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Compressive strength prediction model of lightweight high-strength concrete

***L.N. Zhang*[1], *D.P. He*[1], *W.Y. Xu*[1], *Q.Q. Zhao*[2] ✉, *S.B. Teng*[3]**

[1] *Northeast Forestry University, Harbin, Heilongjiang, China*

[2] *Northeast Agricultural University, Harbin City, Heilongjiang Province, China*

[3] *Heilongjiang Transportation Investment Group Co., Harbin City, Heilongjiang Province, China*

✉ *492954791@qq.com*

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Abstract. A reasonable prediction of the compressive strength of lightweight high-strength concrete is an important basis for determining concrete strength. Through cluster analysis, the key factors affecting the compressive strength of lightweight high-strength concrete are found, and the degree of influence of each factor on the compressive strength is analyzed. We applied linear regression analysis of the relationship between the above factors and the compressive strength using SPSS, and performed multiple non-linear regression to establish a prediction model for the compressive strength of lightweight high-strength concrete using MATLAB. Using RMSE, we tested the simulated and actual values of the model, to determine the applicable conditions of the model through response surface analysis. The results of the study show that: cylinder compressive strength, water-binder ratio, cement dosage, coarse aggregate particle size and sand ratio are the key factors affecting the compressive strength. The R2 values of the single-factor prediction models are all greater than 0.9, and the corresponding coefficients of the lightweight high-strength concrete compressive strength prediction models are 1.46, 18.31, 21.6, –3.28, –71.12, 1.36 and 20.48 respectively; The root mean square error RMSE is all lower than 1.05 MPa. The applicable condition of the prediction model shows that the cylinder compression strength is between 3.2 MPa and 4.9 MPa. When the coarse aggregate particle size is 15 mm~25 mm, the sand ratio is 26 %~35 %, the cement dosage is 450 Kg/m³~500 Kg/m³, and the water-binder ratio is 0.34~0.4, the parameter value range is the optimal prediction space of the model. When the 5 parameters are simultaneously in the optimal prediction interval, the prediction level of the model is the best and the prediction accuracy of the proposed compressive strength prediction model is higher. The model is of great significance to the study of the mechanical properties of lightweight high-strength concrete.

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1. Introduction

Lightweight high-strength concrete has become a hot spot in the industry: it has the characteristics of strong durability, good corrosion resistance and high compressive strength, and its performance and quality can be used for high-rise buildings [1]. As the basis to determine the strength grade of concrete, compressive strength has become a necessary index to determine the quality and production control evaluation of concrete [2, 3].

Most of the research on the compressive strength of lightweight high-strength concrete at home and abroad focuses on the qualitative analysis of the factors affecting the compressive strength and the detection of the compressive strength. For example, Cheng [4] conducted an indoor unconfined uniaxial compression test and believed that admixtures had a significant influence on the early compressive strength of lightweight high-strength concrete. Slonski [5–7] has completed a number of mix ratio tests, and obtained the optimal mix ratio that makes the compressive strength of lightweight high-strength concrete relatively high. Akbari [8] observed the microstructure of lightweight high-strength concrete with scanning electron microscope and determined that the appropriate curing conditions had significant influence on the compressive strength. Based on the cement-based material test, Sobhani [9–11] found that the type of micro beads would affect the density of the material, thus affecting the compressive strength. Costa [12–14] proved through sampling test that proper reduction of cement dosage and corresponding increase of coarse aggregate dosage can ensure concrete strength and prolong concrete service life. Although the above research has confirmed that some factors have influence on the compressive strength of lightweight high-strength concrete, the research object is one-sided and lacks a comprehensive analysis of the compressive strength of concrete in practical engineering.

The testing methods of compressive strength are mainly divided into two categories. One is to use mathematical statistics software to conduct theoretical calculation on the influence parameters of concrete strength, that is, to predict concrete compressive strength by analyzing the concrete mix ratio. For example, Lee [15, 16] used Boromi's formula to predict the compressive strength, and Malachanne [17] established the BP neural network model to predict the compressive strength. The second is the use of tests or instruments for detection, that is, based on the actual mixing in the field through the early strength prediction of late strength method, such as ultrasonic rebound synthesis method, fresh concrete on-site detection method. In the relevant literatures, Boukli [18] proposed the relation formula of fly ash concrete strength, Zhang [19] proposed the bivariate strength formula of fly ash concrete, and Bingol [20] established the strength model of fly ash concrete at different ages by using Statistical Package for Social Sciences (SPSS) software. Although the above prediction methods can predict the compressive strength of lightweight high-strength concrete, the prediction accuracy is not high, because the formulated prediction cannot be applied to all types of lightweight high-strength concrete, the parameters in the prediction model are not comprehensive, and the field detection is not predictable.

In conclusion, the compressive strength prediction method of lightweight high-strength concrete needs to be further improved. In this paper, the relevant research content of the compressive strength of lightweight high-strength concrete is combined with theory and practice, through analysis, the main factors that affect the lightweight high-strength concrete are found out, and the influence degree of the factors is analyzed. The prediction model of 28 days strength of lightweight high-strength concrete is established, and the model is tested. The applicable conditions of the model are determined by surface analysis method. The prediction model of compressive strength of lightweight high-strength concrete can accurately predict the change of compressive strength. The model can provide reference for the design of mix ratio of lightweight and high-strength concrete, and provide experimental basis and theoretical guidance for the mechanical properties of lightweight aggregate concrete. Therefore, the research on the prediction model of compressive strength of lightweight high-strength concrete is of great significance.

2. Methods

2.1. Influence factor extraction

In order to extract the factors that affect the compressive strength of lightweight high-strength concrete in seasonal freezing areas, the existing research results of domestic and foreign literature are analyzed. Mehta [21] used numerical analysis methods to perform regression analysis on factors such as concrete component dosage, curing conditions, admixtures, early strength, water absorption and bulk density, and predicted 28 days compressive strength. Hung [22–24] used 7 variables including the maximum particle size of crushed rock, sand ratio, cement label, slump, water, cement, sand and gravel consumption as input parameters for network training, and 28 days compressive strength as output parameters. Chithra [25, 26] pointed out that the strength of high-strength high-performance concrete is related to many factors such as cement type, aggregate particle size, admixtures and curing conditions. Ambily [27] further advanced the water-cement ratio theory and proposed a strength formula based on the hydrocolloid ratio. Yoon [28] added antifreeze to lightweight high-strength concrete to improve the compressive strength according to the climatic characteristics of seasonal freezing areas.

According to the above analysis, the concrete compressive strength, curing conditions, early strength, water absorption, bulk density, cement type, coarse aggregate particle size, water-binder ratio, cement dosage, sand ratio, water reducing agent and admixture of coarse aggregate concrete etc., the above factors may affect the compressive strength of lightweight high-strength concrete in seasonal freezing areas. In view of the two factors of water absorption and bulk density, since coarse aggregates are pre-wet before mixing to reach a saturated surface dry state, water absorption is not considered in the factors affecting the strength of lightweight high-strength concrete; bulk density as the physical properties of aggregate, it is not considered. Haile [29–31] et al. proposed that water reducers can reduce the water consumption of mixed concrete, thereby increasing the strength of concrete. Since mineral admixtures and water-reducing agents have a recommended dosage before use, the impact of water-reducing agents on the compressive strength of lightweight high-strength concrete is not considered.

The cluster analysis method is used to extract the above factors affecting the compressive strength of lightweight high-strength concrete, as shown in Fig. 1. The 12 influencing factors are numbered, and the numbers are F1 to F12, as shown in Table 1.

Table1. Factors and numbers affecting the compressive strength of lightweight high-strength concrete.

No.	Influencing factors	No.	Influencing factors	No.	Influencing factors
F1	Cylinder compressive strength of coarse aggregate	F5	Water reducing agent	F9	Maintenance conditions
F2	Coarse aggregate size	F6	Early strength	F10	Water absorption
F3	Bulk density	F7	Cement varieties	F11	Sand rate
F4	Water-binder ratio	F8	Admixture	F12	Cement consumption

In Fig. 1, the abscissa is the standard value of influence Z (RIV), and the ordinate is the standard value of influence Z (SDV). The larger influencing factors of the Z (RIV) and Z (SDV) values are F2 (coarse aggregate particle size), F11 (sand rate) and F12 (cement amount) in cluster 2, cluster 3 contains F1 (the barrel compressive strength of coarse aggregate) and F4 (water-binder ratio), indicating that the five factors included in these two clusters have a wide range of influence on the compressive strength of lightweight high-strength concrete, so these five factors It is a key factor. The 7 factors included in the other 2 clusters have a smaller range and degree of influence than the 5 factors in cluster 2 and cluster 3, so they are secondary factors. According to the analysis in Fig. 1, the barrel compressive strength of coarse aggregate, coarse aggregate particle size, water-binder ratio, cement dosage and sand ratio are the key factors affecting the compressive strength of lightweight high-strength concrete.

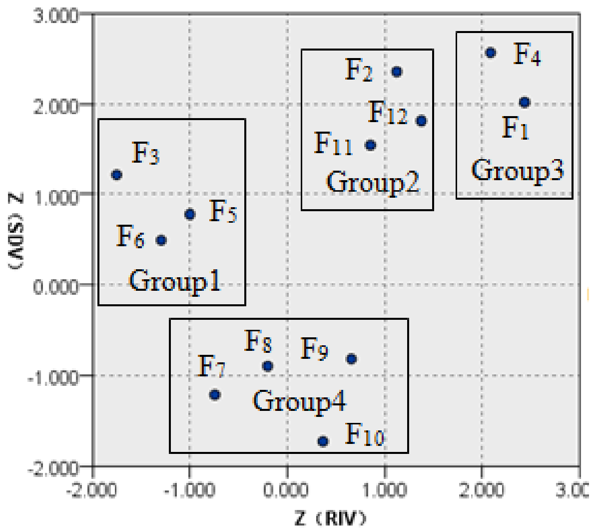

Figure 1. Cluster analysis of influencing factors.

2.2. Analysis of influencing factors

In order to further analyze the degree of influence of the above factors on the compressive strength of lightweight high-strength concrete, establish different amounts of coarse aggregate particle size, water-binder ratio, cement dosage, sand ratio, admixtures and different barrel compressive strengths. The change of compressive strength under the same age conditions, so as to determine the influence of the above factors on the compressive strength by comparing experiments. It adopts China's current national standard GB/T 50081-2002 "Standard for Test Methods of Mechanical Properties of Ordinary Concrete". The size of the test piece is 150 mm×150 mm×150 mm, and the water-permeable concrete specimens composed of different aggregate particle sizes are prepared for comparison test. According to the design principles of ordinary concrete, a set of initial mix ratios are designed, in which the water-cement ratio is 0.35, the sand ratio is 0.3, and the amount of cement per cubic meter of concrete material is 485.71 kg, the amount of sand is 280.09 kg, and the amount of stones is 666.87 kg, the amount of water used is 170 kg. The water-binder ratios selected are 0.3, 0.35 and 0.4 respectively; the sand content is from 35 % to 45 %. The amount of cement is 225 g, 250 g, 275 g, 325 g and 350 g respectively. The coarse aggregate particle size is 5 mm~25 mm. The cylinder compressive strength is 5.7 MPa and 3.2 MPa respectively. The specimens are cured in the curing room, and the curing conditions are temperature 20±2 °C and relative humidity above 95 %.

In order to verify the impact of cylinder compressive strength on the compressive strength, two sets of comparative test pieces were established, each with 5 test pieces, and the same condition of the coarse aggregate particle size, water-binder ratio, cement dosage, sand ratio and admixture was established. The cylinder compressive strength is 3.2 MPa and 5.7 MPa respectively, the comparative analysis of compressive strength is carried out, as shown in Fig. 2. In Fig. 2, the concrete specimen with a cylinder compressive strength of 5.7 MPa is 22.2 %, 21.5 %, 20.5 % and 25.0 % higher than the specimen with a cylinder compressive strength of 3.2 MPa at ages of 5 d, 10 d, 15 d, and 20 d. Indicating that the cylinder compressive strength has a significant influence on the compressive strength of lightweight high-strength concrete. The reason for the analysis is that the strength of lightweight aggregate is significantly lower than that of mortar. The external force is mainly borne by the mortar. When the particle size in the aggregate is large, the mortar skeleton surrounding the aggregate will become weaker, which will result in a decrease in the strength of the concrete. And as the particle size of the lightweight aggregate decreases, its specific surface area increases, and the bonding force with the cement mortar increases. At the same time, the smaller the particle size, the smaller the probability of internal cracks and the increase in resistance to deformation. This allows the particle shape coefficient to be optimized, stress concentration is reduced, and the strength of concrete is improved. From the above analysis, it can be concluded that the cylinder compressive strength is an important factor in determining the strength of lightweight aggregate concrete.

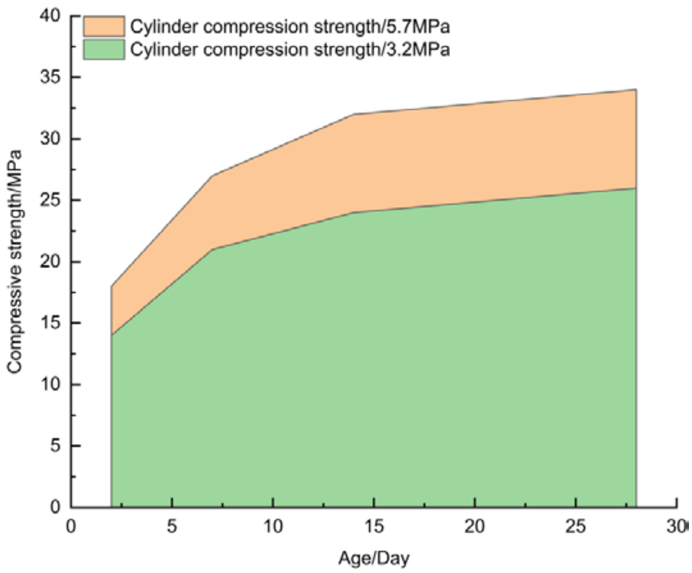

Figure 2. Influence of cylinder compressive strength on concrete compressive strength of different ages.

In order to verify the influence of the particle gradation of coarse aggregate on the compressive strength of lightweight high-strength concrete, four sets of comparative specimens were established under the condition that the cylinder compressive strength, water-binder ratio, cement dosage and sand ratio remain unchanged. 5 pieces for comparison test. Choose four different coarse aggregate particle sizes, which are 5~10 mm, 5~15 mm, 5~20 mm and 5~25 mm, as shown in Fig. 3. According to the analysis in Fig. 3, as the age increases, the compressive strength of each particle size continues to increase, but the compressive strength of 5~15 mm is the largest, and the impact of coarse aggregate particle size on concrete strength is relatively low. The slight difference in compressive strength at the same age is controlled within the range of 5 MPa. The above analysis proves that with the increase of aggregate particle size, the strength of high-strength concrete first increases and then decreases. The aggregate particle size should not exceed 20 mm, and the best particle size is 5~15 mm. The reason for the analysis is that the particle size of the coarse aggregate has an impact on the compressive strength. The larger the particle size of the aggregate, the greater the probability that there will be defects in the concrete component. At this time, the bonding strength of the interface is lower, which will cause the interior of the concrete. The uneven distribution of particles induces a decrease in the strength of the hardened concrete.

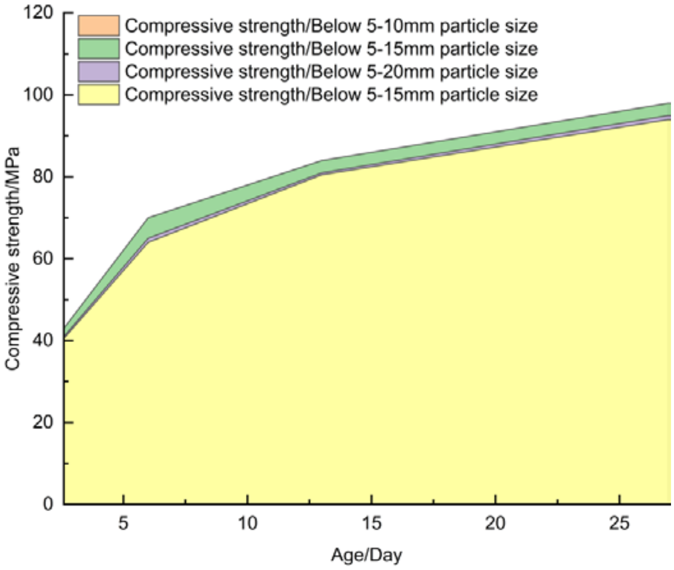

Figure 3. Influence of coarse aggregate size on compressive strength of concrete at different ages.

The size of the sand ratio directly affects the ratio of aggregate to cement stone in the concrete. When the sand ratio is increased, the ratio of light aggregate will decrease and the strength of concrete will increase. So lightweight high-strength concrete needs to increase the sand rate. According to the cluster analysis, sand ratio is an important factor affecting the compressive strength of fine aggregates. In order to further study and determine the impact of sand ratio on compressive strength, concretes with different sand ratio contents were selected. The sand content is 35 %, 37 %, 39 %, 41 %, 43 %, 45 %. When the ages are 3 days, 7 days, 14 days and 28 days, the changes in compressive strength of different ages are analyzed. The situation is shown in Fig. 4. It can be seen from Fig. 4 that the sand ratio has a very obvious influence on the compressive strength of concrete. The greater the sand ratio, the smaller the proportion of light aggregate in the concrete, and the higher the strength of the concrete. When the sand ratio is 39 %, the compressive strength was 35 MPa, 56 MPa, 58 MPa and 64 MPa at the age of 3 days, 7 days, 14 days and 28 days respectively. However, when the sand ratio increases to 39 %, continuing to increase the sand ratio will reduce the compressive strength of the concrete. Compared with the sand ratio of 39 %, the compressive strength of the sand ratio of 45 % decreased by 8.6 %, 5.4 %, 4.3 % and 4 % at the age of 3 days, 7 days, 14 days and 28 days. The main reason is that the sand rate is too large and the concrete is easy to segregate, which leads to uneven formation of the concrete structure, and the concrete damage is easy to break from the part where the aggregate is concentrated.

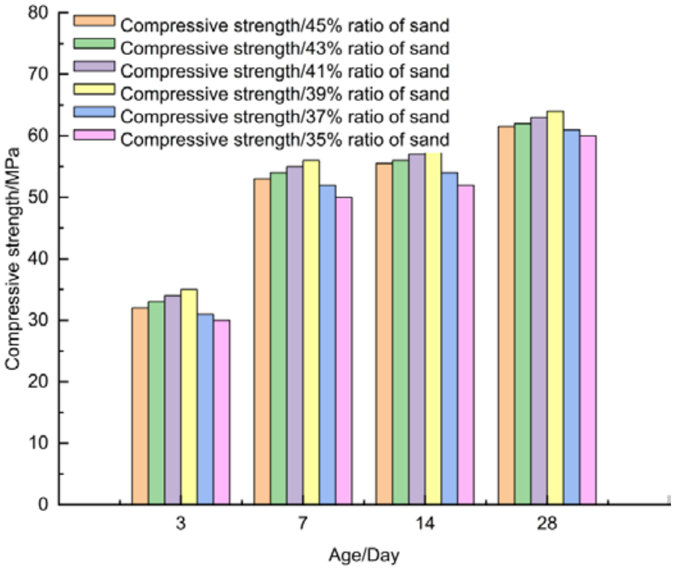

Figure 4. Influence of sand ratio on compressive strength of concrete at different ages.

In order to verify the influence of different cement dosages on compressive strength, the changes in compressive strength at different ages were established when the cement dosages were 225 g, 250 g, 275 g, 300 g, 325 g and 350 g, as shown in Fig. 5. In Fig. 5, when the concrete age is 3 days and the amount of cement is 300 g, the maximum compressive strength of concrete is 34 MPa. When the concrete age is 7 days, the cement dosage with the highest compressive strength of concrete is 325 g, and the pressure value at this time is 56 MPa. In other words, for certain preconditions, there is a cement amount that maximizes the compressive strength of the concrete cube. For the same water-cement ratio, the compressive strength of concrete gradually increases as the amount of cement increases, and when the strength reaches the maximum, it begins to slowly decrease to a certain fixed value. This rule also applies to different ages of concrete.

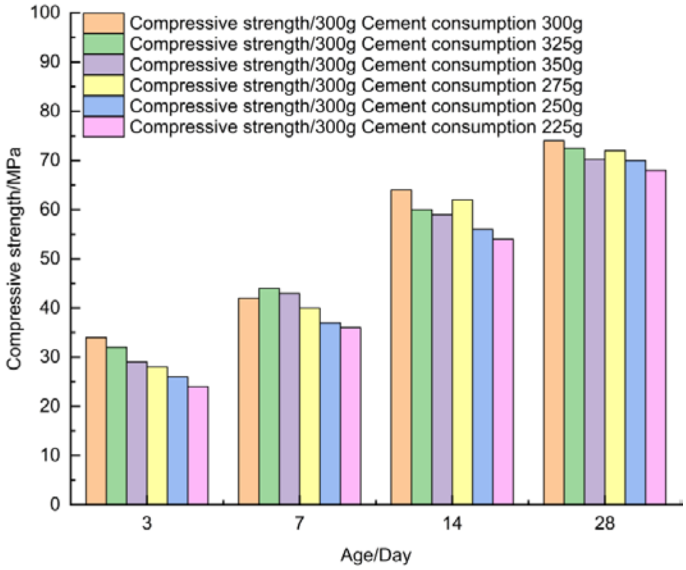

Figure 5. The influence of different cement content on the compressive strength of concrete.

In order to verify the influence of different water-binder ratios on compressive strength, under the condition that the cylinder compressive strength, coarse aggregate particle size, sand ratio and cement dosage remain unchanged, concrete blocks with fly ash content of 35 % were selected [29], compare the compressive strength under different water-binder ratio conditions, as shown in Table 2. It can be seen from Table 2 that the selected fly ash content is 35 %, each of the 3 groups of test pieces is 5, and the water-binder ratio is 0.3, 0.35 and 0.4 respectively. The three groups of concrete blocks A, B, and C have a faster rate of increase in strength during 0 to 7 days of curing, while the rate of strength increase of concrete blocks with a large water-binder ratio slows down. In the early stage of curing of concrete blocks, the water-binder ratio has a significant impact on the strength. The water-binder ratio is negatively correlated with the growth of the compressive strength of the concrete blocks. In the later stage of the curing of concrete blocks, the water-binder ratio and the strength increase are positively correlated. The reason is that concrete blocks with a small water-binder ratio are fully hydrated in the early stage of cement hydration, so the strength increases quickly, but the strength increase is small in the later period of curing. It can be seen that the water-binder ratio can make the lightweight concrete blocks have Stable strength.

Table 2. Influence of water-to-binder ratio on compressive strength.

No.	Fly ash content/%	Water glue ratio	Compressive strength/MPa			
			3d	7d	14d	28d
A	35	0.3	2.61	5.84	8.33	9.53
B	35	0.35	2.79	8.06	7.59	9.08
C	35	0.4	1.92	3.82	6.48	8.78

2.3. Establish a prediction model for the compressive strength of lightweight high-strength concrete

Before establishing a multi-factor regression model, use SPSS software to establish a curve regression model between each factor and the compressive strength of lightweight high-strength concrete, and judge according to the decisive coefficient R^2 value. The functional relationship between a single index and compressive strength, thereby completing a multivariate nonlinear compressive strength prediction model. The cylinder compressive strength, water-binder ratio, cement dosage, coarse aggregate particle size and sand ratio were used as independent variables, and the compressive strength was used as the dependent variable for regression analysis. The regression function and deterministic coefficient R^2 of the influencing factors and compressive strength are shown in Table 3.

Table 3. Regression function and coefficient of determination R^2.

Influencing factors	Correspondence function	R^2
Cylinder compression strength	Logarithmic function	0.991
Aggregate size	Quadratic function	0.972
Sand rate	Linear function	0.975
Water glue ratio	Exponential function	0.999
Cement consumption	Logarithmic function	0.997

In Table 3, each R^2 value is greater than 0.9, which proves that the regression correlation is significant. According to the analysis in Table 3, the smaller the water-binder ratio, the greater the compressive strength; the effect of the amount of cement on the compressive strength of lightweight high-strength concrete increases linearly in the early stage, but the compressive strength is also constrained by aggregate strength. Therefore, the impact of the two compressive strengths rises to a certain maximum point and tends to be stable; the impact of cylinder compressive strength on the compressive strength of lightweight high-strength concrete, after the rapid growth in the early stage reaches a certain maximum, is affected by the strength of cement stone It tends to be stable after the restriction of the particle size; the impact of the particle size on the compressive strength of the coarse aggregate first increases and then decreases; the impact of the sand rate on the compressive strength, increase the sand rate, and sand on the basis of a reasonable sand rate If the ratio value is too large, the amount of coarse aggregate in the concrete will decrease and the concrete strength will decrease accordingly. On the contrary, if the sand ratio value is too small, the concrete strength will increase.

In section 2.2, the coarse aggregate particle size, water-binder ratio, cement dosage, sand ratio, external admixture and different coarse aggregate barrel compressive strengths with different dosages were studied, and the compressive strengths at different ages were analyzed changing trend. The curve regression model between each factor and the compressive strength of lightweight and high-strength concrete was established by SPSS software, and the functional relationship between a single index and the compressive strength could be judged according to the R^2 value of the decisive coefficient, as shown in Table 3. The analysis in Table 3 shows that the above factors will affect the strength of lightweight high-strength concrete. Therefore, the establishment of the strength prediction model of lightweight high-strength concrete requires comprehensive consideration of multiple factors that affect its strength. According to the functional relationship between a single factor and 28 days strength of lightweight high-strength concrete obtained from the analysis, each specific mathematical model can be obtained, and then these models are superimposed to establish a multivariate nonlinear mathematical model. Coarse aggregate barrel compressive strength, coarse aggregate particle size, water-binder ratio, cement dosage and sand ratio are used as separate indicators, and combined with the various influencing factors in Table 3 and the regression function of compressive strength, the relationship is established. In order to simplify the methods and steps in the regression analysis of nonlinear equations, the logarithmic function method is adopted to linearly transform the equations. Finding the natural logarithm of both sides of the equation at the same time, we can get formula 1:

$$y = b_0 + \log_{b1}^{x1} + b_2 x_2^2 + b_3 x_2 + b_4 x_3 + b_5^{-x_4} + \log_{b_6}^{x_5}, \tag{1}$$

where: x_1 is the cylinder compressive strength; x_2 is the aggregate particle size; x_3 is the sand ratio; x_4 is the water-binder ratio; x_5 is the amount of cement; b_k is the regression coefficient, (k = 0, 1, 2, 3, 4, 5, 6)

Use the nonlinear analysis command in Matrix Laboratory to solve the above model, choose the nlinfit command to solve the regression coefficients in the multiple nonlinear model, and establish the parameter estimation of the multiple nonlinear regression model as shown in Table 4. In Table 4, the observed value t of the statistic in the significance test of the regression coefficient of the five variables is greater than the significance level Sig., so the null hypothesis is rejected. The partial regression coefficient is significantly different from 0. The linear relationship between the four explanatory variables and the explained variables is significant, so the independent variables are kept in the equation and are not eliminated.

Table 4. Parameter estimation of multiple nonlinear regression model.

parameter	Parameter Estimation	Standard error	t	Sig.
intercept	1.46	0.03	143.25	0
x_1	18.31	2.93	6.26	0.03
x_2^2	21.6	0.01	3.01	0.04
x_2	–3.28	1.10	2.99	0.06
x_3	–71.12	12.50	5.70	0.05
x_4	1.36	4.73	4.32	0.04
x_5	20.48	6.30	3.25	0.02

According to the parameters in Table 4, the predictive model of the compressive strength of the multivariate nonlinear lightweight high-strength concrete is obtained as formula 2:

$$y = 1.46 + 18.31\ln^{x_1} + 21.6x_2^2 - 3.28x_2 - 71.12x_3 + 1.36^{-x_4} + 20.48\ln^{x_5}. \quad (2)$$

In the formula: x_1 is the cylinder compressive strength; x_2 is the aggregate particle size; x_3 is the sand ratio; x_4 is the water-binder ratio; x_5 is the amount of cement.

3. Results and Discussion

3.1. Model validation

The RMSE (Root Mean Square Error) is used to evaluate the difference between the simulated value and the measured value to verify the rationality of the prediction model for the compressive strength of lightweight high-strength concrete. The RMSE is expressed as formula 3, and the comparison between the measured strength value and the model simulation value is shown in Table 5.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(p_i - o_i\right)^2}{n}}. \quad (3)$$

In the formula: n is the total number of data points; p_i is the simulated value; o_i is the measured value.

According to Table 5, the maximum and minimum RMSE of the compressive strength value predicted by the model and the measured value are 1.05 MPa and 0.96 MPa. 15 sets of data are randomly selected from 30 sets of tests for verification. the R^2 values are 0.96 and 0.92 respectively, which are both higher than 0.9, indicating that the corresponding relationship between the measured value and the simulated value is good, the error is small, and the prediction accuracy of the model is high. Therefore, the proposed compressive strength prediction model.

Table 5. Model simulation compressive strength value and RMSE of measured value.

No.	RMSE/MPa	R^2
1	1.02	0.96
2	1.05	0.93
3	0.97	0.92
4	1.01	0.93
5	0.96	0.96

3.2. Comparison between prediction models

In order to verify the accuracy of the prediction model for compressive strength and the superiority of prediction compared with other models, experiments are needed. In the indoor test, in order to avoid the contingency of the measured values of the compressive strength, 18 standard specification specimens were made, each with a side length of 150 mm. Every 3 specimens are a group, and the average value of the compressive strength of the 3 specimens is taken as the actual measured value of compressive strength. In the test, choose the same cylinder compressive strength, aggregate particle size, sand ratio, water-binder ratio and cement dosage, and the test environment temperature is 20 °C. Compare the measured value of compressive strength and the predicted value of the compressive strength of lightweight high-strength concrete. And J. Shen's [31] concrete compressive strength prediction model prediction value, as shown in Fig. 6 (the figure number will be changed in the following), the abscissa is the number of the 6 groups of specimens, and the ordinate is the compressive strength $f_{cu.k}$, draw the compressive strength value curve under different test piece numbers. It can be seen from Fig. 6 that the predicted model compressive strength curve is closer to the actual measured compressive strength curve than the J. Shen model compressive strength curve. The predictive model has better practicability. At the same time, because the cylinder compressive strength, aggregate particle size, sand ratio, water-binder ratio and the amount of cement in the 6 groups of specimens have different effects on the compressive strength, the predicted value of the compressive strength of the proposed model will be low. In the case of the actual measured value or higher than the actual measured value. To obtain more accurate prediction results, response surface analysis is required to determine the precise applicable conditions of the proposed model. That is, the proposed model predicts the most accurate when the cylinder compressive strength, aggregate particle size, sand ratio, water-binder ratio and cement dosage are used.

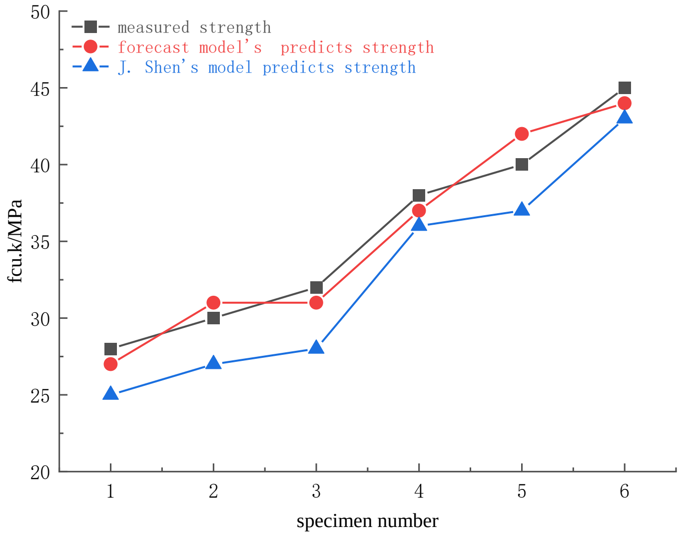

Figure 6. Comparison of predicted compressive strength

3.3. Determination of the applicable conditions of the model

In order to make the model have a higher evaluation accuracy, the surface analysis method is used to determine the applicable conditions of the model. Based on domestic and foreign experience and the characteristics of lightweight high-strength concrete, the value ranges of the five parameters in the model are set as followed: the cylinder compressive strength range is 3.2 MPa~6.6 MPa; the coarse aggregate particle size is 5 mm~25 mm The range of sand ratio is 26 %~44 %; the amount of cement is 450 Kg/m^3 ~550 Kg/m^3; the water-binder ratio is within 0.28~0.4.

In order to facilitate the drawing of test records, the cylinder compressive strength, coarse aggregate particle size, sand ratio, cement dosage and water-binder ratio are represented by symbols in order: CSS, AS, SR, CC and WGR; the codes in the response surface test are in order A, B, C, D, E. According to the number and range of the parameters, select the response surface test with 5 factors and 3 levels. The coding levels and values are shown in Table 6.

Table 6.Coding level and value.

Coding level	A（CSS/ MPa）	B（AS/mm）	C（SR/%）	D（CC/Kg/m³）	E（WGR）
-1	3.2	5	26	450	0.28
0	4.9	15	35	500	0.34
1	6.6	25	44	550	0.4

When the coding level of sand ratio, cement dosage and water-binder ratio is 0, the response surface of design cylinder compressive strength (MPa) and coarse aggregate particle size (mm) against compressive strength is shown in Fig. 7. In Fig. 7, CCS stands for Cylinder compression strength, AS stands for Aggregate size. When the cylinder compressive strength is between 3.2 MPa and 4.9 MPa, the compressive strength increases faster than 4.9 MPa or more. The reason is that in high-strength concrete, after the cylinder compressive strength reaches a certain value, the compressive strength is restricted by the strength of light aggregates and continues to increase. High cylinder compressive strength has little effect on changes in compressive strength, so when the cylinder compressive strength is above 4.9 MPa, the response of compressive strength is low. As the particle size of the coarse aggregate increases, the compressive strength gradually decreases, and the larger the particle size, the faster the rate of decrease. The reason is that the larger the particle size, the faster the particles move in the concrete mixture, resulting in the uneven distribution of particles seriously affects the compressive strength. Therefore, when the particle size is 15 mm or more, the response to compressive strength is more sensitive.

When the coding level of cylinder compressive strength, coarse aggregate particle size and water-binder ratio is 0, the response surface of design sand ratio (%) and cement dosage (Kg/m³) compressive strength is shown in Fig. 8. In Fig. 8, CC stands for Cement consumption, and SR stands for Sand rate. As the sand ratio increases, the compressive strength gradually increases. When the sand ratio exceeds 35 %, the increase in compressive strength tends to be flat, and the sand ratio begins to decrease after it exceeds 39 %. The reason is the larger sand ratio. The proportion of lightweight aggregates can be reduced, thereby increasing the compressive strength. If the sand ratio is too large, the concrete will be easily segregated and its structure will be uneven. At this time, the compressive strength will decrease and the concrete will easily collapse. Therefore, when the sand ratio is below 35 %, the response to compressive strength is higher. Increasing the amount of cement can increase the compressive strength, but after 500 Kg/m³, the increase in compressive strength becomes smaller. The reason is that the excessive amount of unilateral cement will increase the heat of hydration, causing the internal temperature difference of the concrete to be too large, and cracks may occur. Which affects the improvement of compressive strength, at this time the response of cement dosage to compressive strength is low.

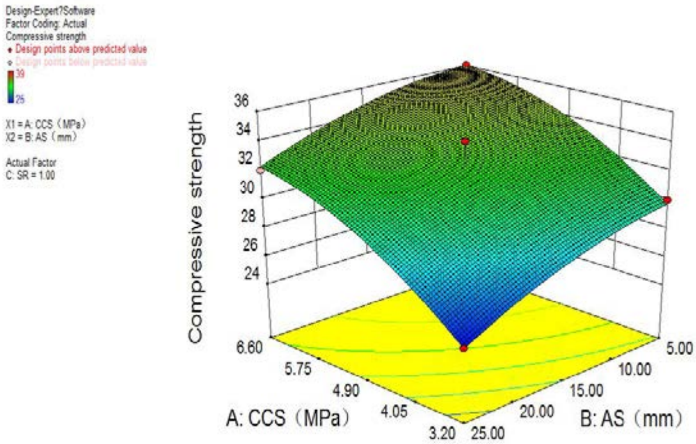

Figure 7. Response surface of A and B compressive strength.

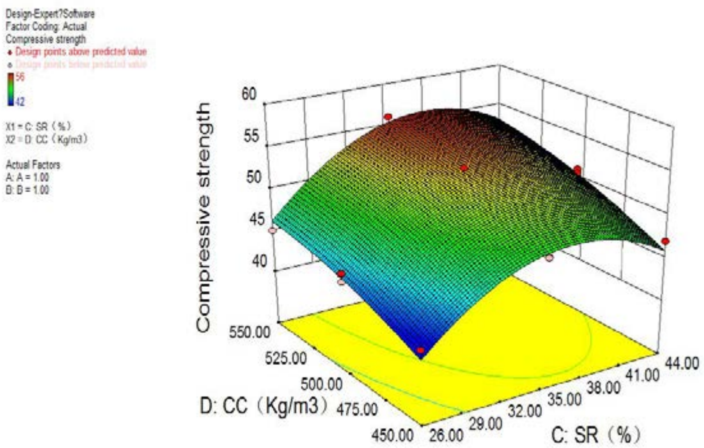

Figure 8. Response surface of C and D compressive strength.

When the coding level of cylinder compression strength, coarse aggregate particle size and sand ratio is 0, the response surface of the designed cement dosage (Kg/m³) and water-binder ratio to the compression strength value is shown in Fig. 9. In Fig. 9, CC represents Cement consumption, WGR represents Water glue ratio. As the water-to-binder ratio increases, the compressive strength gradually decreases, and the larger the water-binder ratio, the faster the strength decreases. The reason is that a larger water-binder ratio will significantly increase the fluidity of the cement paste and cause the slurry to drip severely. The adhesion between the aggregates becomes poor, resulting in a rapid decrease in compressive strength. Therefore, when the water-binder ratio is greater than 0.34, the response to compressive strength is higher.

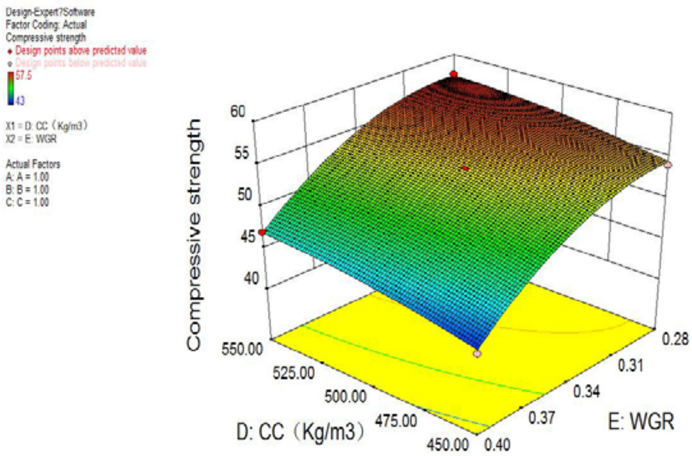

Figure 9. Response surface of D and E compressive strength.

Combining the analysis of the response surface above, it can be seen that if the response surface tends to be flat, it means that within the parameter value range corresponding to the surface, the compressive strength cannot change synchronously with the parameter value, and the compressive strength has a low response to parameter changes. At this time, the prediction accuracy of the compressive strength prediction model of lightweight high-strength concrete is low. If the slope of the response surface is large, the compressive strength will change significantly, and the corresponding parameter value range will be more suitable for model prediction. According to the results of response surface analysis, the cylinder compressive strength is between 3.2 MPa～4.9 MPa, the coarse aggregate particle size is between 15 mm～25 mm, the sand ratio is between 26 %～35 %, the amount of cement is between 450 Kg/m^3 ～500 Kg/m^3 , and the water-binder ratio is between the parameter value range from 0.34 to 0.4 is the optimal prediction space of the model. When the five parameters are in the optimal prediction space at the same time, the prediction level of the model is the best.

4. Conclusions

1. Using cluster analysis method, it is proposed that the cylinder compressive strength, water-binder ratio, cement dosage, coarse aggregate particle size and sand ratio in clusters 2 and 3 are the five key factors that affect the compressive strength.

2. The R^2 value of the single-factor prediction model for the compressive strength of lightweight high-strength concrete is greater than 0.9, which proves that the regression analysis of the compressive strength, water-binder ratio, cement dosage, coarse aggregate particle size, sand ratio and compressive strength is reasonable.

3. A multivariate nonlinear lightweight high-strength concrete compressive strength prediction model is established, and the corresponding coefficients of the model are 1.46, 18.31, 21.6, –3.28, –71.12, 1.36 and 20.48.

4. In the comparison between the model prediction and the measured value, the root mean square error RMSE is lower than 1.05 MPa, and the prediction accuracy of the proposed compressive strength prediction model is higher.

5. The applicable conditions of the prediction model are determined. The cylinder compressive strength is between 3.2 MPa~4.9 MPa, the coarse aggregate particle size is between 15 mm~25 mm, the sand ratio is between 26 %~35 %, and the amount of cement is between 450 Kg/m^3~500 Kg/m^3. The parameter value range when the water-binder ratio is 0.34~0.4 is the optimal prediction space of the model. When the 5 parameters are in the optimal prediction space at the same time, the prediction level of the model is the best.

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Information about authors:

***Lina Zhang**, PhD*
ORCID: https://orcid.org/0000-0002-2024-3806
E-mail: 53860470@qq.com

***Dongpo He**,*
ORCID: https://orcid.org/0000-0003-2427-1086
E-mail: hdp@nefu.edu.cn

***Wenyuan Xu**, PhD*
ORCID: https://orcid.org/0000-0002-1397-9305
E-mail: xuwenyuan@nefu.edu.cn

***Qianqian Zhao**, PhD*
ORCID: https://orcid.org/0000-0002-0209-4181
E-mail: 492954791@qq.com

***Shubin Teng**,*
ORCID: https://orcid.org/0000-0002-2258-3708
E-mail: 53860470@qq.com

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