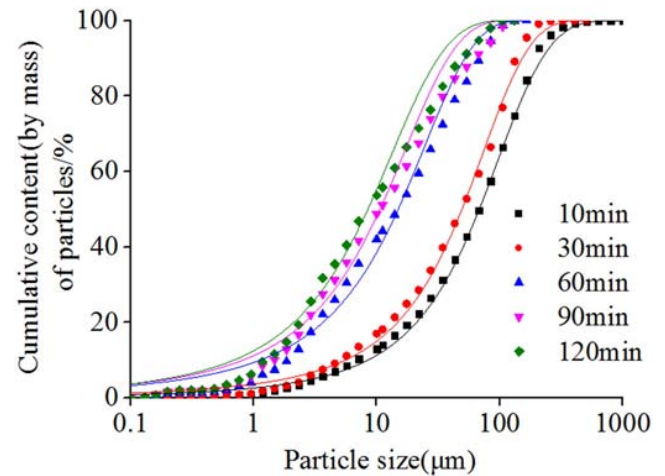


Fig. 7. Swrebec function fitting of glass powder ground for different times respectively.

glass powder is not larger than 50 μm , which coincides with the PSD in Figs. 1 and 2.

For the purpose of quantitatively describing the grinding kinetic behavior of glass powder, linear regression analysis has been conducted on the relationships between equivalent particle size as well as SSA of glass powder and logarithm of grinding time, based on which the fitting curves are obtained and fitting equations are plotted as shown in Figs. 4 and 5. The fitting curves of two figures display that both the equivalent particle size and SSA of glass powder show a good linear relation with logarithm or double logarithm of grinding time. These fitting equations can also be used to quantitatively describe the grinding kinetic behavior of glass powder.

3.4. Effect of grinding time on PSD characteristics

3.4.1. RRB (Rosin–Rammler–Bennet) model

Besides fineness, the PSD characteristics of cementitious materials also determine the development of hydration process and strength [13–15]. In addition, grinding time can also affect the PSD characteristics of glass powder from its fineness. Therefore, it is a matter of great importance to make clear the PSD characteristics of glass powder with different grinding times, which not only can promote the understanding of influence of PSD characteristics on cement hydration, but also provide some reference to adjusting the processing parameters of the grinding technology.

Researchers agree that most of the PSD should conform to RRB (Rosin–Rammler–Bennet) distribution model as follows [16],

$$R = \exp \left[- \left(\frac{d}{d^*} \right)^n \right] \quad (3)$$

Where, d is particle size of powder; d^* is characteristic particle size (which is equal to the corresponding particle size when the sieve residue reaches 36.79%), reflecting the particle size of most particles; n is the uniformity coefficient, the higher the n value, the more compact the PSD. d^* and n play a dominant role in determination of the distribution characteristics, to put it another way, the PSD of any particle system described by using the RRB distribution model can be distinguished with values of n and d^* .

The measured data of cumulative PSD of glass powder is fitted according to RRB distribution model. The fitting curves and relevant parameters are shown in Fig. 6 and Table 5 respectively.

As shown in Fig. 6, the cumulative PSD curves of RRB distribution function describe well the measured data. From Table 5, the characteristic particle size of glass powder calculated by RRB distribution model

Table 5
Distribution index and characteristic particle sizes.

Material	Grinding time/min	n	$d^*/\mu\text{m}$	
			x^* (measured value)	x^* (fitted value)
Glass powder	10	0.962	92.864	98.061
	30	0.953	67.966	76.464
	60	0.805	23.609	25.167
	90	0.786	18.356	18.850
	120	0.791	15.332	15.459
Cement	–	1.092	17.847	20.81

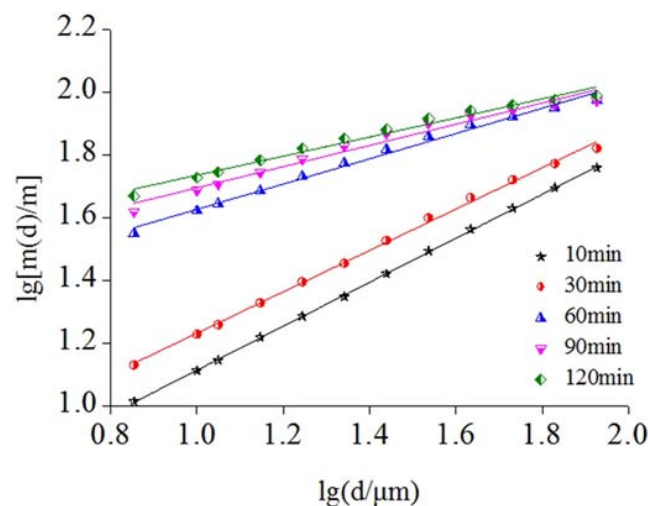
Table 6Parameters of Swrebec function and a comparison of R^2 -Adj with RRB models.

Model	Parameters	Grinding time (min)				
		10	30	60	90	120
Swrebec	$x_{\max}$ (um)	1000	509.7	165.77	132.42	132.42
	x_{50} (um)	68.31398	49.32321	14.96047	10.63603	8.47997
	b	3.81449	3.32352	3.00627	3.12818	3.38368
	R^2 -Adj (%)	99.9	99.7	98.8	98.2	98.1
RRB	R^2 -Adj (%)	99.9	99.8	99.8	99.7	99.7

is relatively close to the measured characteristic particle size, which indicates that the cumulative PSD of glass powder complies with RRB distribution model. With increasing grinding time, both the characteristic particle size and the distribution index of glass powder show a downward trend in general. Besides, the distribution index of all glass particles is smaller than that of cement. The characteristic particle size of glass powder ground for 90 min is almost the same as that of cement while it is finer than that of cement ground for 120 min. These results illustrate that the grinding process cannot only levigate glass powder, which can influence the hydration process and strength development, but also widen the PSD, which may be propitious to ameliorate the gradation distribution of cement-glass powder composite binder, improve the packing density as well as reduce the porosity of hardened paste. It's worth noting that the distribution index of glass powder ground for 90 min slightly increases, which may be related to the fact that these glass powder particles may reunite and form some "secondary particle", leading to narrowing of the PSD of glass powder [17–18].

3.4.2. Swrebec model

A new popular mathematic model, Swrebec function model, has been introduced recently as a tool to fit the PSD of fine ground materials and even as an alternative to traditional functions such as RRB model because of its independence on the date set being analysed and high goodness-of-fit for the studied samples [19]. The Swrebec function model was initially proposed by Ouchterl only to fit coarse size distributions, as in the case of blasting and crushing process [20], fine grinding process of quartz sand suspension [21], as well as the PSD of detrital sediment [19], all with a good fitting in the full size range. In the light of the above, it should be considered whether Swrebec function yields very good fitting conditions even in the case of glass powder.

**Fig. 8.** $\lg[m(d)/m]$ – $\lg d$ curves.

The cumulative passing function $F(x)$ follows

$$F(x) = \frac{1}{1 + f(x)} \quad (4)$$

Considering $f(x_{\max}) = 0$ and $f(x_{50}) = 1$, the function is fixed at $x_{\max}$ and x_{50} , so $f(x)$ can be expressed as follows,

$$f(x) = \left[\frac{\ln\left(\frac{x_{\max}}{x}\right)}{\ln\left(\frac{x_{\max}}{x_{50}}\right)} \right]^b \quad (5)$$

As a consequence, the Swrebec distribution function can be described as,

$$F(x) = \frac{1}{1 + \left[\frac{\ln\left(\frac{x_{\max}}{x}\right)}{\ln\left(\frac{x_{\max}}{x_{50}}\right)} \right]^b} \quad (6)$$

where, $F(x)$ is cumulative passing at x size; $x_{\max}$ is maximum size; x_{50} is the size passing 50% weight and b is the curve undulation parameter.

The fitting results of the PSD of glass powder ground for different times by Swrebec model are plotted in Fig. 7 and relevant parameters are listed in Table 6, where very good fitting curves as well as high values of correlation coefficient for fitted date are obtained and just slightly lower than that of RRB models. Thus it can be confirmed that Swrebec function can also be used to describe PSD in fine grinding process of glass powder.

3.5. Fractal features of the PSD of glass powder

The introduction of fractal theory provides a refreshing research view for PSD in recent years. The macro-fracture of powder materials usually develops from meso-damage, which undergoes the process of occurrence, growth, extension, aggregation and impenetration of inner defects. The process from meso-damage to macro-fracture shows fractal features [22–23]. Relevant researches [24] have shown that the macro-fracture of powder materials is formed by aggregation of smaller broken groups, while these smaller broken groups are originated from micro-cracks. This self-similar crushing behavior will inevitably lead to the same self-similar characteristic of broken powders' PSD. At present, fractal theory is widely used to simulate and describe the self-similar characteristic of PSD [25–27].

Glass, a typical brittle material, will be broken into several small similar pieces with certain probability because of the collision of external force during the grinding process, where a portion of pieces are further broken into smaller similar pieces. By this way, more and more similar

Table 7

Fractal dimensions of PSD of glass powder.

Grinding time/min	10	30	60	90	120
D	2.301	2.342	2.598	2.643	2.697
R^2	0.999	0.998	0.991	0.981	0.980

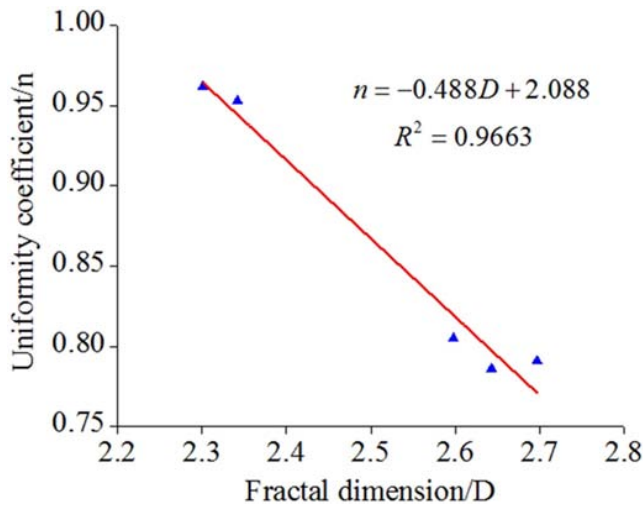


Fig. 9. Linear relationship between fractal dimension and uniformity coefficient.

fine broken fragments are obtained. So, in this study, the PSD of glass powder is preliminarily considered to have fractal feature during the grinding process. And the fractal dimension (D) of PSD of glass powder is calculated in accordance with the formula below [28],

$$D = 3 - b \quad (7)$$

Where, b is the slope of $\lg[m(d)/d] - \lg d$ curves, in which $m(d)$ is the quality of particles with particle size below d , m is the total mass of particles, $m(d)/m$ is actually the cumulative content of particles with particle size below d .

The $\lg[m(d)/d] - \lg d$ curves are plotted in Fig. 8, from which the b values are obtained and then the fractal dimension of PSD is calculated according to formula (4). The results are shown in Table 7. The $\lg[m(d)/d] - \lg d$ curves of glass powder are well fitted with the determination coefficient R^2 higher than 0.980 (in Table 7). It is confirmed that the PSD of glass powder has fractal features.

3.5.1. Relationship between fractal dimension and characteristic particle size as well as uniformity coefficient

Relationship between fractal dimension and uniformity coefficient as well as characteristic particle size of glass powder is plotted in Figs. 9 and 10 respectively. Both uniformity coefficient and characteristic particle size show a negative linear correlation to fractal dimension

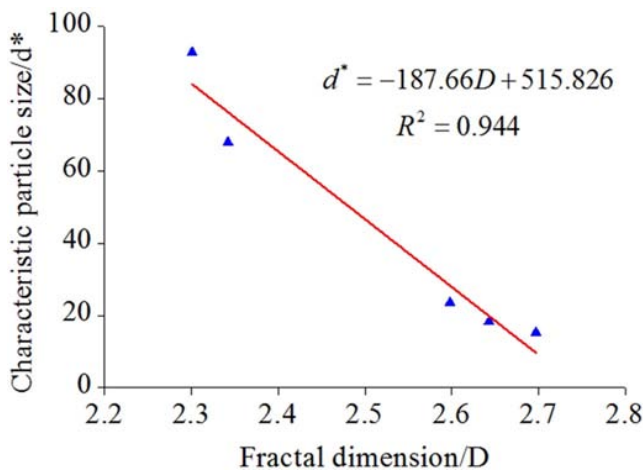


Fig. 10. Linear relationship between fractal dimension and characteristic particle size.

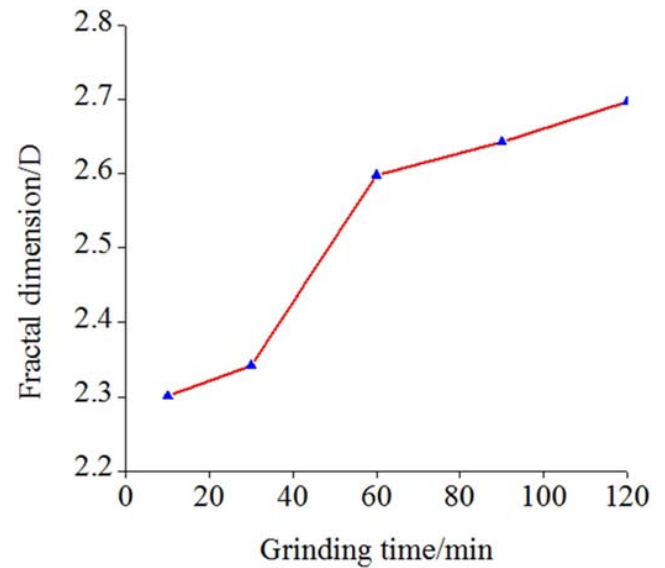


Fig. 11. Relationship between grinding time and fractal dimension.

of PSD. The larger the D value, the smaller the value n , which means poorer uniformity and a wider PSD. The larger the D value, the smaller the value d^* , which implies smaller particle size of most particles. On the whole, the fractal dimension cannot only characterize its fineness but also reflect the uniformity of PSD for glass powder.

3.5.2. Relationship between fractal dimension and SSA

Relationships between grinding time and fractal dimension as well as SSA are shown in Figs. 11 and 12 respectively. As shown in Figs. 11 and 12, both the fractal dimension and SSA of glass powder increase over grinding time, and the change trends of two curves are highly similar. After 30 min, the growth rate of fractal dimension and SSA tend to slow down with increasing grinding time. The greater the fractal dimension or SSA, the more difficult for particles to be ground.

Relationship between fractal dimension and SSA of glass powder is shown in Fig. 13. The SSA of glass powder shows a positive linear correlation to its fractal dimension of PSD. It can be explained that fractal dimension reflects the dispersion tendency and the uniformity of PSD. And SSA is closely related to the variation of PSD, particle shape and particle structure [29]. To some degree, the fractal dimension and SSA are

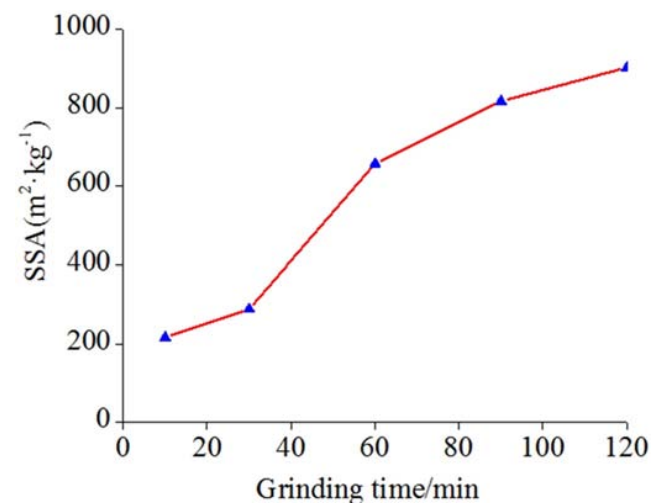


Fig. 12. Relationship between grinding time and specific surface area.

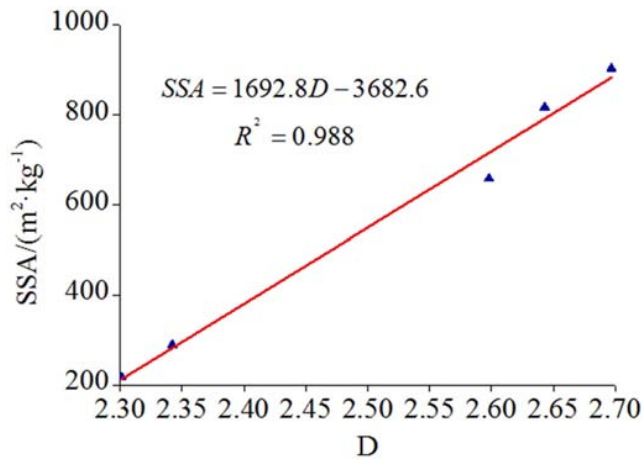


Fig. 13. Relationship between fractal dimension and SSA.

essentially the same. As a result, a new technical index namely fractal dimension of particle size can also be utilized to characterize the PSD features of glass powder.

3.6. Effect of grinding time on activity index of glass powder

The compressive strength of mortars containing 30% glass powder ground for different times is tested at 3, 28, and 90 days and compared with pure cement mortar according to Chinese standard GB/T 17671-1999. For all mortars, water to binder ratio is 0.5 and sand to binder ratio is 3. The activity index of glass powder is calculated in accordance with Chinese standard GB/T1596-2005 as follows,

$$H = \frac{R}{R_0} \times 100 \quad (8)$$

Where, H is the activity index; R is the compressive strength of mortar containing 30% supplementary cementitious materials and R_0 is the compressive strength of pure cement mortar.

The testing results are shown in Table 8. Relationship between grinding time and activity index of glass powder at different ages is shown in Fig. 14. The activity index of glass powder shows a positive linear correlation to grinding time, indicating that the activity index of glass powder, especially for that at early ages, can be improved by increasing grinding time.

Additionally, the effect of PSD of glass powder on its activity index is also investigated by using gray correlational analysis model, which is designed to analyze the various correlations among some sub-factors (sub-sequences) under the same main factors (primary-sequences) or the correlations among factors in the same layer [30–32].

First of all, the PSD of glass powder ground for 60, 90, and 120 min is respectively divided into six intervals and the mass fraction of each interval is figured out as listed in Table 9.

After that, the gray correlation model is established. This model regards the PSD of glass powder as sub-sequences ($X_i, i = 1 \dots 6$) and the activity index of glass powder at 3, 28, and 90 days as primary-

Table 8
Compressive strength of mortars and activity index of glass powder.

Grinding time/min	Compressive strength/MPa			Activity index/%		
	3 days	28 days	90 days	H ₃	H ₂₈	H ₉₀
60	11.74	27.04	35.25	38	54	57
90	14.91	29.06	39.53	48	58	64
120	16.93	30.78	41.3	54	62	67
Cement	31.09	49.98	61.43	–	–	–

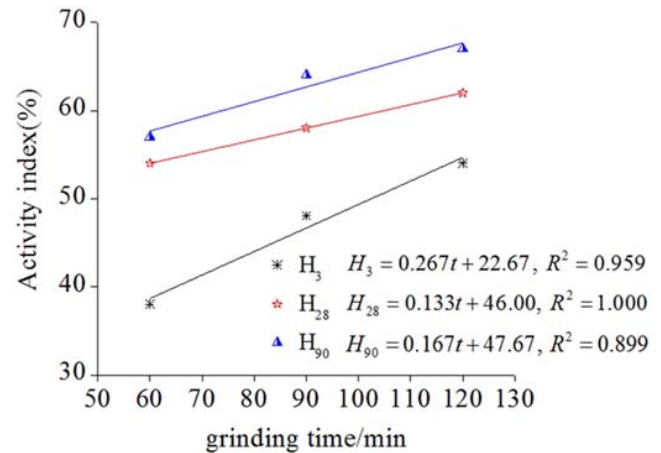


Fig. 14. Relationship between grinding time and activity index of glass powder.

sequences ($Y_j, j = 1, 2, 3$). Then, the grey relation degree and relational polarity of the PSD of glass powder and its activity index is respectively calculated as shown in Table 10.

According to Table 10, the relational polarity exhibits characteristics of orderliness. When the particle size of glass powder is smaller than 20 μm , the mass fraction of particles in each distribution interval has a positive effect on its activity index for all ages, which indicates that the increment of particles with size less than 20 μm would be advantageous to improving the strength for all ages, and is just inversed for the particles with size larger than 20 μm .

Furthermore, there exist some differences among the positive relation degree. As for samples at 3 days, the mass fraction of particles ranging 0–3 μm has greater positive effect on the activity index of glass powder compared with that of particles ranging 3–10 μm and 10–20 μm . With regard to samples at 28 and 90 days, the mass fraction of particles ranging 3–10 μm , though, has the maximum positive effect on the activity index of glass powder, followed by the mass fraction of particles ranging 10–20 μm and 0–3 μm in order. These indicate that particles ranging 0–3 μm have a maximum positive effect on the activity index of glass powder at early age while particles ranging 3–10 μm contribute most at later stage.

Grinding process is propitious to increase the mass fraction of particles ranging 0–3 μm and 3–10 μm . However, when the mechanical force is exerted continuously up to a certain time, such as 90 min as mentioned above in this paper, on the particles, it will not make much difference for increasing the mass fraction of particles ranging 0–3 μm and 3–10 μm . Instead, it may lead to unnecessary and meaningless consumption of energy. As a result, 90 min is chosen as the optimal grinding time for glass powder in consideration of economical and technical benefits.

4. Conclusions

The following conclusions were drawn:

- (1) The grinding process of glass powder can be quantitatively described by grinding kinetic equation. The grinding efficiency of

Table 9
Mass fraction of glass powder with particle size in six intervals/%.

Sample	0–3 μm	3–10 μm	10–20 μm	20–30 μm	30–65 μm	>65 μm
C	18.08	23.96	15.00	11.22	20.10	11.63
D	22.74	26.02	16.03	11.29	14.44	9.48
E	26.31	27.32	15.59	9.37	15.48	5.94

Note: C, D, and E refer to glass powder ground for 60, 90, and 120 min respectively.

Table 10

Grey relation degree and relational polarity of glass powder's PSD and its activity index.

Primary-sequences	Sub-sequences					
	X_1 (0–3 μm)	X_2 (3–10 μm)	X_3 (10–20 μm)	X_4 (20–30 μm)	X_5 (30–65 μm)	X_6 (>65 μm)
Y_1 (3 days)	0.98	0.77	0.74	–0.62	–0.51	–0.53
Y_2 (28 days)	0.74	0.99	0.85	–0.65	–0.54	–0.50
Y_3 (90 days)	0.78	0.96	0.86	–0.66	–0.53	–0.53

glass powder is fairly high at the beginning and slow down a grinding progresses, and draws near to zero after 120 min.

- (2) The equivalent particle size of glass powder descends while its SSA increases gradually with the increase of grinding time. Furthermore, both of the equivalent particle size and SSA of glass powder show a good linear relation to logarithm or double logarithm of grinding time.
- (3) The cumulative PSD of glass powder correlates well with RRB distribution model. Both of the characteristic particle size and the distribution index of glass powder show a downward trend. The grinding process cannot only levigate the glass powder, but also widen its PSD. In addition to RRB model, Swrebec function model can also be reasonably used to describe and represent PSD of glass powder during the grinding process.
- (4) The PSD of glass powder shows fractal features. Both the uniformity coefficient and the characteristic particle size show a negative linear correlation to fractal dimension of PSD. The SSA of glass powder is in good linear relation to its fractal dimension of PSD. The fractal dimension of PSD increases over grinding time, thus glass powder gets more difficult to be ground.
- (5) The activity index of glass powder increases with grinding time. The mass fraction of particles ranging 0–3 μm has a maximum positive effect on its activity index at early age while particles ranging 3–10 μm contribute most at later stage. As a result, 90 min is chosen as the optimal grinding time for glass powder in consideration of economical and technical benefits.

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