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RESPONSE SURFACE METHOD TO OPTIMISE CONCRETE STEAMING PROCESS PARAMETERS

LANDI ZHENG*, CHUNMING XIAO**, ***, #MINXIA ZHANG*, SHENGRONG LIAO**, ***, ZHE ZHOU**, ***

*School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454000,
**Road and Bridge International Co., Ltd, Beijing 101100, China,
***Road & Bridge Southern China Engineering Co., Ltd. Zhongshan 528400, China

#E-mail: zhangminxia@126.com

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The present paper adopts the response surface method to optimise the performance of steam-cured concrete by taking the compressive strength of the steam-cured concrete as the main property. Based on the single-factor test, a constant temperature time, constant temperature, heating rate, and cooling rate were selected as independent variables, and the strength of the steam-cured concrete was selected as the response value. A four-factor, three-level response surface centre combination test was designed to analyse the effects of the different factors on the strength of the steam-cured concrete. The optimum steam curing parameters for the strength of steamed concrete are a constant temperature time of 28 h; a constant temperature of 43 °C, a heating rate of 12 °C·h^{-1} and a cooling rate of 15 °C·h^{-1}. Under these conditions, the theoretical strength of the concrete is 52.9 MPa. The experimental results were verified under these conditions, and the strength of the steamed concrete was 53.8 MPa, which is basically consistent with the theoretical prediction of the response surface model and can be used for the actual production, it can provide some technical support for the steam curing technology of concrete in practical engineering.

INTRODUCTION

Steam curing is a method to accelerate the hydration of cement in concrete by using hot water vapour, which has the advantages of significantly improving the early strength of concrete, accelerating the mould turnover, shortening the production cycle and improving the production efficiency, and is widely used in the production of precast concrete components [1-3]. The parameters include a constant temperature time, a constant temperature, heating rate, and cooling rate; the change of steam curing parameters will directly affect the hydration of cement and its components and the characteristics of the hydration products [4-7].

If the steam curing parameters are not set properly; not only can they not improve production efficiency, but they are also responsible for quality defects, the deterioration of concrete performance, wasting energy, and other problems [8-10]. As a result, it was necessary to analyse the factors influencing the performance of steam curing on concrete, to provide a reference basis for the reasonable selection of steam curing parameters and to improve the concrete quality.

Famy et al. [11] showed that the longer the constant temperature maintenance time, the higher the strength of the release, but the greater the damage to the structure as the constant temperature time increases. The generated shielding film is covered with the unhydrated products, resulting in incomplete hydration, which creates a huge potential problem for the later stages and requires higher costs to produce. Likewise, as the curing temperature increases, the number of microcracks and the chance of larger microcracks will be significantly increased, leading to a tendency for the strength of the steamed concrete to decrease with an increasing constant temperature [7, 12, 13].

The results of X. Ping's study showed that too fast a heating rate would lead to a large increase in the harmful pores in the concrete, resulting in a significant decrease in the mechanical properties of the concrete. In order to optimise the unfavourable problems encountered in the steaming process, scholars at home and abroad have conducted a series of research studies on steaming systems, the mix proportion and other aspects. Jinyan Shi [14] studied the effect of the curing system on the long-term mechanical strength of steam-cured concrete, and the results showed that decreasing the heating and cooling rates could improve the late strength of the steam-cured concrete. With an increase in the constant temperature, the concrete obtained a higher strength in the early stage. However, too high a constant temperature increases the expansion and deformation of the gas-liquid phase inside the concrete, which results in larger expansion stresses and increases the size of the pores or microcracks in the concrete, which adversely affects the concrete strength [15,16]. Studies have shown that when extending the time of the constant temperature and increasing the constant temperature, it will not only adversely affect the strength of concrete, but also cause a waste of energy and lead to an increase in the project costs [17]. Therefore, it is very meaningful to optimise the steam curing process parameters of concrete. The response surface optimisation method is a commonly used test optimisation method, which is widely used in agriculture, biology, food, engineering and other fields [18-21]. It is characterised by a short experimental period, strong applicability, good predictive performance, and the ability to reveal the interaction of multiple influencing factors.

The present article first performs single-factor tests to determine the optimal values for the constant temperature time, constant temperature, heating rate, and cooling rate. Then it uses a response surface analysis to establish the relationship between the compressive strength and steam hardening parameters. Subsequently, it determines the economic benefits of the practical steam curing system by optimising the appropriate conditions of the variables.

EXPERIMENTAL

Materials

The cement is PO 42.5 Ordinary Portland cement produced by China Resources Cement Plant, with a 28-d compressive strength of 55 MPa and fineness of 2.0 %; the fine aggregate is manufactured sand with a fineness modulus of 2.64 and a mud content of 0.5 %; the coarse aggregate is Shaanxi Xianyang limestone, a 5-10 and 10-20 two-gradation mix, and the water reducing agent is polycarboxylate superplasticiser produced by Sobute New Materials Co., Ltd. The water reduction rate ≥ 30; tap water was used. According to JGJ 55-2011 “Ordinary Concrete Proportioning Design Regulations”, the proportion for this test was designed with C50 as the base proportion and the water-cement ratio was 0.33. The test proportion is shown in Table 1.

Fabrication process

Process: Mixing the C50 concrete → In the mould → Removing the mould → Moving into the steam curing box → Conducting the com-pressive strength test after reaching the age of steam curing → Recording the test data.

Equipment: SJD-60 single-shaft concrete mixer, ZKY-400B steam quick curing box.

Single-factor experimental design

The concrete was configured according to the preparation process, and the basic steam curing parameters of the concrete were: constant temperature time of 18 h, constant temperature of 50 °C, heating rate of 10 $°C \cdot h^{-1}$ and cooling rate of 10 $°C \cdot h^{-1}$. Based on the basic steam curing parameters, a single-factor test was conducted by changing the constant temperature time, constant temperature, heating rate and cooling rate as the investigating factors, with the strength as the index. The effect of the different single-factor conditions on the concrete’s strength was analysed, and the size of the change of the four factors was optimised separately to determine their effect on the concrete’s strength.

RESULTS

Effect of the constant temperature time on the strength of the steam-cured concrete

Keeping the other parameters unchanged, the constant temperature was 50 °C, the heating rate was 10 $°C \cdot h^{-1}$ and the cooling rate was 10 $°C \cdot h^{-1}$. The constant temperature time was set to 6 h, 12, 18, 24, 30, 36, 42, 48 and 54 hours, and the strength was used as the evaluation index for the single-factor test.

From Figure 1, it can be seen that the strength of the steam-cured concrete increased rapidly in the first period with the increase in the constant temperature time. This is mainly because the longer the temperature curing time, the higher the degree and quantity of the cement hydration, while more mineral admixtures in the concrete participate in the secondary hydration reaction, the higher the structural strength of the concrete [22, 23]. When the constant temperature is 6 h, the cement hydration reaction is not sufficient because the curing time is too short, resulting in a lower concrete strength; when extending the time, the strength continuously increases, and when the constant temperature time is 12 h, the strength increases by 30 % compared to the demoulded strength at 8 h, and when the time is 24 h, the strength increases by 10 % compared to 12 h. When the constant temperature time is higher than 30 h, the growth rate becomes slow. The constant temperature time of 36 h strength increased the strength by 5 % compared to 30 h, while 54 h increased it by only 3 % compared to 48-h

Table 1. Mix proportions.

Material	Cement	Manufactured sand	Gravel (5-10 mm)	Gravel (10-20 mm)	Water	Water reducer
Material consumption per $m^3 \cdot kg^{-1}$	480	785	200	800	160	5.8

strength. This is mainly because the late steam curing concrete hydration reaction has completed most of the late strength growth.

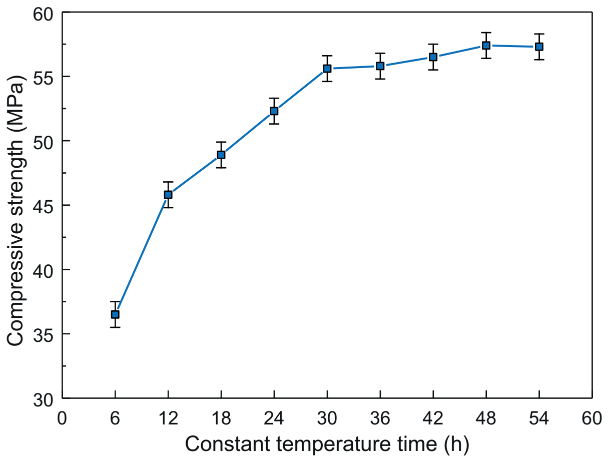

Figure 1. Effect of the constant temperature time on the strength of the steam-cured concrete.

From the above results, it can be seen that the longer the temperature maintenance time the higher the strength, but the enhancement rate gradually slows down after 30 h. If the steam curing time is too long, it will further damage the structure, increase the internal porosity and cracks, and generate a protective film covering the unhydrated cement, causing an incomplete hydration reaction, which will cause a huge hidden problem for the late stage. Moreover, the longer the constant temperature steaming time, the greater the cost of the fuel consumed. The constant temperature curing of 30 h met the required strength requirements of the project, reducing the energy consumption by about 20 % compared with the same curing conditions of 42 h. Therefore, it is reasonable to select 30 h as the constant temperature time in this paper.

Effect of the constant temperature on the strength of the steam-cured concrete

Keeping the other parameters unchanged, the constant temperature time was 18 h, the heating rate was 10 °C·h^{-1} and the cooling rate was 10 °C·h^{-1}. The constant temperature was set to 40 °C, 50 °C, 60 °C, 70 °C and 80 °C, and the strength was used as the evaluation index for the single-factor test.

As can be seen from Figure 2, with the increase in the constant temperature of the concrete curing, the compressive strength of the concrete showed an increasing and then decreasing trend. That is because at higher temperature, the solubility of the cement minerals increases, which accelerates the hydration reaction of the cement and, thus, the speed of the concrete hardening. However, the law of cement hydration reaction did not fundamentally change, but only the duration of each hydration period was shortened with the increase in temperature [24, 25]. When the constant temperature is too low, there is no excessive elevation of the hydration reaction of the cement, which leads to the slow hydration rate of the cement; when the constant temperature exceeds 70 °C, it reduces the compressive strength of the concrete. Meanwhile, for ordinary Portland cement, although the higher temperature accelerates the cement hydration, the effect of the temperature accelerated the cement hydration process gradually decreases with the continuing curing time. The shielding film formed due to the rapid local hydration reaction, which is denser and less permeable compared to that formed at lower temperature maintenance, which directly leads to any further hydration process becoming difficult. The rate of the hydration reaction becomes slower in the later stages of cement hardening and the degree of hydration of the cement decreases, thus, making the later strength growth lower than that at standard curing. Although the higher the temperature, the higher the strength, but when the temperature exceeds a certain limit, it also leads to the late strength of the concrete decreasing. Therefore, 50 °C was chosen as the constant temperature in this paper.

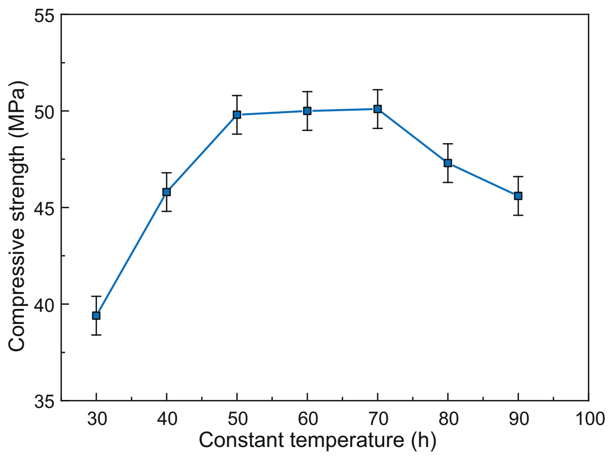

Figure 2. Effect of the constant temperature on the strength of the steam-cured concrete.

Effect of the heating rate on the strength of the steam-cured concrete

Keeping the other parameters unchanged, a constant temperature of 50 °C, a constant temperature time of 18 h, and a cooling rate of 10 °C·h^{-1} were used, and the heating rate was set to 5, 10, 15, and 20 °C·h^{-1}, and the strength was used as the evaluation index for the single-factor test.

As can be seen from Figure 3, the strength of the steamed concrete first increases with the slowing down of the heating rate under the premise that the constant temperature of 50 °C is maintained for 18 h, and the growth slows down after the heating rate reaches

10 °C·h^{-1}. When the heating rate is faster, such as the rate of heating up to 20 °C·h^{-1}, the strength appears to decrease. When the heating rate is 30 °C·h^{-1}, the concrete strength is significantly lower than the rest of the group of concrete, it can be seen that the early too high heating rate is not conducive to the growth of the concrete strength. Therefore, the rate of heating needs to be controlled within a certain range, otherwise it will cause damage to the structure and the strength of the concrete. This is mainly due to too fast of a heating rate, while accelerating the hydration reaction of cement, will cause expansion deformation, the temperature stress generated at this time causes damage to the internal structure of the concrete, while too fast of a hydration reaction will lead to the generation of larger holes, internal structure deterioration and other phenomena to the internal structure of the concrete, where the development of the later performance and strength is more unfavourable [26]. Although a too slow of a heating rate does not affect the strength development of the concrete, it is not conducive to the turnover of the formwork and increases the production cost at this stage. Considering the practical situation, 10 °C·h^{-1} was chosen as the heating rate and about 2 ~ 3 hours as the heating time in this paper.

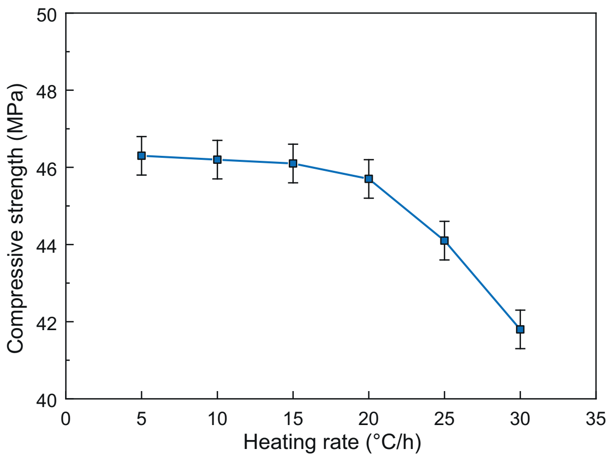

Figure 3. Effect of the heating rate on the strength of the steam-cured concrete.

Effect of the cooling rate on the strength of the steam-cured concrete

Keeping the other parameters unchanged, the constant temperature was 50 °C, the constant temperature time was 18 h, the heating rate was 10 °C·h^{-1}, and the cooling rate was set to 5, 10, 15, and 20 °C·h^{-1}, and the single-factor test was conducted with the strength as the evaluation index.

As can be seen from Figure 4, the concrete specimens were cooled down at the rates of 10, 20 and 30 °C·h^{-1}, and the cooling rate had little effect on the ejection strength. The compressive strength of the samples cooled at 10 °C·h^{-1} was 1.08 % higher than that of 20 °C·h^{-1}, and the 3-d strength was about 1.02 % higher. Because the cooling of the concrete reached a higher strength, the speed of cooling on the concrete strength is less, but the cooling rate for bulk concrete should still not be too fast; otherwise, it will increase the brittleness of the concrete, produce directional holes, cracking and other harmful phenomena, reduce the strength of the structure, affecting the after hydration. On the other hand, if the cooling rate is too slow, it will reduce the flow efficiency of the mould, resulting in high costs and lower construction efficiency. Therefore, based on the comprehensive practical results, a cooling rate of 10 °C·h^{-1} was selected in this paper.

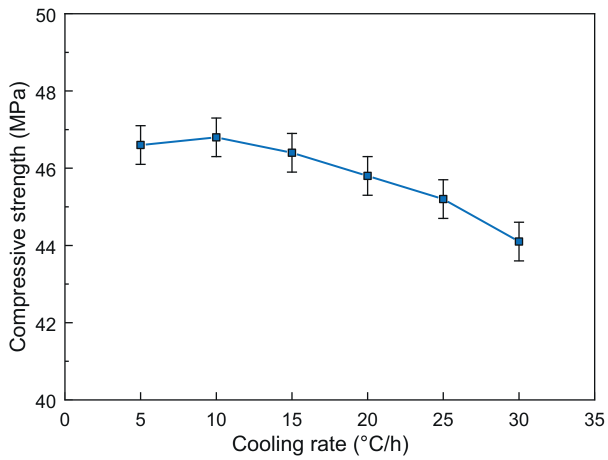

Figure 4. Effect of the cooling rate on the strength of the steam-cured concrete.

Optimisation and analysis of the concrete steaming process based on the response surface methodology

Response surface experimental design

Based on the single-factor test, the best value obtained from the compressive strength test of the autoclaved concrete was taken as the reference, and one was taken as the response surface level on its left and right, too. The response surface analysis of four factors and three levels was carried out with the compressive strength as the response value, and the design of the response surface test factors and levels is shown in Table 2.

Table 2. Response surface test factor level table.

Independent variable	Variable level		
	Low (-1)	Middle (0)	High (+1)
A – Constant temperature time (h)	24	30	36
B – Constant temperature (°C)	40	50	60
C – Heating rate (°C·h^{-1})	5	10	15
D – Cooling rate (°C·h^{-1})	5	10	15

Table 3. Response surface experiment design and results.

Run	A – Constant temperature time (h)	B – Constant temperature (°C)	C – Heating rate (°C·h^{-1})	D – Cooling rate (°C·h^{-1})	Compressive strength (MPa)
1	36	40	10	10	53.8
2	30	50	15	5	54.5
3	24	60	10	10	49.8
4	30	40	15	10	50.9
5	24	40	10	10	45.5
6	24	50	5	10	48.9
7	24	50	15	10	48.1
8	30	60	10	5	57.8
9	24	50	10	15	48.5
10	30	60	10	15	57.5
11	36	50	15	10	57
12	30	50	5	15	56.1
13	24	50	10	5	48.7
14	36	50	10	5	57.3
15	30	50	5	5	56.7
16	30	60	5	10	57.9
17	30	50	10	10	55.9
18	36	50	5	10	57.4
19	30	40	10	15	51.8
20	30	50	10	10	56.2
21	30	50	10	10	56.5
22	36	50	10	15	56.9
23	30	40	10	5	51.7
24	30	60	15	10	54.5
25	30	50	10	10	56.6
26	30	40	5	10	50.7
27	30	50	15	15	56.2
28	36	60	10	10	57.1
29	30	50	10	10	56.6

Table 4. Regression model variance analysis.

Source	Sum of Squares	Degrees of freedom	Mean sum of Square	F-Value	P-Value
Model	370.45	14	26.46	63.19	< 0.0001
A	208.33	1	208.33	497.48	< 0.0001
B	76.00	1	76.00	181.49	< 0.0001
C	3.52	1	3.52	8.41	0.0117
D	0.0075	1	0.0075	0.018	0.8954
AB	0.25	1	0.25	0.60	0.4526
AC	0.040	1	0.040	0.096	0.7618
AD	0.01	1	0.01	0.024	0.8794
BC	3.24	1	3.24	7.74	0.0147
BD	0.040	1	0.040	0.096	0.7618
CD	1.32	1	1.32	3.16	0.0973
A^2	62.70	1	62.70	149.73	< 0.0001
B^2	22.42	1	22.42	53.54	< 0.0001
C^2	2.51	1	2.51	5.99	0.0282
D^2	0.003045	1	0.003045	0.007271	0.9333
Residual	5.86	14	0.42	–	–
Lack of Fit	5.49	10	0.55	5.90	0.0509
Pure Error	0.37	4	0.093	–	–
Cor Total	376.31	28		–	–

R^2 = 0.9844 R^2 (Adj) = 0.9688 C.V. = 1.2 % (P-Values < 0.05 were considered significant)

Response surface test results

The response surface analysis was performed on the selected four factors using Design Expert 10.0 software, and the results of the response surface tests are shown in Table 3.

Regression analysis and analysis of variance

The experimental data in Table 3 were analysed using Design Expert 10.0 software, and the test data were fitted by quadratic polynomial regression to obtain the regression model equations for the compressive strength and constant temperature time (A), constant temperature (B), heating rate (C), and cooling rate (D):

$$\text{Compressive strength} = 56.36 + 4.17A + 2.52B - 0.54C + 0.025D - 0.25AB - 0.1AC - 0.05AD - 0.9BC - 0.1BD + 0.58CD - 3.11A^2 - 1.86B^2 - 0.62C^2 - 0.022D^2.$$

An analysis of variance was performed on the regression model, and the results are shown in Table 4. The p-values reflect the significance of each coefficient in the model; the larger the p-value, the less significant the corresponding coefficient; conversely, the larger the p-value, the more significant the corresponding coefficient.

As can be seen from Table 4, the regression model ($P < 0.0001$) is extremely significant, and the lack of fit ($P = 0.0509 > 0.05$) is not high, indicating that the experimental results are a little distorted by other factors. The model has good stability, and the optimisation of the steamed concrete process parameters can be carried out. The model correlation coefficient (R^2) and correlation correction coefficient ($R^2(Adj)$) were 0.9844 and 0.9688, respectively, which were similar and both were greater than 0.9, indicating that the experimental and predicted values under the optimal process conditions of the steam curing process had good correlation. The precision of the model fit was 28.747, which was greater than 4. It also indicated that the model is important for the prediction of compressive strength of the concrete. In addition, the low coefficient of variation (CV) of 1.2 % < 10 % indicates a good fit and high experimental accuracy and confidence, so the model can be used for the prediction and analysis of the steam curing process parameters.

Response Surface Interaction

Design Expert 10.0 software was used to fit the experimental data and establish the contour and response surface models, which can provide a more intuitive understanding of the effect of the steam curing parameters on the strength of the concrete. As can be seen in Figure 5, the response surface slope of the constant temperature time (*A*) and constant temperature (*B*) is steep, indicating that the interaction between *AB* has a significant effect level on the strength of the steam-cured concrete. The slope of the response surface of the heating rate (*C*) with the constant temperature time (*A*) and constant temperature (*B*), is steeper, indicating that the interaction between *CA* and *CB* has a more significant effect on the strength of the steam-cured concrete. The slope of the response surface of A with *D*, *B* with *D*, and *C* with *D* is slower, indicating that the interaction between them has a smaller effect on the strength of the steam-cured concrete.

From the response surface plots, it can be seen that the strength of the concrete increases with the increase in the constant temperature and time in the selected range of constant temperature and time. However, with the increase of both, the trend of the concrete strength growth becomes slower or no growth occurs.

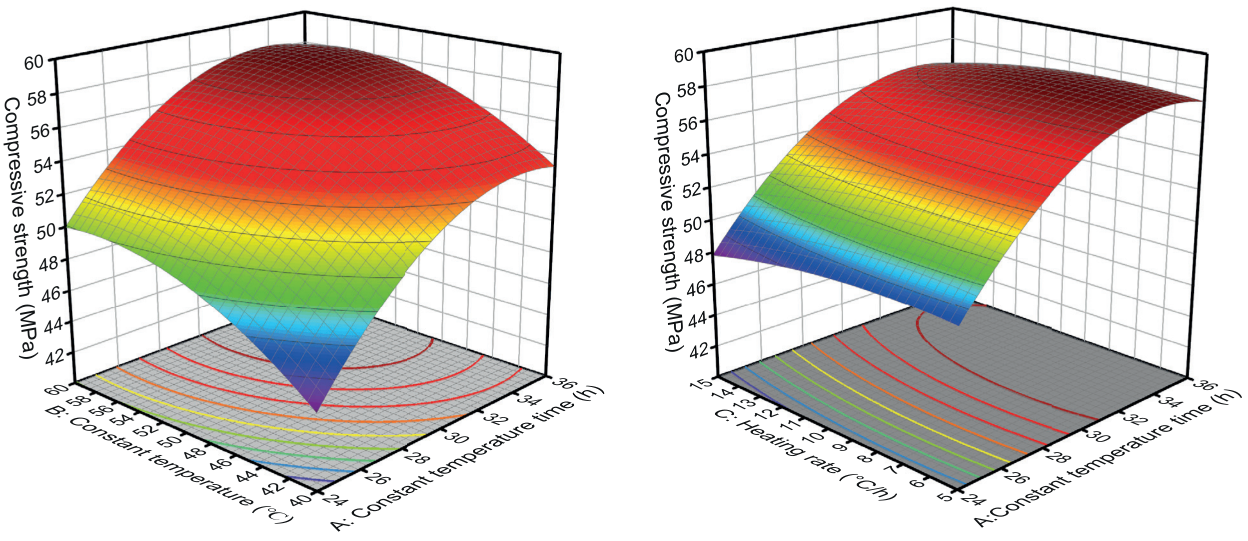

Figure 5. Response surface map of the interaction between the factors. *(Continue on next page)*

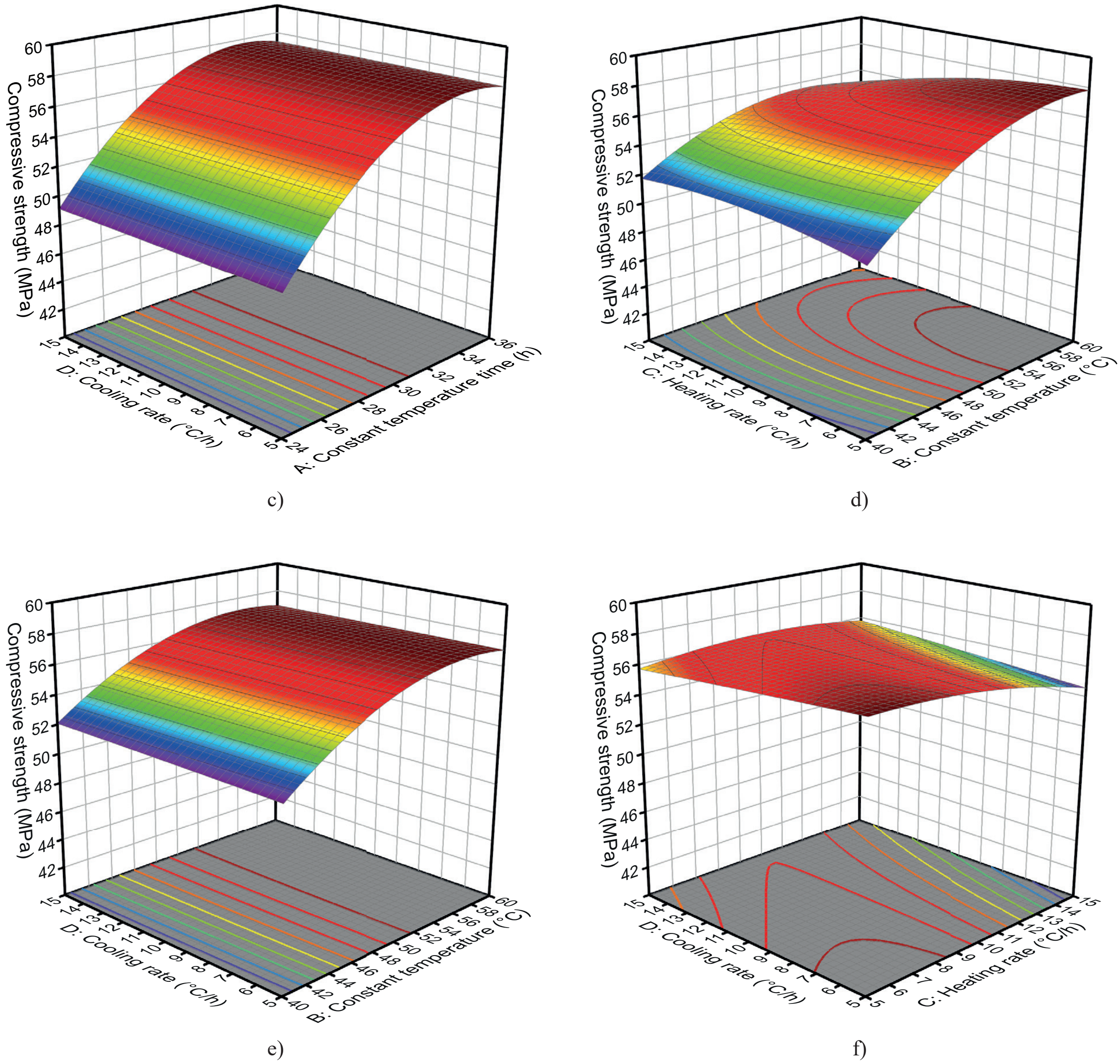

Figure 5. Response surface map of the interaction between the factors.

In the strength change of the steam-cured concrete, the surface along the axis of the constant temperature time is slightly steeper than the surface along the axis of the constant temperature, so the effect of the constant time is slightly greater than that of the constant temperature. In the selected range of the constant temperature time and heating rate, the strength of the concrete increases with the increase in the constant temperature time and heating rate. However, a heating rate greater than 20 $°C \cdot h^{-1}$ can cause a "structural damage" effect caused by the rapid heating rate of the concrete, which is detrimental to the development of the physical and mechanical properties of the concrete. The surface along the direction of the axis of the constant temperature time is steeper than the surface along the direction of the axis of the heating rate, so the effect of the constant temperature time is greater than that of the heating rate.

In the selected range of the constant temperature time and cooling rate, the strength of the steam-cured concrete increases with the increase in the constant temperature time, and the increasing trend becomes slower after a certain strength as when the concrete reaches a certain strength, it can resist deformation, so the effect of the cooling rate will not change significantly, and the arc of the change of the constant temperature time curve is steeper than the cooling rate, indicating that the effect of the constant temperature time is more obvious. No significant effects on the strength of the steam-cured concrete occurred within the selected ranges of the constant temperature - rate of heating, constant temperature - rate of cooling, and heating - cooling rates. Overall, the order of the effects of the steam curing parameters on the strength of concrete was: constant temperature time > constant temperature > heating rate > cooling rate.

CONCLUSION

- The response surface optimisation results showed that: the compressive strength of the steam-cured concrete reached the optimum value when the constant temperature time was 28 h, the constant temperature was 43 °C, the heating rate was 12 $°C \cdot h^{-1}$ and the cooling rate was 15 $°C \cdot h^{-1}$.
- Based on the results of the single-factor test, the response surface method was used to optimise the concrete steaming process and to establish a quadratic regression equation model between the steam curing parameters and the compressive strength of concrete. The mathematical model is proved to be reliable and can be used for the prediction of the strength of steamed concrete and the optimisation of the process parameters.
- Through the response surface analysis of the steam curing parameters, the main effect relationships of the four steam curing parameters were determined as: constant temperature time > constant temperature > heating rate > cooling rate.

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