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Research Article

Research and Model Prediction on the Performance of Recycled Brick Powder Foam Concrete

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In order to achieve resource conservation, protect the environment and realize the sustainable development of the construction industry, the low energy resource utilization of construction waste was explored. In this paper, the effect of air bubble swarm admixture, recycled brick powder admixture, water to material ratio, and HPMC content on the physical and mechanical properties of recycled brick powder foam concrete was investigated by conducting a 4-factor, 5-level orthogonal test with recycled brick powder as fine aggregate, and the effect of each factor on the physical and mechanical properties of recycled brick powder foam concrete was derived, and the optimum ratio of recycled brick powder foam concrete was determined by analysing the specific strength. Five machine learning models, namely, back propagation neural network improved by particle swarm optimization (PSO-BP), support vector machine (SVM), multiple linear regression (MLR), random forest (RF), and back propagation neural network (BP), were used to predict the compressive strength of recycled brick powder foam concrete, and the PSO-BP model was found to have obvious advantages in terms of prediction accuracy and model stability. The experimental results and prediction models can provide experimental and theoretical references for the research and application of recycled brick powder foam concrete.

1. Introduction

With the development of urbanization, the amount of construction and demolition waste is increasing rapidly. In China, about 1.8 billion tons of construction waste are generated every year [1]. In the past, construction waste was often dumped or landfilled, which not only wasted land and resources but also polluted the environment. Xiao et al. [2] reported that, about 80% of construction waste was reusable construction waste, such as waste concrete, bricks, and glass. Therefore, it has become an effective way to use construction waste as recycled aggregate for cement-based materials. Recycled concrete aggregates are equipped with similar properties to natural aggregates, which have been widely used in concrete production. Previous studies [3–5] have reported that recycled brick powder (RBP) has similar characteristics as supplementary cementitious materials, such as high content of SiO_2 and Al_2O_3. However, waste clay brick aggregates are of high crushing value and water absorption, which limits their large-scale application in concrete. Therefore, the effective utilization of clay bricks recovered from construction waste has become a top priority.

Foam concrete takes the cement-based cementitious materials, admixtures, and so on, as the main cementing materials. The admixtures and water, or some granular lightweight aggregates, are added to make slurry. It is a lightweight concrete material that contains a large number of tiny, independent, and evenly-distributed bubbles formed by casting and curing at the construction site or in the factory [6]. In recent years, foam concrete has been widely used in the field of civil engineering as a building material with excellent performance. Foam concrete consumes a large amount of cementitious material [7], with more expensive costs and lower strength than structural concrete. Reducing the amount of cementitious materials while maintaining its light weight and increasing strength is an important direction for studying the mix ratio of foam concrete [8].

Studies have shown that adding fillers and improving the pore structure can effectively increase the strength of foamed concrete [9–13]. Domestic and foreign scholars have explored the possibility of replacing cementitious materials with various materials [14–18]. However, few reports have emerged on using recycled brick powder as a filler for foam concrete.

In this paper, recycled brick powder was prepared based on the waste clay bricks produced by demolishing houses in rural areas. Based on the test of ordinary foam concrete, recycled brick powder and hydroxypropyl methyl cellulose ether (HPMC) foam stabilizer was added to explore the influence of bubble group content, recycled brick powder content, water-to-material ratio, and HPMC content on the compressive strength of recycled brick powder foam concrete. The pore size distribution and microscopic morphology were observed, the parameter sensitivity of various factors were analyzed through neural network and machine learning theory, and the compressive strength of recycled brick powder foam concrete cubes was predicted.

2. Experiment Overview

2.1. Raw materials

2.1.1. Cement. The cement should also have high strength and not compromise the stability of the foam, based on compliance with the Chinese standard "General Silicate Cement" (GB175-2007) [19]. Conch brand P.O.42.5 ordinary Portland cement was used in this experiment. The chemical composition and basic properties of the cement are shown in Table 1.

Table 1: Chemical composition of cement.

Component	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3
Content (%)	22	4.2	5.2	63	1.5	2.2

Table 2: Basic properties of cement.

Item	Index	Results	Judgement
Initial set time (min)	≥60	176	Qualified
Final set time (min)	≤600	310	Qualified
3d flexural strength (MPa)	≥3.5	4.2	Qualified
28d flexural strength (MPa)	≥6.5	7.1	Qualified
3d compressive strength (MPa)	≥17	22.3	Qualified
28d compressive strength (MPa)	≥42.5	48.2	Qualified

2.1.2. Recycled Brick Powder. Crush the waste clay bricks to Table 2 particles of about 4.75 mm with a hammer crusher and use a ball mill to grind them for one hour to obtain regenerated recycled brick powder particles of 10 to 80 μm. Figure 1 shows the waste clay bricks, and Figure 2 shows the recycled brick powder.

Figure 1: Waste clay bricks.

Figure 2: Recycled brick powder.

2.1.3. Foaming Agent. The HT composite foaming agent produced by Henan Huatai Building Materials Co., Ltd., was used, while its physical properties are shown in Table 3.

The foaming agent performance test was carried out in accordance with the Chinese standard "Technical Regulations for Air-bubble Mixed Lightweight Soil Filling Engineering," and the results showed that the HT compound foaming agent diluted 30 times had the lowest water secretion and the smallest settling distance. The preparation process is shown in Figure 3.

2.1.4. Foam Stabilizer. HPMC produced by Fuqiang Fine Chemical Co., Ltd., was adopted, and its physical performance indicators are shown in Table 4. Figure 4 shows a photograph of the hydroxypropyl methyl cellulose ether (HPMC).

2.2. Calculation of mix Ratio. The commonly-used methods of concrete mix design comprised the volume method and mass method. Due to the light mass of bubbles, the volume method was adopted in this research after a comprehensive consideration [20]. According to formula (5.2.1-1) in the Chinese standard "Technical Specification for Foamed Mixture Lightweight Soil Filling Engineering," the mix ratio calculation is conducted, and the expression is as follows:

Table 3: Physical performance indicators of HT composite foaming agent.

HT	Appearances	Density (g/cm^3)	Solid content (%)	pH value	Dilution ratio	Settlement distance for 1 h (mm)	Bleeding rate for 1 h (%)
	Dark brown	1.05	23.8	9.2	15~30	≤50	≤70

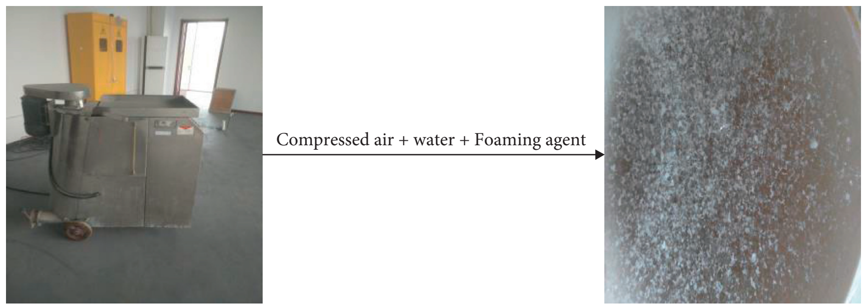


Figure 3: Foam preparation process.

Table 4: Physical performance indicators of HPMC.

Indicator results	Appearances	Viscosity (Pa s)	PH value	Water content (%)
	White powder	150	6.5	2.1

Figure 4: HPMC.

$$\frac{m_c}{\rho_c} + \frac{m_w}{\rho_w} + \frac{m_f}{\rho_f} + \frac{m_f}{\rho_f} = 1. \quad (1)$$

In the formula, m_c: cement dosage per cubic meter of foam concrete (kg); ρ_c: cement density (kg/m^3); m_w: water consumption per cubic meter of foamed concrete; ρ_w density of water (kg/m^3), taking 1000 kg/m^3; m_f.: amount of air foams per cubic meter of foam concrete (kg); ρ_f.: density of air foams (kg/m^3); m_m: mixture amount of foam concrete per cubic meter (kg); ρ_m: density of the admixture (kg/m^3).

2.3. Mixture Ratio Data of Ordinary Foam Concrete. To explore the performance difference between recycled brick powder foam concrete and ordinary foam concrete, ordinary foam concrete test blocks were made as a control group. The ordinary foam concrete adopted the orthogonal test of two factors and five levels, and the change range of the bubble swarm content was 3% to 7%, while the change range of the water-cement ratio was 0.45 to 0.65. The data is shown in Table 5.

2.4. Test Pieces Preparation and Test Methods. Ordinary foam concrete specimens were made according to the following process: (1) Accurately weigh the quality of cement; (2) Add water of accurate quality into the mixer, and then quickly stir for 150 seconds; (3) Add the foaming agent aqueous solution to the cement foaming integrated machine, pressurize the air to foam, prepare to measure the mass of the bubble group, and quickly add it to the cement slurry of construction waste, and stir for 120 seconds. When the mixing is uniform and no bubbles have emerged on the surface of the slurry, the fluidity test is conducted immediately. After meeting the requirements of 160 to 200 mm, quickly pour it into a 100 mm × 100 mm × 100 mm mold, and gently flip the mold to prevent irregular test blocks: (4) After standing for 36 hours, scrape the surface of the mold and remove it with an air gun. To fulfill the strength requirements, it needs to be stored in a standard curing room with a temperature of 20 ± 2°C and a humidity of 95% or more, as well as normal curing for 28 days.

The process of making recycled brick powder foam concrete specimens (1) was as follows: Accurately weigh the quality of cement, recycled brick powder and HPMC, and drily mix with a mixer for 150 seconds. The process from (2) to (4) was the same as that of the control group. The preparation process for the recycled brick powder foam concrete specimens in this paper is shown in Figure 5.

Table 5: Mixture ratio data of ordinary foam concrete.

Group number	Bubble volumes (%)	Water cement ratio	Cement (g)	Bubble groups (g)	Water (g)
1	3	0.45	728.55	21.86	327.85
2	3	0.50	702.95	21.09	351.48
3	3	0.55	679.08	20.37	373.49
4	3	0.60	656.78	19.70	394.07
5	3	0.65	635.90	19.08	413.34
6	4	0.45	635.90	25.44	286.16
7	4	0.50	616.30	24.65	308.15
8	4	0.55	597.88	23.92	328.83
9	4	0.60	580.52	23.22	348.31
10	4	0.65	564.15	22.57	366.70
11	5	0.45	564.15	28.21	253.87
12	5	0.50	548.73	27.44	274.37
13	5	0.55	534.02	26.70	293.71
14	5	0.60	520.13	26.01	312.08
15	5	0.65	506.95	25.35	329.52
16	6	0.45	506.95	30.42	228.13
17	6	0.50	494.42	29.67	247.21
18	6	0.55	482.49	28.95	265.37
19	6	0.60	471.12	28.27	282.67
20	6	0.65	460.28	27.62	298.18
21	7	0.45	460.28	32.22	207.13
22	7	0.50	449.93	31.50	224.97
23	7	0.55	440.03	30.80	242.02
24	7	0.60	430.56	30.14	258.34
25	7	0.65	421.48	29.50	273.96

Figure 5: Test piece preparation process for recycled brick powder foam concrete.

The dry density of the control and experimental group specimens were measured according to the Chinese standard "Foam Concrete" [21]; the determination of the compressive strength of the control group and the experimental group could refer to the Chinese standard "Standard for Test Methods of Mechanical Properties of Ordinary Concrete" and "Test methods of Autoclaved aerated Concrete" [22].

2.5. Orthogonal Mix Ratio Design. Recycled brick powder foam concrete adopted an orthogonal test of 4 factors and 5 levels, that was, the orthogonal test table was L25 (4^5). The four factors of bubble group content, recycled brick powder content, water-to-material ratio, and HPMC content were used, respectively, for experimental research. The specific level factor data is shown in Table 6.

3. Experimental Results and Analysis

3.1. Orthogonal Experiment Results. The orthogonal test results of recycled brick powder foam concrete are shown in Table 7.

The orthogonal test results of ordinary foam concrete are shown in Table 8.

According to the orthogonal test results in Tables 7 and 8, the compressive strength is analyzed through the extremely poor method [23]. The larger the range value is, the greater the influence of this factor on the compressive strength would be. The results are shown in Tables 9 and 10.

The influence order of various factors on the compressive strength of recycled brick powder foam concrete can be obtained from Table 9 as follows: bubble volume > recycled brick powder volume > the ratio of water to

Table 6: Orthogonal test factor level of experimental group.

Level	Factor			
	Bubble volumes (A) (%)	Recycled brick powder volume (B) (%)	Water to material ratio (C) (%)	HPMC content (D)
1	3	10	0.45	0.03
2	4	20	0.5	0.04
3	5	30	0.55	0.05
4	6	40	0.6	0.06
5	7	50	0.65	0.07

Table 7: Orthogonal test results of recycled brick powder foam concrete.

Group number	Dry density (kg/m^3)	28 d compressive strength (MPa)	Specific strength ($N{\cdot}m{\cdot}kg^{-1}$)	Group number	Dry density (kg/m^3)	28 d compressive strength (MPa	Specific strength ($N{\cdot}m{\cdot}kg^{-1}$)
1	1171.10	6.07	5185.30	14	710.85	0.84	1186.89
2	1210.25	5.80	4792.61	15	838.75	2.37	2830.70
3	988.00	5.76	5833.35	16	806.80	2.11	2621.41
4	1072.75	4.55	4241.30	17	952.50	2.82	2955.64
5	1039.45	3.09	2975.81	18	857.60	2.47	2882.64
6	997.15	5.17	5183.17	19	647.65	1.74	2686.56
7	854.25	4.23	4947.38	20	889.40	1.25	1404.43
8	680.85	3.11	4570.76	21	769.50	2.15	2794.67
9	937.55	2.26	2410.22	22	975.85	2.58	2645.59
10	1071.20	3.04	2838.83	23	851.15	1.51	1777.36
11	988.20	5.31	5369.92	24	675.20	1.96	2901.14
12	1008.45	2.76	2736.92	25	786.60	0.96	1226.04
13	721.45	1.46	2020.72				

Table 8: Orthogonal test results of ordinary foam concrete.

Group number	Dry density (kg/m^3)	28 d compressive strength (MPa)	Specific strength ($N{\cdot}m{\cdot}kg^{-1}$)	Group number	Dry density (kg/m^3)	28 d compressive strength (MPa)	Specific strength ($N{\cdot}m{\cdot}kg^{-1}$)
1	743.55	2.290	3079.82	14	591.6	1.182	1997.97
2	722.38	2.229	3085.63	15	590.3	1.014	1717.77
3	707.6	1.998	2823.63	16	644.1	1.734	2692.13
4	714.9	2.012	2814.38	17	628.7	1.548	2462.22
5	639.4	1.668	2608.70	18	584.1	0.949	1624.72
6	536.0	0.880	1641.79	19	599.7	1.212	2021.01
7	735.2	2.109	2868.61	20	550.3	0.919	1670.00
8	797.1	2.408	3020.95	21	608.4	1.229	2020.05
9	648.6	0.853	1315.14	22	500.1	0.875	1749.65
10	567.4	0.830	1462.81	23	672.7	1.462	2173.33
11	713.8	1.657	2321.38	24	592.8	1.073	1810.05
12	638.2	1.471	2304.92	25	567.4	0.951	1676.07
13	615.9	1.631	2648.16				

Table 9: Analysis of extreme differences in compressive strength of recycled brick powder foam concrete.

	Bubble volumes	Recycled brick powder volume	Water to material ratio	HPMC content
K1	5.06	4.16	3.00	2.77
K2	3.56	3.64	3.32	2.88
K3	2.55	2.86	3.70	3.11
K4	2.08	2.27	2.70	3.16
K5	1.83	2.14	2.36	3.17
Extreme difference value R	3.22	2.02	1.35	0.40
Rank	1	2	3	4

Table 10: Analysis of extreme differences in compressive strength of ordinary foam concrete.

	Bubble volumes	Water cement ratio
K1	2.04	1.56
K2	1.42	1.65
K3	1.39	1.69
K4	1.27	1.27
K5	1.12	1.08
Extreme difference value R	0.92	0.61
Rank	1	2

material > HPMC content. Table 10 shows that the amount of bubble exerts a greater effect on the compressive strength of ordinary foam concrete.

The data in Tables 9 and 10 is visualized, as shown in Figure 6.

Figure 6(a) shows that the compressive strength of recycled brick powder foam concrete and ordinary foam concrete both show a decreasing trend with the increase of the amount of air bubble, which drop by 63.6% and 45.1%, respectively. The increase in the bubble volume poses a significant effect on reducing the compressive strength of recycled brick powder foam concrete. The main reasons are as follows: (1) the increase in the bubble volume is accompanied by the decrease in the amount of cementitious material, which are the main source of the strength of recycled brick powder foam concrete; (2) the increase in the bubble volume will increase the pore volume and produce numerous harmful pores, which will make the pore distribution in the specimen uneven and reduce the strength.

Figure 6(b) shows that the compressive strength of recycled brick powder foam concrete is decreased by 48.6% with the increase in the amount of recycled brick powder. The main reasons are as follows: (1) the increase in the amount of recycled brick powder is accompanied by the decrease in the amount of cement, which leads to the reduction of C-S-H hydration products and the decrease in strength; (2) the reduction of cement content has led to the deformation of a dense skeleton in part of the recycled brick powder; (3) the main component of recycled brick powder is glassy SiO_2, which is an inert material. Although it contains a small amount of Al_2O_3, most of the substances do not participate in the early hydration reaction of cement-based materials, while the increase in the substitution rate will reduce the strength; (4) the mixture of recycled brick powder poses a dilution effect on the cement and increased the effective water-cement ratio.

Figure 6(c) shows that the compressive strength of recycled brick powder foam concrete and ordinary foam concrete are increased at first and then decreased with the increase in water-to-material ratio. The reasons are as follows: (1) when the water-to-material ratio is within the range of 0.45 to 0.55, the compressive strength of recycled brick powder foam concrete is increased with the increase of the water-to-material ratio. As recycled brick powder is of a certain pozzolanic activity, the water demand is more than that of virgin materials. As the amount of water is increased, the pozzolanic activity of recycled brick powder helps in generating more C-S-H gel, which further improves the microstructure of recycled brick powder foam concrete, thereby increasing its strength [24]. (2) When the water-to-material ratio is between 0.60 and 0.65, the compressive strength of recycled brick powder foam concrete is decreased as the water-to-material ratio is increased, which is mainly due to the following: (1) the amount of water is excessive. Due to the different densities, the denser components in the recycled brick powder are left underneath, and the bubbles and remaining cementitious materials are on the top, leading to delamination; (2) excessive water thickens the bubble group liquid film, which will accelerate the bleeding under the action of gravity, leading the bubble group to bursting prematurely or forming numerous harmful holes, thereby reducing the strength.

Figure 6(d) shows that the compressive strength of recycled brick powder foam concrete is increased with the increase of HPMC content, while the increasing rate is gradually slowed. The reasons are as follows: with the increase in the HPMC content, the performance of the bubble group is improved, the shape of the pores, the distance between the holes, and the pore diameter are all improved. Moreover, the bubble group is uniformly distributed in the slurry. Therefore, the strength is improved. However, as the strength of recycled brick powder foam concrete is mainly derived from cementitious materials, the upward trend tends to be flat.

3.2. Determination of the Optimal Mix Ratio. The specific strength is the ratio of the strength of a material to its dry density, and it is an important indicator to measure the light weight and high strength of the material [21]. The greater the specific strength is, the better the light-weight and high-strength performance of the material would be [25]. Table 7 shows that the specific strength of the test blocks under the mix ratios in the 3rd group is the largest, as the level of recycled brick powder foam concrete that fulfilled the requirements of light weight and high strength is $A_1B_3C_3D_3$. That is, the optimal mixing ratio is 3% of the bubble group content, 30% of the recycled brick powder content, 0.55 of the water-to-material ratio, and 0.05% of the HPMC content. It can be concluded from Table 8 that the specific strength of the test block is the largest under the mix ratios in the 2nd group, that is, the optimal mix ratio of ordinary foam concrete is 3% of the bubble group content and 0.50 water-cement ratio.

For the optimal mix ratio of recycled brick powder foam concrete, the water-to-cement ratio is 0.55, while for the optimal mix ratio of ordinary foam concrete, the water-cement ratio is 0.50. That is, adding recycled brick powder requires more water to promote the complete hydration of the cementitious material. The dry density of the 3rd group of specimens in Table 7 is 988 kg/m^3, while the 28 d compressive strength is 5.76 MPa; The dry density of the 2nd group of specimens in Table 8 is 722.38 kg/m^2, and the 28 d compressive strength is 2.229 MPa. The compressive strength of recycled brick powder foam concrete with 28 d compressive Strength is 2.58 times that of ordinary foam concrete, while the compressive strength of dry density

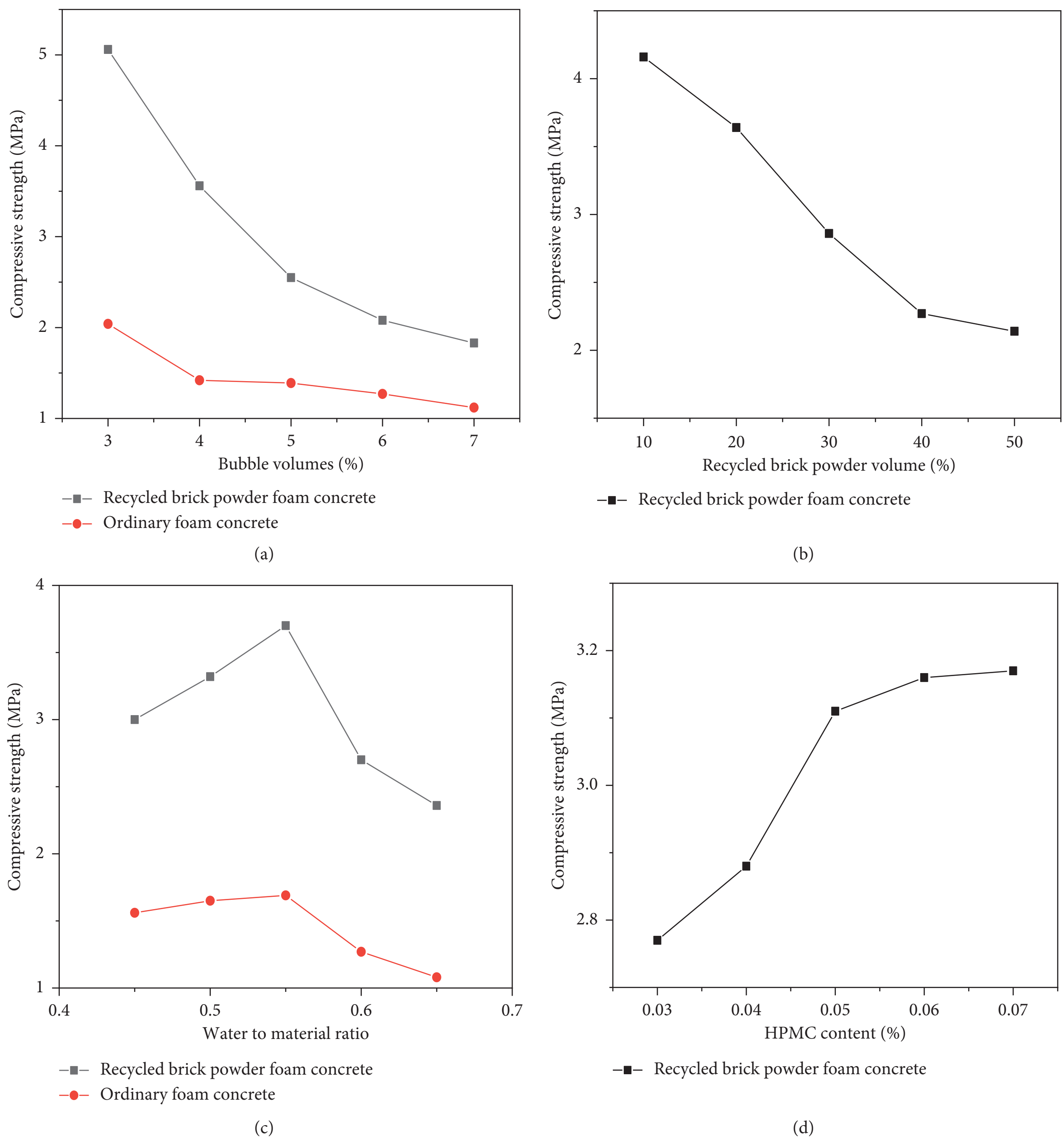


Figure 6: Changes in the influence of various factors on compressive strength.

recycled brick powder foam concrete is 1.37 times that of ordinary foam concrete. Although the addition of recycled brick powder will increase the dry density of foam concrete, the increase in compressive strength is even greater.

3.3. Microscopic Morphology Analysis. The optimal mix ratio test piece can be observed by the SU8100 scanning electron microscope, and the test results are shown in Figure 7.

The pore diameter of the samples was measured by the NanoMeasure software. Figure 3 shows that the average pore diameter of the ordinary Figure 8 foam concrete is 109.73 μm, and the average pore diameter of the recycled brick powder foam concrete is about 72.17 μm, a reduction of 34.2%. The pore wall thickness in Figure 7(b) is obviously greater than that in Figure 7(a). Obvious micro-filling effects can be found. Therefore, the added recycled brick powder refines the pores, increases the compactness of the concrete matrix, and improves the compressive strength of the recycled brick powder foam concrete. When the multiplying factor is 50x, the pore diameter is large with obvious connecting holes in Figure 8(a). In Figure 8(b), the pore diameter is smaller, the pore structure is more uniform, the wall between the pores is dense, the communicating pores

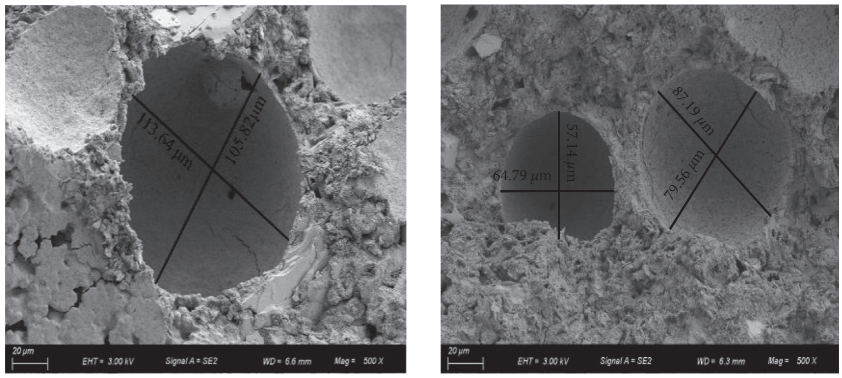


Figure 7: Photograph of 28 d hydration of the specimen when scanned by electron microscope at 500x.

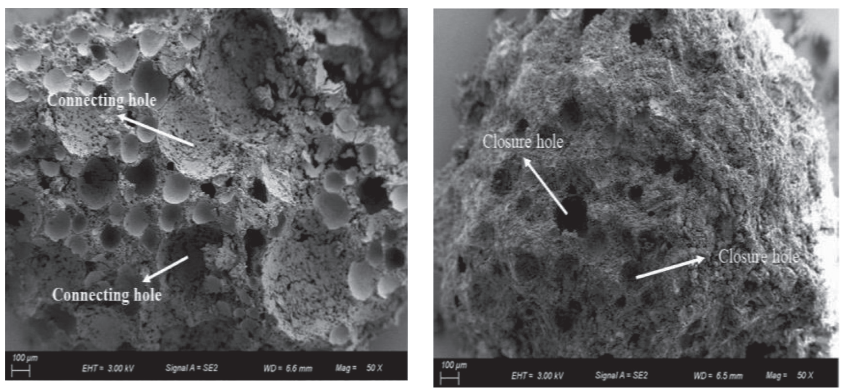


Figure 8: Photograph of 28 d hydration of the specimen when scanned by electron microscope at 50x.

are less, and the closed pores are more. As a foam stabilizer, HPMC reduces the occurrence of harmful pores such as connecting holes in the test piece, and makes the pore distribution more uniform.

3.4. Correlation Analysis of Various Factors and Recycled Brick Powder Foam Concrete. To investigate the correlation between the compressive strength of recycled brick powder foam concrete and the bubble volumes, the amount of recycled brick powder, the water-to-material ratio, and the HPMC content, the Pearson correlation coefficient was used for analysis. The Pearson correlation coefficient [26] (also known as covariance correlation or Bravais–Pearson correlation) describes the degree of correlation between two fixed-ratio, linearly correlated variables (measurement value series) that are not less than affected by their units (also known as tightness). The Pearson correlation coefficient is calculated based on the covariance and product of mean difference of two variables, and its calculation formula is as follows:

$$r = \frac{\operatorname{cov}(x, y)}{S_x \bullet S_y} = \frac{\sum_i^n \left((x_i - \overline{x}) \bullet (y_i - \overline{y}) \right)}{n \bullet S_x \bullet S_y}. \tag{2}$$

In the formula: $\operatorname{cov}(x, y)$ is the covariance of variables x and y; S_x and S_y are the variances of variables x and y; n is the number of variables; $\overline{x}$ and $\overline{y}$ are the mean values of variables x and y, respectively. The value of the correlation coefficient is generally between −1 and 1. The greater the absolute value of the correlation coefficient is, the stronger the correlation of 2 variables would be. If the absolute value of the correlation coefficient is close to 1, it indicates that a perfect linear correlation exists between the two variables; if it is close to 0, no linear correlation exists between the two variables [27].

In the Figure 9, $X1$, $X2$, $X3$, and $X4$ represent the volume of bubble volumes, the volume of recycled brick powder, water-to-material ratio, and HPMC content, respectively. $Y1$ represents the compressive strength of recycled brick powder foam concrete. The order of correlation is as follows: bubble volume > recycled brick powder volume > the ratio of water to material > HPMC content, which is consistent with the results from the orthogonal test analysis. The amount of bubble volume poses a significant effect on the compressive strength of recycled brick powder foam concrete.

3.5. PSO-BP (Back Propagation Neural Network Improved by Particle Swarm Optimization) Prediction. For the recycled brick powder foam concrete, due to the increase in its components, the hydration reaction mechanism is not

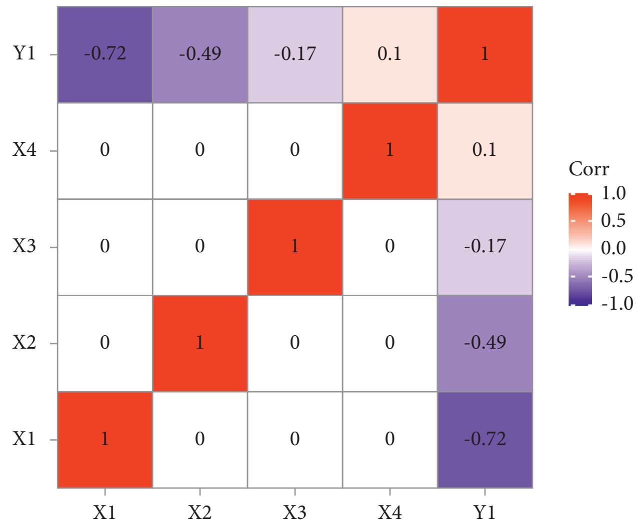


FIGURE 9: Heat map of the correlation between each factor and the compressive strength of the cube.

completely clear. The influencing factors are complex and interactive, which manifests as a specific high-dimensional nonlinear law [28]. The BP neural network is an effective method to solve high-dimensional nonlinear problems. Among them, the PSO-BP [29] neural network defines the initial weights and thresholds of the BP neural network as the particles in the particle swarm optimization algorithm. All particles form a group, and the optimal solution is found through cooperation and information-sharing between individuals in the group. The defects of multiple local extreme points in the BP neural network and difficulty in establishing mathematical models can be avoided. The PSO-BP model consists of the following steps [29].

Step 1. Enter the mix ratio and compressive strength data of recycled brick powder foam concrete and randomly assign 70% of the data as the training set and 30% of the data as the test set.

Step 2. Initialize the parameters of the BP neural network.

Step 3. The initial weights and thresholds are extracted from the BP neural network, encoded as a set of particles in the PSO (group size N). Initialize the number of iterations t, maximum number of iterations t_{max}, inertia weight W, and acceleration factor $c1$ and $c2$.

Step 4. Assume the position of each particle X_i and the velocity of each particle V_i in space.

Step 5. Evaluate the fitness value of all particles and obtain the best personal solution *pbest* and the best group solution *gbest*.

Step 6. Use *pbest* and *gbest* to correct the velocity of each particle $V_i(t+1)$.

Step 7. Correct the position of each particle $X_i(t+1)$.

Step 8. Repeat Step 4 to Step 6 until $t \geq t_{max.}$

Step 9. The optimized position *gbest* can be obtained.

Step 10. The optimized BP neural network model is trained with the training set, and the accuracy of the model is verified with the test set.

The establishment process of the PSO-BP neural network in this paper is shown in Figure 10.

Taking cement quality, bubble group quality, recycled brick powder quality, water and HPMC quality as input independent variables, and the compressive strength of recycled brick powder foam concrete as output dependent variables, a 5-1-11-1 PSO-BP neural network was established. The prediction of the cubic compressive strength of recycled brick powder foam concrete and the strength of the specimen are compared as shown in Figure 11.

Figure 11 shows that the predicted compressive strength of the PSO-BP model is close to the actual value, that is, the prediction result of the PSO-BP model is more accurate, with small errors and high fitting accuracy.

3.6. Model Performance Comparison. The prediction performance of the PSO-BP model was compared with various models, including the support vector machine (SVM), multiple linear regression (MLR), random forest (RF), and artificial neural network (BP) models. The fitting effect is shown in Figure 12.

Figure 12 shows that most of the scattered data of the prediction model of PSO-BP are concentrated in and around the 100% regression line. While SVM, MLR, RF and BP scattered point data are very discrete, the data in Figure 11 is fitted according to the form of $y = a_0x + a_1$.. Compared with the four models in the control group, the a_0 value of the PSO-BP model is closer to 1 and a_1 values are closer to 0. The

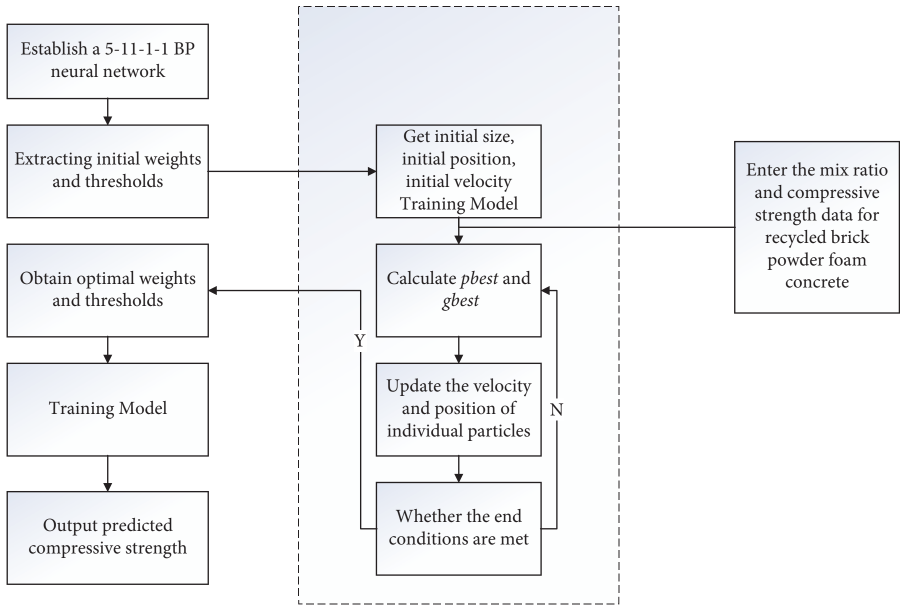


Figure 10: Establishment process of PSO-BP neural network.

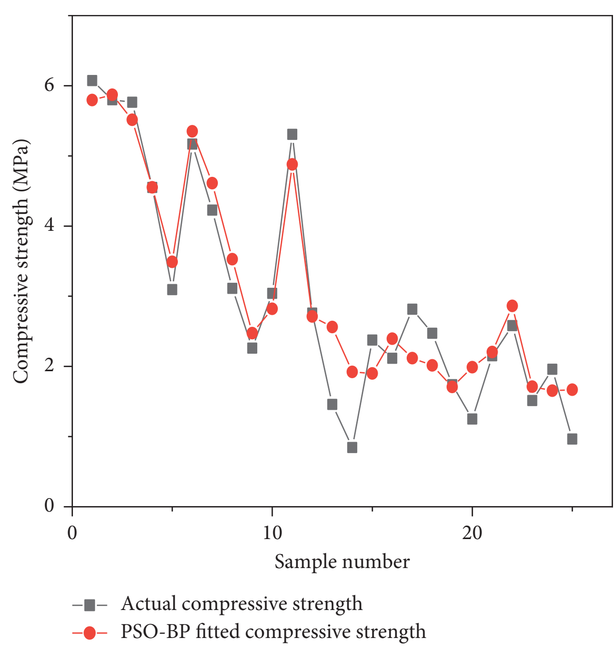


Figure 11: PSO-BP model fitting effect diagram.

prediction accuracy of the PSO-BP model is higher and the error is smaller.

3.7. Statistical Indicators of the Model. In this paper, five statistics were selected to evaluate the prediction accuracy of the PSO-BP model and the control model, as the coefficient of determination (R^2), the mean square error (RMSE), the mean error (MAE), the calculation formula of the average absolute deviation percentage error (RMAE), and benefit coefficient (E) [30–32]. The calculation formula is shown in Table 11.

According to the evaluation index formula describes in Table 11, the calculation results are shown in Table 12.

The coefficient of determination R^2 is widely used in regression problems to estimate the correlation between the target value and the predicted value; RMSE and MAE are two standards used to measure the average error between the target and the predicted output; RMAE represents the average percentage size of the total absolute deviation error between the target value and the predicted output; the efficiency coefficient E (%) represents the prediction accuracy of the model. The value of R^2 is close to 1, the values of RMSE, MAE, and RMAE are close to 0, and the value of E is

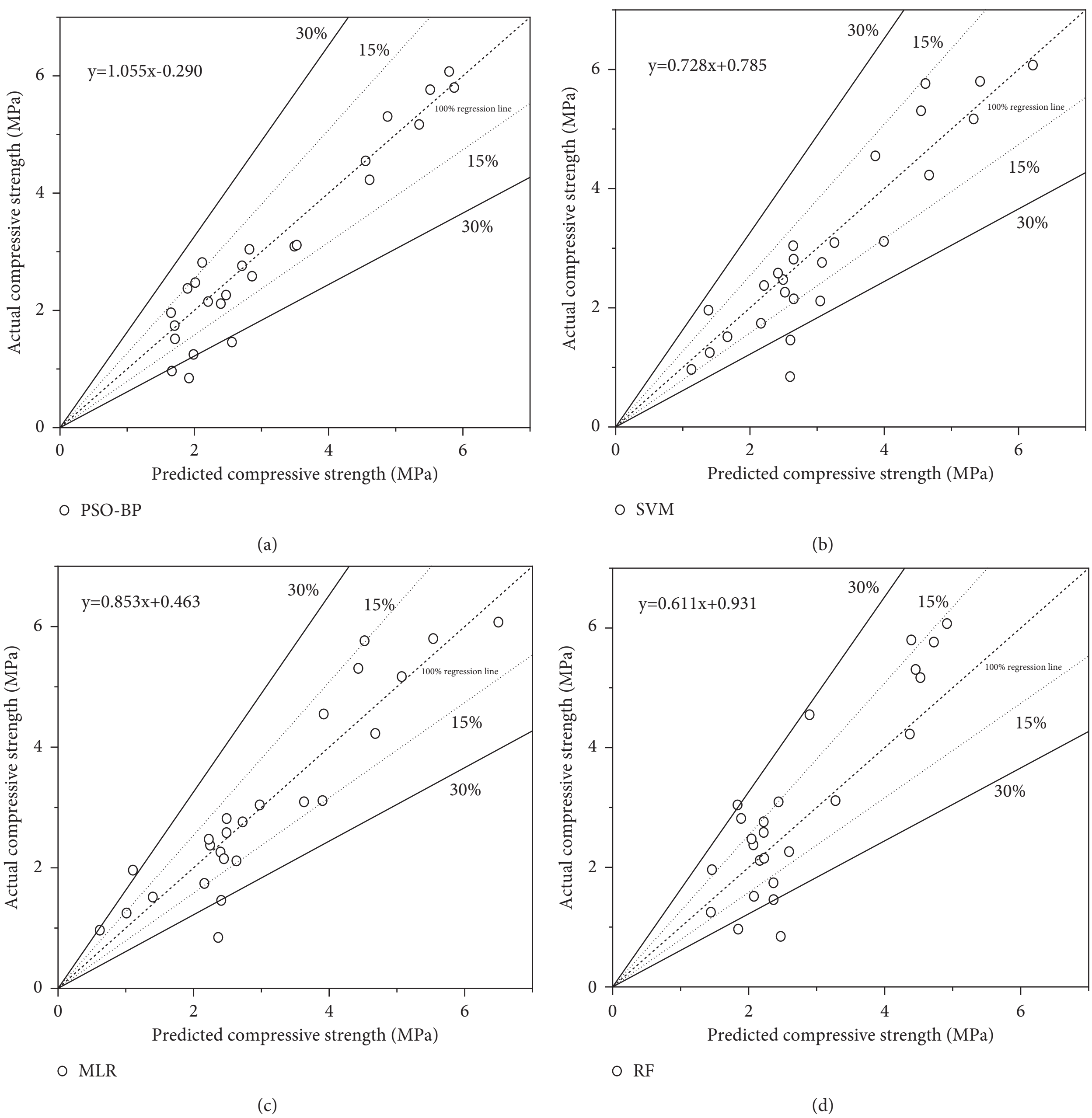
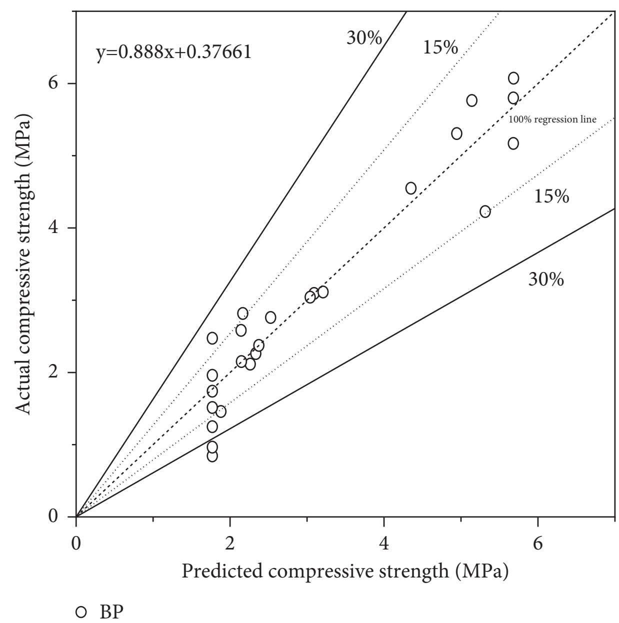


Figure 12: Continued.



(e)

Figure 12: Scattered distribution diagram of predicted and actual values of each model.

Table 11: Calculation formula of statistical indicators.

Measure	Calculation
Coefficient of determination ($R2$)	$R^2 = 1 - 1/N\sum_{i=1}^{N}(Y_i - \overline{Y})^2/1/N\sum_{i=1}^{N}(Y_i - \overline{Y})^2$
Root mean square error (RMSE)	$\text{RMSE} = \sqrt{1/N\sum_{i=1}^{N}(Y_i - \overline{Y})^2}.$
Mean absolute error (MAE)	$\text{MAE} = 1/N\sum_{i=1}^{N} abs(Y_i - y_i).$
Root mean absolute error (RMAE)	$\text{RMAE} = 100 \bullet MAE/\overline{y}$
Coefficient of efficiency (E)	$E(\%) = 1 - \sum_{i=1}^{N}(Y_i - \overline{Y})^2/\sum_{i=1}^{N}(Y_i - \overline{Y})^2.$

y_i was the actual target value, $\overline{y}$ was the average value of y_i; Y_i was the predicted value, $\overline{Y}$ was the average of Y_i; and N was the number of model data.

Table 12: R^2, RMSE, MAE, RMAE, and E (%) results of different models.

Model	R^2	RMSE	MAE	RMAE	E (%)
PSO-BP	0.957	0.466	0.352	11.673	90.867
SVM	0.782	0.634	0.482	15.979	77.391
MLR	0.853	0.599	0.464	15.399	85.296
RF	0.611	0.827	0.689	22.858	71.945
BP	0.888	0.472	0.372	12.325	87.094

more than 90%, which mean that the accuracy of the model is higher [33]. Table 12 has shown that the PSO-BP prediction model is of higher R^2 and E (%) values than other models, as well as lower RMSE, MAE, and RMAE values. That is, the PSO-BP model can accurately predict the compressive strength of recycled brick powder foam concrete.

As can be seen from Figure 13, the relative error values of the PSO-BP model are mostly concentrated around the value of 0, and its performance is relatively stable, while the relative error values of the other models fluctuate widely. Combined with Figure 13 and Table 12, it can be seen that the PSO-BP model can make more accurate predictions and its performance is significantly better than the rest of the models.

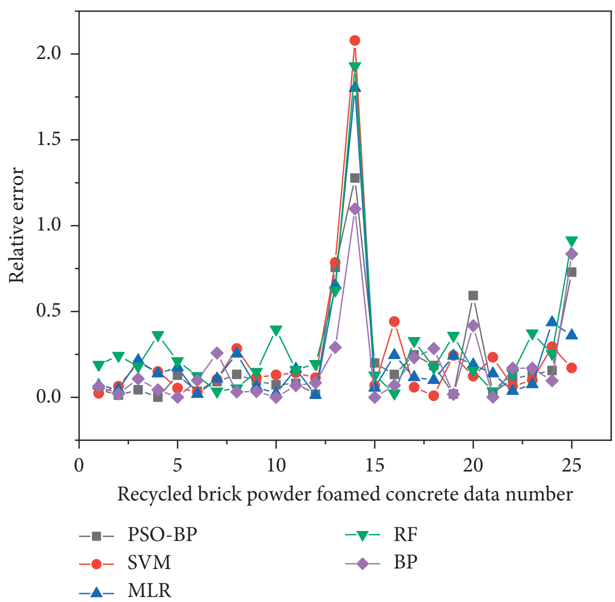


Figure 13: Relative error plots for each model.

4. Conclusion

In this paper, experimental research on the mechanical properties of recycled brick powder foam concrete was carried out, and a neural network model was established to accurately predict the compressive strength based on the compressive strength data of recycled brick powder foam concrete, and the main conclusions reached are as follows.

(1) The range analysis was conducted on the orthogonal test data of recycled brick powder foam concrete, and the results have shown that the influence of various factors on the compressive strength of recycled brick powder foam concrete in descending order is the bubble volumes, the amount of recycled brick powder, water-to-material ratio, and HPMC content.

(2) Comparing the specific strength of each group of recycled brick powder foamed concrete finds that the optimal mixing ratio of recycled brick powder foam concrete fulfilling the requirements of light weight and high strength is 3% bubble group content, 30% recycled brick powder content, 0.55 water-to-material ratio, and 0.05% HPMC content.

(3) With the increase in the bubble volumes, the compressive strength of recycled brick powder foam concrete is decreased, while the reduction effect is significant; with the increase in the amount of construction waste, the compressive strength of recycled brick powder foam concrete exhibits a slow decline; with the increase in the water-to-material ratio, the overall compressive strength of recycled brick powder foam concrete is increased and decreased; with the increase in HPMC content, the compressive strength of recycled brick powder foam concrete is gradually increased, but the increased amount is not as huge.

(4) Two improvements of the compressive strength of recycled brick powder foam concrete is analyzed from a microscopic point of view. One is that the added recycled brick powder refines the pores and increases the compactness of the concrete matrix. Moreover, the foam stabilizer HPMC reduces the damage of the bubble group during the preparation of the test piece and reduces the generation of harmful holes, such as connecting holes.

(5) The PSO-BP model predicts the compressive strength of recycled brick powder foam concrete with high prediction accuracy and data reliability. It provides an effective method for exploring the changing law of the strength of recycled brick powder foam concrete under multiple factors.

While the work in this paper is beneficial to the progress of subsequent foam concrete research, the following issues remain to be further explored due to the time and conditions of the tests and some human uncontrollable factors.

(1) Although the pore structure of recycled brick powder foam concrete has been observed by electron microscopy scanning in this paper, only a few specimens have been studied and future experiments related to the pore structure need to be designed in order to derive the specific influence of pore structure characteristics on the performance of recycled brick powder foam concrete.

(2) Due to time and equipment constraints, a large database was not constructed for neural network model training. With the continuous research on recycled brick powder foam concrete, a large amount of experimental data should be used to train the neural network model in the future, thus supporting the application of the constructed neural network model to engineering practice.

Data Availability

The data supporting the conclusion of the article are shown in the relevant figures and tables in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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