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Research Article

Analysis on the Strength of Cement Mortar Mixed with Construction Waste Brick Powder

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The pile-up of massive construction waste causes serious challenges to environment and engineering practice. In order to promote the reuse rate of construction waste bricks, the effects of the content and fineness of construction waste brick powder and of brick powder-silica flour mixture on the strengths of cement mortar were experimentally investigated. Based on the test results, the significance of the particle characteristics of brick powder on mortar strength was analyzed by grey entropy method. The experimental results show that the early strength of cement mortar decreases due to the addition of brick powder; the reduction is, however, not significant when the content of brick powder is less than 10%; the 28 d strength of cement mortar increases with a proper content of brick powder. The grey entropy analysis indicates that the particle characteristics have strong influence on the activity of brick powder and mortar strength; the strength is significantly dependent on specific surface area and the fraction of particles smaller than 20 μm. Fine brick powder and silica flour can improve the macroscopic strengths of cement mortar by affecting the type and quantity of hydration products and the structure of interfacial transition zone between cement paste and sand.

1. Introduction

The construction waste is a kind of solid wastes that are produced due to building demolition. Its annual production is huge, while the recycling rate is less than 5% [1]. The main components of construction waste are bricks and concrete blocks [2–5]. In recent years, many studies have been focused on investigating the properties and reuse methods of waste concretes, and correspondingly the recycling rate of waste concretes is high [6–10]. Researches on waste bricks have been limited to their applications as recycled aggregate, or the effect of waste brick powder content on the performance of cement-based materials [11–13]. For example, [14] showed that the addition of brick powder can produce certain pozzolanic effect and improve the compressive strength of specimens. Xue et al. [15] concluded that brick powder has low activity and thus needs to be activated.

Due to the existence of cracks, high water absorption ability, and low strength of waste brick, its recycling rate is very low; on the other hand, the chemical composition of brick powder is similar to that of cement and mineral additives, which means that the waste bricks have certain activity after being pulverized [16]. Therefore, the brick powder can be a potential additive for concrete engineering [12, 17]. However, compared with mineral additives such as the mineral powder and fly ash, researches on brick powder lack in-depth theoretical analysis and are not systematic or complete. In other words, the efficient utilization technology for waste bricks is not mature.

The activity of mineral additives is related not only to their chemical activity, but also to their particle characteristics, which include particle size and shape and particle distribution state [18]. In a certain range of fineness, the particle distribution state of powder materials will directly influence the macroscopic performance of cement-based materials. Some scholars have studied the relationship between the activity index of mineral additives and their specific surface areas. However, the specific surface area is an overall indicator for all particles consisting of the mineral additives. It cannot reflect the influences of particles with different ranges of sizes or accurately describe the particle distribution characteristics of powder materials, which is affected by the content of very fine particles (<3 μm). Therefore, even though the specific surface areas of different powder materials are similar, the differences between their particle shapes and distributions will result in different macroscopic properties of these materials [19]. At present, the particle size distribution of mineral additives has not attracted enough attention. In fact, particle size distribution has a significant impact on the strength and durability of cement-based materials (e.g., [20, 21]).

In summary, few researches have been focused on the influence of particle characteristics and particle size distribution of brick powder on the properties of cement-based materials. More investigations regarding how to control the brick powder particles are of importance. It has been realized that improving the fineness of cementitious materials can improve their activities as well as the workability, strength, and other properties of concrete [22]. Unfortunately, the extent to which the powder materials should be ground has not been well understood. Therefore, further study on the particle characteristics of cementitious materials has certain theoretical and practical values.

In view of this, by testing and analyzing the basic properties and particle characteristics of cement, brick powder, and silica flour, the present study investigated the influences of the fineness and content of brick powder and brick powder-silica flour mixture on the compressive and flexural strengths of cement mortar. In addition, the significance of the characteristics of brick powder particles on the strengths of cement mortar was investigated through grey entropy analysis. By using the [23] particle packing model, the particle size distribution of powder material at the closest packing condition was obtained, and the filling effects of brick powder and silica flour on the cement paste were analyzed, and the influence mechanism of brick powder on the macroscopic performance of cement mortar was analyzed by SEM (scanning electron microscope). The results of the present study can reveal the influence laws of different particle characteristics of brick powder on mortar strength, facilitate reasonable control of the particle distribution of brick powder (therefore achieving high activation effect), and provide theoretical supports for the application of brick powder and the improvement of the performance of cement-based materials.

2. Experimental Materials and Setup

2.1. Materials. Cement mortar specimens were prepared in the present study for investigation. The ordinary 42.5# Portland cement and the natural river sand with a fineness index of 2.48 were used. The silica flour has a SiO_2 fraction higher than 90%. The construction waste brick was obtained from building demolition, from which the brick powder was prepared in laboratory, through crushing, pulverizing, and sieving. Two types of brick powder with different degrees of fineness (i.e., fine and coarse, labelled as BP1 and BP2, respectively) were prepared and used in the present study. The chemical and mineralogical compositions of the cement and brick powder were determined by X-ray fluorescence (XRF) and X-ray diffraction (XRD) tests. The results are summarized in Table 1 and Figure 1.

It can be seen that the brick powder has similar chemical compositions as the cement. However, compared with cement, the brick powder has much lower content of CaO, while its SiO_2 and Al_2O_3 fractions are higher. The main chemical components of the cement and brick powder are CaO and SiO_2, respectively. They have approximately the same amount of Na_2O. From Figure 1, it is clear that the main minerals consisting of cement are the clinker minerals such as calcium silicate, calcium aluminate, and calcium aluminate ferrite and some portion of calcium carbonate, while the brick powder mainly contains quartz, aluminum oxide, hematite, and some CaO.

Figure 2 presents the SEM images of the cement and fine brick powder. It can be seen that there is a distinct difference between the micromorphologies and particle sizes of the two materials. The cement owns a gap particle size distribution, and its particles generally have sharp edges. Some smaller particles, however, exist on the surfaces of larger cement particles. On the other hand, the particle size distribution of the fine brick powder is more reasonable. It contains particles with different sizes, in the range of several microns to 20 μm. Compared with the cement, the particles of brick powder are finer and generally rounded or subrounded. This indicates that if the brick powder is mixed with cement, the finer particles of the former can fill the gap between the latter's particles, resulting in better particle size distribution and a compact structure. In other words, the brick powder has good filling effect.

In summary, the brick powder has similar chemical compositions with the cement and other mineral admixtures such as fly ash and mineral powder. Table 1 also indicates that the sum of silicon and ferric and aluminum oxides of brick powder is 72.33%, which coincides with the restrictions of ASTM C618 [24] that limits the sum of those oxides to be at least 70% for pozzolans. In addition, the brick powder has reasonable particle size distribution and is finer than cement. Therefore, the brick powder could be used as a potential concrete admixture, but its properties need to be further studied.

2.2. Experimental Scheme and Testing Methods. The particle characteristics of the cement, two types of brick powder with different fineness (i.e., BP1 and BP2), and silica flour were tested by using the Mastersizer 2000 laser particle size analyzer. Cement mortar specimens with different contents and fineness of brick powder and with both brick powder and silica flour were prepared, along with the control specimens which did not contain brick powder or silica flour. The detailed testing scheme is summarized in Table 2.

Table 1: Chemical compositions of cement and brick powder (by wt%).

Material	Component						
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O
Cement	19.34	6.57	47.95	3.22	1.58	1.48	0.63
Brick powder	52.64	14.53	9.03	5.16	3.00	1.87	2.54

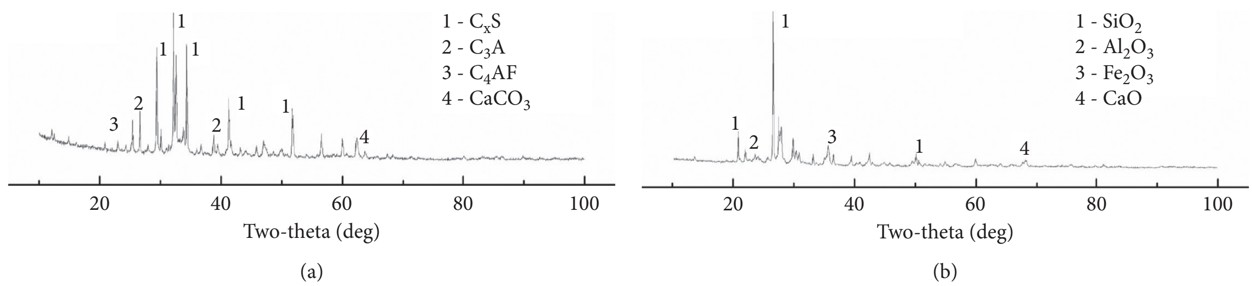

Figure 1: The XRD results of (a) cement and (b) brick powder.

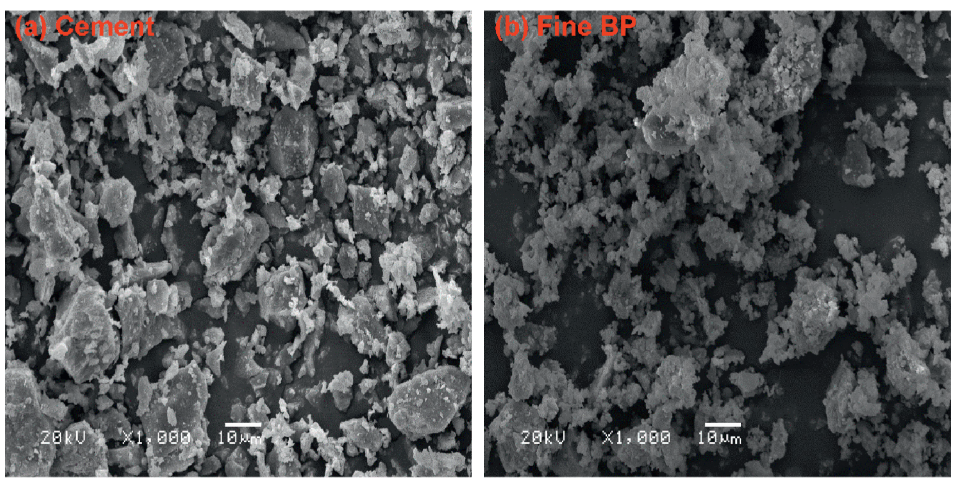

Figure 2: The SEM images of (a) cement and (b) fine brick powder.

Table 2: Strength test scheme for cement mortar specimens.

Serial number	∗Brick powder content (wt%)	Serial number	*I*Brick powder + silica flour	
			Brick powder content (wt%)	Silica flour content (wt%)
Ctrl	0		—	
BP1-10	10	BP1-5:5	10	10
BP1-20	20	BP1-6:4	12	8
BP1-30	30	BP1-7:3	14	6
BP2-20	20	BP2-5:5	10	10

Notes: Ctrl is the control specimen, which did not contain any brick powder or silica flour. BP1 and BP2 are the fine and coarse brick powder, respectively. ∗Only brick powder was added to replace a certain portion of cement (or the content of brick powder), as indicated by the numbers in the table. *I*Both brick powder and silica flour were added to replace cement. The ratios indicate the ratio of brick powder content to silica flour content.

The cement mortar specimen was 160 mm in length, 40 mm in width, and 40 mm in height. Three identical specimens were prepared under each condition, and 108 specimens in total were prepared. In terms of the control specimens, 450g cement and 1350g sand were used, and the water-cement ratio was 0.5. The prepared specimens were demoulded after curing for 24 hours in an environmental chamber (with the temperature of $20 \pm 1^{\circ}C$ and relative humidity ≥90%) and then cured in water (with the temperature of $20 \pm 1^{\circ}C$) to the desired age.

The effects of the addition of brick powder and silica flour on the 7 d and 28 d compressive and flexural strengths of the cement mortar specimens were investigated. The strength tests were referred to the Chinese standard [25]: *Test Methods of Cement and Concrete for Highway Engineering*. In addition, the microstructures of the 28 d cement mortar specimens with brick powder, brick powder-silica flour, and control specimen were analyzed by using SEM.

The samples used for the SEM test were small cubes with side length typically smaller than 10 mm. They were taken from the center of the cement mortar specimens. The surfaces of the cubic samples were polished first, and the samples were then submerged in anhydrous ethanol for hydration termination. Finally, the surfaces of the cubic samples were sprayed with gold, and they were ready for the SEM test.

3. Experimental Results and Analysis

3.1. Particle Characteristics of the Powder Materials. Table 3 summarizes the particle characteristics of the three powder materials, namely, cement, brick powder, and silica flour. It can be seen that the silica flour has the highest specific surface area, with a value of 525 m^2/kg. This is followed by the fine brick powder, cement, and coarse brick powder. In terms of the area and volume mean particle sizes, they have inverse order compared with specific surface area. This is reasonable since the smaller the particle sizes, the higher the specific surface area.

The specific surface area and mean particle sizes can represent the fineness of powder materials to a certain degree. However, the performance of the powder materials is influenced not only by their fineness and particle shapes, but also by their particle size distributions. The particle size distributions of the three powder materials are summarized in Table 4. It can be seen that the silica flour and fine brick powder contain a large portion of particles smaller than 20 μm, while they do not have many large particles (e.g., larger than 40 μm). The cement and coarse brick powder, on the other hand, have relatively high fraction of large particles. Compared with cement, the amounts of particles smaller than 10 μm in the silica flour and fine brick powder increase by 180.4% and 141.1%, respectively, and those of particles larger than 40 μm decrease by 50.2% and 40.8%, respectively. By referring to Table 3, it is clear that, in the silica flour and fine brick powder, the increase of <20 μm particles and decrease of >40 μm particles manifest as the increase of specific surface area and reduction of area and volume mean particle sizes.

3.2. Results of the Strength Tests. The effects of the content and fineness of brick powder on the strength of cement mortar specimens are shown in Figure 3. It can be seen that the addition of brick powder has similar influence laws on the 7 d and 28 d compressive strength and flexural strength of cement mortar, while the influence degrees are different. For brick powder with a specific fineness, the strengths of cement mortar decrease with the increase of brick powder content. The early strengths of mortar generally reduce by the addition of brick powder, except that when the content of brick powder is 10%, the 7 d flexural strength increases by a small amount of 4.2%. When the content of brick powder is 30%, the 7 d compressive strength and flexural strength of mortar decrease by 26.5% and 19.4%, respectively. This is because the early activity of brick powder is low, and its filling effect (through small particle sizes and reasonable particle size distribution) cannot compensate the adverse effect caused by the decrease of cement content, which yields less hydration products. When the content of brick powder is less than or equal to 20%, the 28 d strength of the specimens with brick powder is higher than that of the control specimen. When the content of brick powder is 10%, the 28 d compressive strength and flexural strength of mortar increase by 6.3% and 17.3%, respectively.

This is because the pulverized brick powder has reasonable particle morphology and relatively high specific surface area, which can play a certain role in filling, dispersing, homogenizing, and densifying, thus improving the secondary gradation of cementitious materials and forming a compact structure between the particles of cementitious materials. The active substances in the brick powder can have secondary hydration reaction, which can improve the type and quantity of hydration products in the cement mortar. Furthermore, the addition of brick powder can promote the hydration of cement and improve the structure of brick powder-cement cementitious system. As a result, the 28 d strength of cement mortar is improved.

Compared with the compressive strength, both the 7 d and 28 d flexural strengths increase significantly. This is because the flexural strength of mortar specimen is greatly affected by the structure of cement-sand transition zone. When the amount of brick powder is small, the fine brick powder can fill the gaps between cement particles. In addition, the brick powder can absorb certain amount of water, therefore reducing the bleeding phenomenon in the mortar and improving the structure of the transition zone between cement paste and sand. Consequently, the flexural strength of the specimen is improved.

Comparing the compressive and flexural strengths of specimens BP1-20 and BP2-20, it can be seen that the strengths of mortar specimens with 20% fine brick powder are higher than those with 20% coarse brick powder. The 28 d compressive strength and flexural strength of BP2-20 decrease by 14.1% and 16.7%, respectively, compared with BP1-20. This is because the finer the particles of brick powder, the better the filling effect and microaggregate effect and the higher the efficiency of secondary hydration reaction. Therefore, in order to guarantee the strengths of cement mortar and to maximize the utilization rate of construction waste bricks, the appropriate content for brick powder could be 10%~20%.

Figure 4 shows the strength test results for mortar specimens mixed with brick powder and silica flour. It can be seen that the strengths of mortar can be significantly improved by adding both brick powder and silica flour. They are higher than the strengths of the control specimen and of the specimens mixed with brick powder only. With the increase of the ratio of brick powder content to silica flour content, the 7 d, 28 d compressive strengths, and 7 d flexural

Table 3: Particle characteristics of different powder materials.

Material	Specific surface area (m^2/kg)	Area mean particle size (μm)	Volume mean particle size (μm)
Cement	443	23.86	32.21
Silica flour	525	13.37	20.51
BP1	461	15.11	21.15
BP2	430	18.47	24.34

Table 4: Particle size distributions of different powder materials (%).

Material	Particle size distribution				
	<10 μm	10~20 μm	20~40 μm	40~60 μm	>60 μm
Cement	9.05	32.31	35.12	14.15	9.37
Silica flour	25.38	39.53	23.37	8.36	3.36
BP1	21.82	42.58	21.67	9.36	4.57
BP2	18.69	30.28	27.86	14.61	8.56

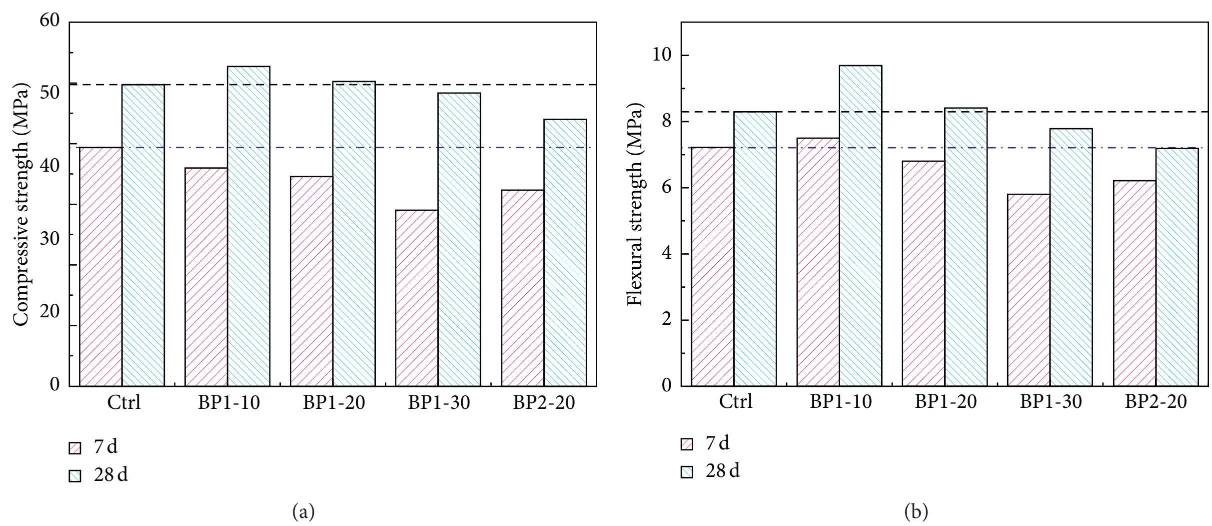

Figure 3: The effect of brick powder on the (a) compressive strength and (b) flexural strength of cement mortar.

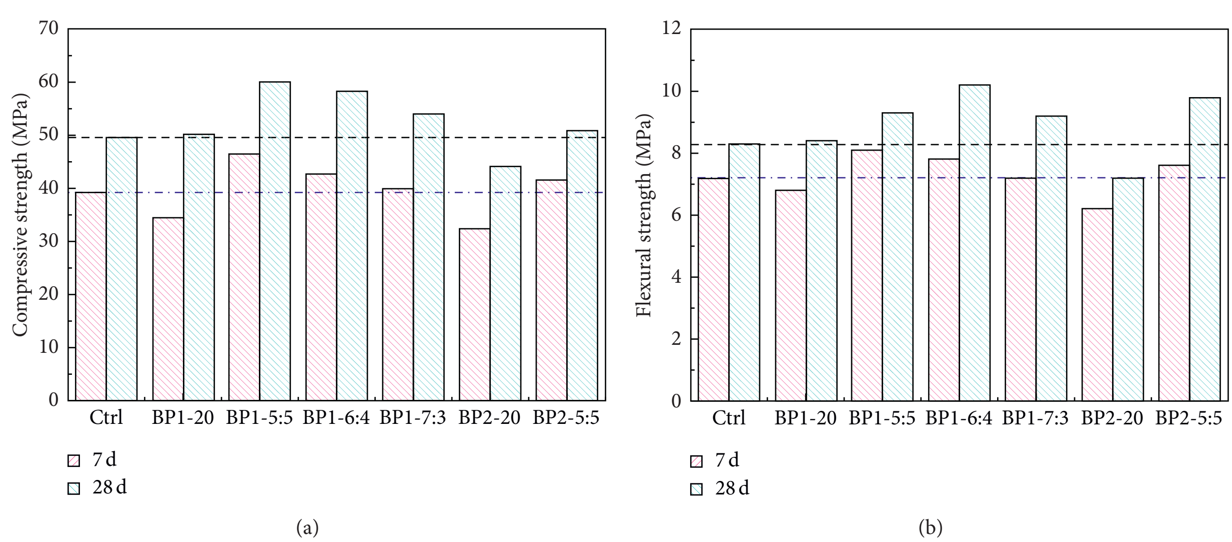

Figure 4: The effect of brick powder-silica flour on the (a) compressive strength and (b) flexural strength of cement mortar.

strength of mortar specimens decrease, while the 28 d flexural strength increases at first and then decreases. When the ratio is 5 : 5, the 28 d compressive strength and flexural strength of mortar specimens increase by 17.6% and 12.0%, respectively.

This is because the fine silica flour can further fill the gaps between brick powder-cement particles and widen the secondary particle gradation of cementitious system. This can form a more reasonable microscopic structure than that of brick powder-cement cementitious system and improve the compactness of the system. In addition, the activity of silica flour is high, and the silica flour, cement, and brick powder can be hydrated for a second time, which can compensate the adverse effect caused by the relatively low activity of brick powder, improve the compositions of hydration products and structure of transition zone, and thus improve the strengths of cement mortar. In summary, with proper techniques to chemically and physically activate the brick powder, it can be an economic and environmentally friendly mineral additive.

Comparison between the results of BP2-5:5 with BP2-20 suggests that there is a certain superposition effect between the coarse brick powder and silica flour. Compared with BP2-20, the 7 d and 28 d compressive strengths of BP2-5:5 increase by 28.8% and 15.5%, respectively, and the 7 d and 28 d flexural strengths increase by 22.6% and 36.1%, respectively. Compared with BP1-5:5, the strength of BP2-5:5 is lower. This further shows that the fineness of brick powder has a significant impact on its activity, and the finer the brick powder, the higher its activity.

3.3. Grey Entropy Analysis of Mortar Strength and BP Particle Features. The grey relational theory investigates the geometric proximity between various factors of a system. It can investigate the influencing factors of a certain characteristic in the system by a small number of samples. The significance of these influencing factors on the characteristic can be quantified by the correlation degree. The grey entropy is put forward on the basis of grey relational analysis, which overcomes the shortcomings of local point relation tendency and information loss in the grey relational analysis method, and can more effectively distinguish the main and secondary factors in a system.

In order to explore the influences of particle characteristic and particle size distribution on the activity of cementitious materials and to optimize the particle size distribution of brick powder, the 7 d and 28 d compressive strength and flexural strength activity indices of cement mortar (i.e., the ratio of the strength of mortar mixed with brick powder to that of the control specimen) are taken as the parent sequences, and the particle characteristic and size distribution parameters of brick powder are taken as the subsequences for grey entropy analysis.

Table 5 summarizes the grey entropy values of mortar strength activity index and brick powder particle characteristic. It can be seen that the particle characteristic has significant influences on the strength activity index of mortar mixed with brick powder. The influences of particle characteristic of brick powder on the 7 d and 28 d compressive strength and 28 d flexural activity indices of mortar are the same, and the order of significance is specific surface area > area mean particle size > volume mean particle size, while the significance order of the influences on the 7 d flexural strength activity index of mortar is specific surface area > volume mean particle size > area mean particle size.

It can be concluded that the specific surface area and area mean particle sizes of the brick powder have strong influence on the strength of cement mortar (especially for the 28 d mortar strength), which could be the comprehensive indices to evaluate the properties of the brick powder. The larger the specific surface area, the more complex the surface morphology of the brick powder particles. This can increase the reaction area for cement hydration and strengthen the bonding and frictional forces between particles. Therefore, a compact structure is formed between the particles of different powder materials. This is consistent with the above test results that the finer the brick powder, the higher the mortar strengths.

The grey entropy analysis results for mortar strength activity index and particle distribution of brick powder are summarized in Table 6. It can be seen that the grey entropy between strength activity index and brick powder particle distribution is orderly. The order of the grey entropy between compressive strength activity index and the particle distribution of brick powder is the same as that of flexural strength and particle distribution of brick powder. The influence of <40 μm brick powder particles on the strength activity index is more significant, and the correlation degree between the content of <10 μm particles and the activity index is the largest. This indicates that this particle size range (i.e., < 10 μm) has the greatest positive contribution to the activity of brick powder and is therefore the key factor.

In summary, only when the particle size of brick powder is less than a certain value can it play a positive role in mortar strength. Therefore, it is beneficial to increase the strength activity index of mortar mixed with brick powder by properly increasing the content of particles <20 μm (especially <10 μm) and reducing the quantity of particles >40 μm.

3.4. Filling Effect of Powder Materials on Cementitious System. The study in [23] showed that the particle size distribution of powder materials should meet the following standard to achieve a close packing:

$$w_1(D) = 100\left(\frac{D}{D_{\max}}\right)^n, \tag{1}$$

where $w_1(D)$ is the mass percentage of particles smaller than D (μm); $D_{\max}$ is the maximum particle size in the particle system, which is 138.038 μm; n is the distribution parameter.

Researches have shown that the porosity of cement-based materials decreases with the decrease of n value. When n decreases to 1/3, the porosity reaches the minimum, and further decrease of n value does not have significant influence. Through regression analysis of the particle size distribution curves of cement, fine brick powder, and coarse

Table 5: Grey entropy of mortar strength activity index and BP particle characteristic.

Strength activity index		Specific surface area (m^2/kg)	Area mean particle size (μm)	Volume mean particle size (μm)
Compressive strength (MPa)	7 d	1.0000	0.9524	0.9363
	28 d	0.9942	0.9377	0.9229
Flexural strength (MPa)	7 d	0.9990	0.9461	0.9863
	28 d	0.9902	0.9329	0.9186

Table 6: Grey entropy of mortar strength activity index and BP particle distribution.

Strength activity index		<1 μm	10~20 μm	20~40 μm	40~60 μm	>60 μm
Compressive strength (MPa)	7 d	0.9956	0.9727	0.9461	0.8813	0.8113
	28 d	0.9997	0.9854	0.9380	0.8769	0.8113
Flexural strength (MPa)	7 d	0.9978	0.9783	0.9427	0.8794	0.8113
	28 d	1.0000	0.9890	0.9352	0.8754	0.8113

brick powder, their n values are determined as 0.655, 0.381, and 0.648, respectively. This shows that the fine brick powder has better filling effect. By taking n as 0.33, the closest packing condition can be obtained according to (1). The individual percent retained and percentage passing curves (i.e., particle size distribution) of the powder materials and the closest packing condition are shown in Figure 5. It can be seen that the individual percent retained and percentage passing curves of different powder materials have basically the same variation rule.

Figure 5(a) shows that the content of fine particles (<20 μm) in silica flour, fine brick powder, and coarse brick powder is larger than that of cement, while their coarse particles contents are smaller than those of cement. Figure 5(b) shows that the particle size distribution curves of cement, coarse brick powder, fine brick powder, and silica flour gradually move to the left, i.e., towards the finer particle direction, indicating that the above materials gradually become finer. In other words, compared with cement, there are more particles with smaller size and less particles with larger size in silica flour and fine brick powder.

When a certain amount of silica flour and fine brick powder is added into the coarser cement particle system, the gaps between coarse particles can be filled by finer particles, which play a role in dispersion and densification. This facilitates the formation of a more reasonable particle gradation than cement, thus improving the packing and densification performance of cement-brick powder or cement-silica flour-brick powder cementitious system. In the early stage of hydration, the hydration degree of brick powder is relatively low, and its activity is closely related to the packing density of cementitious system. The pore water between particles can be limited by the increase of packing density of the cement-brick powder system. This increases the content of free water in the slurry, which can facilitate the hydration of powder materials. In addition, it can positively influence the pore structure of the cement-brick powder system and improve the strength of mortar mixed with fine brick powder and silica flour-brick powder. Moreover, the finer brick powder particles can improve the density of the transition zone between cement paste and aggregate such as sand, reduce the thickness of the interfacial transition zone, and improve the macroscopic mechanical properties of cement mortar.

It can be seen from Figure 5(a) that there are four intersection points (i.e., A, B, C, and D) between the individual percent retained curves of powder materials (i.e., cement, fine and coarse brick powders, and silica flour) and that of the closest packing condition. When the particle size is between A to B and C to D, the curve of the closest packing condition is between that of cement and those of the other powder materials. This indicates that, in these two particle size ranges, the proportion between cement and powder materials can be adjusted to achieve the closest packing. When the particle size is smaller than point A or larger than point D, compared with the curve of the closest packing condition, the contents of particles in cement and the other powder materials are less. As a result, it is impossible to achieve the closest packing condition by adjusting the particle content of powder materials. Similarly, the particle content of powder materials between B and C is higher than that of the closest packing condition. Therefore, it cannot reach the closest packing condition by adjusting the particle content of powder materials in this range.

Based on the above analysis, although the brick powder and silica flour are finer than cement, the cement-brick powder and cement-brick powder-silica flour cementitious systems after mixing are not the closest packing in the whole particle size range. Therefore, further efforts should be put to improve the particle distribution of brick powder, which is favorable to the formation of a reasonable particle size distribution of cementitious system and reaching the closest packing condition, and to improve the physical and chemical activities of the cementitious system. This can improve the macroscopic performance of cement-based materials and the recycling efficiency of construction waste bricks.

3.5. Microstructure of Cement Mortar with Brick Powder. Figure 6 shows the 5000 times SEM images of the control specimen and specimens with brick powder and brick powder-silica flour, cured for 28 d. It can be seen that, at the age of 28 d, the internal microscopic morphology of the mortar specimens with brick powder or brick powder-silica flour is relatively dense, compared with the control specimen; and the addition of brick powder has a certain impact

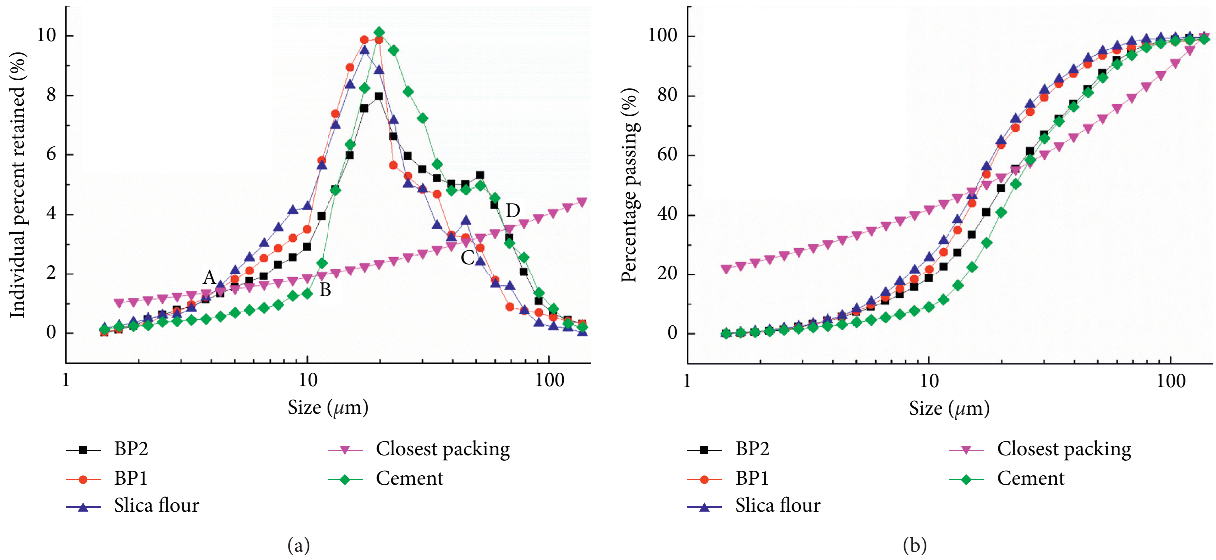

Figure 5: The (a) individual percent retained and (b) percentage passing of different powder materials.

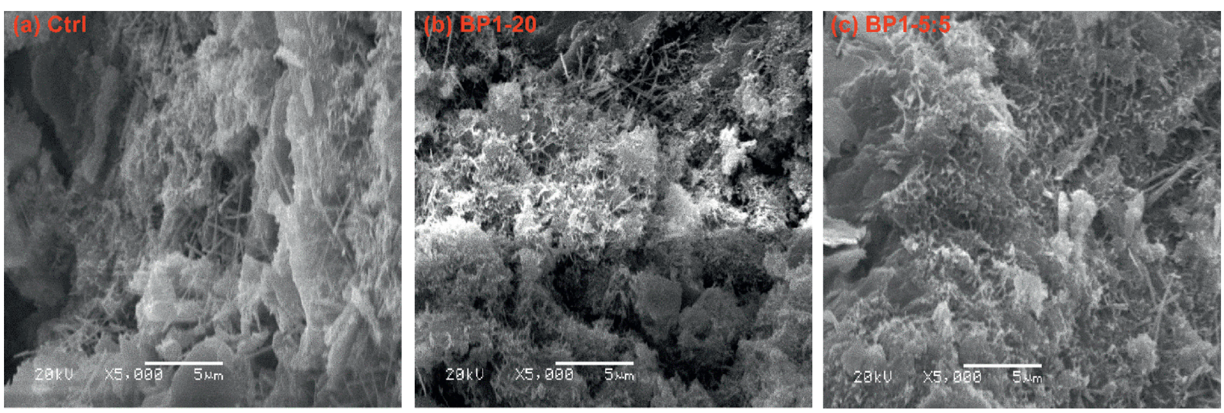

Figure 6: The SEM images of (a) control specimen, (b) BP1 20, and (c) BP1 5 : 5.

on the morphology and quantity of hydration products in cement mortar.

It can be seen from Figure 6(a) that the internal microscopic morphology of the control specimen is relatively loose, and there are many pores and cracks. The hydration products are mainly needle ettringite and flaky $Ca(OH)_2$, and the content of C–S–H is small. Figure 6(b) shows that, in the mortar specimen mixed with brick powder, the content of needle ettringite and flaky $Ca(OH)_2$ is reduced, and the content of flocculent and clustered C–S–H increases. The brick powder-silica flour composite can further improve the internal compactness of mortar specimen, as shown in Figure 6(c). Therefore, by adjusting the amount of brick powder and its particle size and distribution, the cement-brick powder cementitious system can achieve good particle grading, which can improve the recycling efficiency of construction waste brick.

4. Conclusions

In this paper, the influences of the content and particle characteristics of brick powder and the mixture of brick powder and silica flour on mortar strengths were studied. By using grey entropy analysis, the significance of particle characteristics of brick powder on the strengths of mortar was investigated, and the key control indices of brick powder were highlighted. The microstructures of cement mortar with and without brick powder and silica flour were compared. The major conclusions are summarized below:

(1) The addition of brick powder reduced the early strengths of mortar specimen, and the compressive strength decreased more than the flexural strength. Considering both the mortar strength and the maximum utilization of waste bricks, the appropriate content for brick powder can be 10%~20%. The mixture of brick powder and silica flour can exert superposition effect and significantly improve mortar strengths. With the increase of the ratio of brick powder content to silica flour content, the increase of strengths gradually decreased.

(2) The particle characteristic and particle size distribution parameters of brick powder significantly

affect mortar strength. The specific surface area and area mean particle size have the most significant influence on the strength of mortar; thus they are the significant factors affecting the activity of brick powder. The strength of mortar can be significantly improved by increasing the content of particles smaller than 20 μm (especially smaller than10 μm).

(3) The cement-brick powder and cement-brick powder-silica flour cementitious systems are not the closest packing in the whole particle size range. Therefore, further efforts should be put to improve the particle distribution of brick powder and reach the closest packing condition. When the cementitious system reaches the maximum compactness, the performance of cement-based materials will be improved and the recycling efficiency of construction waste brick will be increased.

(4) The fine brick powder and silica flour can improve the macroscopic performance of cement mortar by affecting the type and quantity of hydration products in the cement mortar and the structure of interfacial transition zone between cement paste and sand.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Dr. Cuizhen Xue, Dr. Hongxia Qiao, and Dr. Qiong Feng designed the testing plan, analyzed the testing results, and drafted the manuscript. Ms. Hui Cao and Ms. Qiong Li conducted the tests and analyzed the testing results.

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