

Article

Study on the Performance Optimization of Plant-Growing Ecological Concrete

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Abstract: The response surface regression model of plant-growing ecological concrete is established based on the factors of the water–binder ratio, fly ash content, and design porosity, with 28-day compressive strength, connectivity porosity, and pH value as response variables. Based on optimizing the mix proportion with the regression model, different dosages of acetic acid are used as excitation agents to increase the compressive strength and reduce the alkalinity of plant-growing ecological concrete to enhance its service life and vegetation performance. The results show that the compressive strength of plant-growing ecological concrete with a water–binder ratio of 0.3, a fly ash content of 26%, and a design porosity of 22% was 10.32 MPa, the connectivity porosity was 20.00%, and the pH value was 11. After the addition of acetic acid at 0.4% of the mass of the cementitious material, the compressive strength increased by 40.29%, and the pH value decreased by 6.33%. This study proposes a cost-effective means and provides data support for the engineering application of plant-growing ecological concrete.

Keywords: plant growing ecological concrete; pervious concrete; mix proportion optimization; response surface method; acid-activated



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1. Introduction

Ecological concrete is an emerging, green, and sustainable concrete material that is widely used in the construction of road slopes, riverbank protection, urban landscapes, and ecological fish reefs [1–4]. Ecological concrete includes two types: eco-friendly load-reducing concrete and eco-compatible concrete. The former refers to concrete that, during production, transportation, use, demolition, and recycling, helps to save energy and resources, reduce pollutant emissions, absorb industrial waste, and minimize the impact on the ecological environment [5,6]. The latter refers to concrete that can reduce the impact on the ecological environment, absorb various pollution sources within the ecological environment, coexist harmoniously with organisms such as plants and animals, regulate ecological balance, and improve the ecological environment [7]. Vegetation concrete is a research direction within eco-compatible concrete. Yang [8] believe that vegetation concrete includes two main types: the first type is porous concrete structures dominated by coarse aggregates, and the second type focuses on planting soil as the main research object. To distinguish and incorporate the nomenclature of other scholars, this paper refers to the first type of coarse aggregate vegetation concrete as plant-growing ecological concrete and conducts research based on this. As shown in Figure 1, plant-growing ecological concrete can be simply viewed as aggregates formed by bonding a large amount of coarse aggregates with a small amount of cementitious materials.



Figure 1. Plant-growing ecological concrete.

Similar to pervious concrete, plant-growing ecological concrete is a porous concrete material made by mixing cementitious materials, aggregates, water, and additives. It typically uses single or binary particle-size coarse aggregates and contains a minimal amount of fine aggregates to ensure the formation of a honeycomb-like porous structure [9–11]. This allows it to provide suitable living spaces for animals, plants, and microorganisms, promoting ecological system regulation and increasing biodiversity. Traditional concrete structures have a heavy self-weight, high cost, and obvious signs of human alteration, which significantly undermine the functionality of rivers and green spaces as ecological corridors and nature reserves due to their poor permeability and ground hardening processes, causing severe damage to the ecosystems where the projects are located [12]. The interconnected porous structure of ecological concrete successfully resolves the contradiction between “greening and hardening,” providing ample pores for plant growth and runoff infiltration, thus achieving ecological water circulation and vegetation restoration functions while meeting the needs of engineering protection [13–15]. In the ecological rehabilitation process of riverbanks, desert sands, and exposed slopes, ecological concrete initially plays a role in flood control and drainage or sand fixation. Once vegetation cover meets the anchoring requirements, the less durable plant-growing ecological concrete naturally weathers and breaks apart, removing traces of human intervention and ultimately achieving the ecological restoration of natural landscapes.

The growth of plant root systems requires, on one hand, sufficient space along with good water permeability and aeration; on the other hand, it also requires a relatively suitable pH, which necessitates controlling the alkalinity of the concrete. Therefore, to meet the requirements for vegetation while achieving the necessary engineering strength, plant-growing ecological concrete imposes demands on pore structure and alkalinity control. This study first utilized the water–binder ratio, the replacement rate of fly ash, and the designed porosity as control parameters, with compressive strength, continuous porosity rate, and pH value as evaluation criteria. A total of 17 experimental groups involving three response factors at three levels and three response values were conducted using the design of experiments with response surface methodology; subsequently, the key properties of plant-growing ecological concrete were predicted using the established response surface regression model to obtain a suitable mix proportion; finally, to address the remaining issues of insufficient strength and excessive alkalinity, acetic acid was employed as an activator to enhance the performance. The abovementioned work aimed to explore the relationship between different response factors and values, to build a reasonable regression model, and to provide a cost-effective stimulation method in the hope of offering data support and reference for the practical engineering application of plant-growing ecological concrete.

2. Materials

- (1) Cementitious material: Ordinary Portland cement (P.O 42.5R) and Grade I fly ash were chosen, with specific test parameters as shown in Tables 1 and 2.

Table 1. Cement inspection indices.

Density ($\text{kg}\cdot\text{m}^{-3}$)	Standard Consistency /%	Specific Surface Area ($\text{m}^2\cdot\text{kg}^{-1}$)	Initial Setting Time /min	Final Setting Time /min	3-Day Compressive Strength /MPa	28-Day Compressive Strength /MPa
3040	27	384	172	230	27.3	52.6

Table 2. Fly ash inspection indices.

Fineness / μm	Water Requirements Ratio /%	SO ₂ Content /%	Free CaO Content /%	Cl [−] Content /%	CaO Content /%
≤ 45	93.02	2	0.65	0.01	6.7

- (2) Coarse aggregate: Natural pebbles with a single gradation ranging from 20.00 to 26.50 mm were selected, and their characteristics are elucidated in Table 3.

Table 3. Properties of coarse aggregate.

Pebble Size /mm	Packing Density ($\text{kg}\cdot\text{m}^{-3}$)	Compact Packing Density ($\text{kg}\cdot\text{m}^{-3}$)	Apparent Density ($\text{kg}\cdot\text{m}^{-3}$)	Bulk Density in the Loose State /%	Bulk Density in the Compacted State /%
20.00~26.50	1490	1660	2593	42.53	35.97

- (3) Admixture: A reinforcing agent for pervious concrete was adopted. The dosage of the enhancer is 3.3% of the mass of the binder material, and its specific components are shown in Table 4.

Table 4. Formulation of reinforcing agent (parts by weight).

Nano Silicon Powder	Water Reducer	Cellulose	Calcium Sulfate Crystal Whiskers	Trisodium Phosphate	Calcium Carboxylate	Alkaline Metal Carbonates	Formamide
50~80	10~15	2~4	8~10	5~8	1.5~5	2~6	0.5~2

- (4) Acetic acid: The composition of acetic acid is presented in Table 5.

Table 5. Composition of glacial acetic acid.

CH ₃ COOH	Cl [−]	SO ₄ ^{2−}	Fe	Cu	Pb	(CH ₃ CO) ₂ O
≥ 99.5	≤ 0.0001	≤ 0.0002	≤ 0.0001	≤ 0.00005	≤ 0.00005	≤ 0.02

- (5) Water: Sourced from the local tap water in Xinjiang.

In addition to glacial acetic acid, all the above material properties and dosage meet the requirements of pervious concrete specifications (JC_T 2558-2020) [16].

3. Methods

3.1. Response Surface Methodology

Response Surface Methodology (RSM) is an experimental design approach that uses logical experiment point selection to obtain data from a smaller number of experimental groups. It employs a multivariate regression quadratic equation to fit response factors and values, optimizing design objectives through the regression equation [17,18]. Compared to other experimental design methods, the regression model established by RSM can effectively reflect the interaction of multiple factors, thus precisely and effectively predicting various indicators of the research objective.

Box–Behnken design and Central Composite Design are commonly used response surface experimental design methods. The Box–Behnken design has fewer design points and lower operational costs than the Central Composite Design with the same number of influencing factors [19]. Its factor design levels are always three, and it never reaches a situation where all factor values are at extreme states. Therefore, this experiment establishes a regression model based on the Box–Behnken principle of response surface methodology.

3.2. Experimental Research

The experiment selected three influencing factors (water–binder ratio, fly ash content, and designed porosity) as response factors and three experimental values (compressive strength, continuous porosity, and pH value) as response values to determine the optimal mix proportion. The current general consensus is that the designed porosity of vegetated ecological concrete is generally between 20% and 30%. A porosity that is too low will restrict plant growth, while a porosity that is too high will result in insufficient concrete strength. Based on the research findings of Kováč, Zhu, Chen, and others [20–23], we conducted single-factor experiments on each of these three influencing factors and determined their reasonable value ranges. As shown in Table 6, the water–binder ratio, fly ash content, and designed porosity each have three levels, named W/B (0.25, 0.30, 0.35), F (10%, 20%, 30%), and P (22%, 26%, 30%), respectively. A total of 17 groups of mix proportions were obtained (including five sets of central point repeat experiments for error calculation) [24].

Table 6. Material consumption of mix proportion test.

Test	W/B	F /%	P /%	Cement /($\text{kg}\cdot\text{m}^{-3}$)	Coarse Aggregate /($\text{kg}\cdot\text{m}^{-3}$)	Fly Ash /($\text{kg}\cdot\text{m}^{-3}$)	Water /($\text{kg}\cdot\text{m}^{-3}$)
1	0.25	10	26	249	1627	28	69
2	0.35	10	26	231	1627	26	90
3	0.25	30	26	194	1627	83	69
4	0.35	30	26	180	1627	77	90
5	0.25	20	22	301	1627	75	94
6	0.35	20	22	278	1627	70	122
7	0.25	20	30	143	1627	36	45
8	0.35	20	30	132	1627	33	58
9	0.30	10	22	325	1627	36	108
10	0.30	30	22	253	1627	108	108
11	0.30	10	30	155	1627	17	52
12	0.30	30	30	120	1627	52	52
13	0.30	20	26	213	1627	53	80
14	0.30	20	26	213	1627	53	80
15	0.30	20	26	213	1627	53	80
16	0.30	20	26	213	1627	53	80
17	0.30	20	26	213	1627	53	80

The optimized mix ratio for the plant-growing ecological concrete was obtained through the response surface methodology regression model, and using this ratio, the study on acetic acid activation was conducted. The acetic acid content was 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, 0.7%, 0.8%, respectively, of the mass of the cementitious materials. After

being thoroughly mixed with the mixing water, it was added to the mixer for stirring. The compressive strength and pH value changes of the plant-growing ecological concrete with added acetic acid were tested, along with the conduct of vegetative performance tests.

3.3. Testing Methods

- (1) Method of specimen formation: The aggregate particle size of plant-growing ecological concrete is relatively large, and the specimen size should not be too small. This test prepares it into a cubic specimen of 150 mm × 150 mm × 150 mm (Figure 2). The molded specimen is covered with plastic film and cured in the curing room for 3 days before demolding. The demolded specimen is lightly watered during daily maintenance to replenish moisture loss and cured until 28 days for testing.



Figure 2. The specimen placed in the mold.

- (2) Compressive Strength: The side of the specimen was selected as the compression surface to ensure that the compressed surface was relatively flat and free of protrusions. The compressive strength test was conducted using the DYE-2000 digital pressure testing machine (Cangzhou Huaheng Testing Instrument Co., Ltd., Cangzhou, China), and the specific testing operations were carried out in accordance with the relevant provisions of the (GB/T50081-2019) “Standard Test Methods for Mechanical Properties of Ordinary Concrete” [25]. Considering the low strength of the specimen, continuous and uniform loading was applied during the test, with the loading rate controlled at 0.3 MPa/s to 0.5 MPa/s.
- (3) Continuous Porosity: The porosity of plant-growing ecological concrete includes effective and ineffective pores. Effective pores refer to the pores within the concrete specimens that are connected to the external air, while ineffective pores refer to the enclosed pores that are not connected to the external air. It is evident that the effective porosity rate discussed in this paper pertains to the pores that substantially affect permeability, air permeability, and the growth of plant roots, which is different from the effective porosity rate defined for other materials. To distinguish, this paper refers to the experimental method in “Ecological Concrete Slope Protection Technology and Application” [26] and names the effective porosity rate as continuous porosity. The drainage method is utilized to measure the continuous porosity of plant-growing ecological concrete, as shown in the following formula:

$$P = \left(1 - \frac{W_2 - W_1}{V} \right) \times 100\% \quad (1)$$

In the formula, P represents the continuous porosity of the specimen, which is the percentage of the volume of continuous pores that can communicate with the external environment to the total volume of the specimen; W_1 is the mass of the specimen after

being immersed in water for 24 h, measured by a hydrostatic balance; W_2 is the mass of the specimen after it is removed from the water, drained of excess water, and left to sit for 24 h until its mass no longer changes noticeably; V is the volume of the test piece obtained by caliper measurement and calculation.

- (4) Concrete alkalinity test: To determine the dilution pH of soluble solids in cement paste, the in-situ leaching method was adopted. We scraped off the cement paste from the broken concrete pieces and ground it into a powder that passed through a standard sieve with a 0.074 mm aperture. The powdered cementitious material was mixed with distilled water at a mass ratio of 1:10, stirred evenly, and left to stand for 1 h. After standing, the supernatant was taken, the powder residue in the filtrate was filtered out, and then the determination was carried out. The determination method followed the standard (HJ 1147-2020) "Water Quality-Determination of pH Value-Electrometric Method" [27].
- (5) Planting test: The experiment utilized three methods: pure soil natural planting, planting of test pieces after alkali reduction treatment, and planting of test pieces without alkali reduction treatment. Each method was set with 10 samples. Each sample had a planting area of 150 mm × 150 mm and 100 seeds of tall fescue were sown. The ultimate criterion was whether the roots of the tall fescue could penetrate the soil layer and reach into the concrete, to analyze the vegetative effectiveness of the plant-growing ecological concrete. As shown in Figure 3, the planting soil was a mix of inorganic soil, organic fertilizer, coconut coir, and vermiculite in a 7:2:2:1 ratio. As illustrated in Figure 4, soaking the specimens in nutrient soil diluted with water before the planting experiment can effectively fill the pores of the specimens, which is beneficial for the subsequent growth of the plants.



Figure 3. Inorganic soil, organic fertilizer, coconut coir, and vermiculite.



Figure 4. Concrete pore filling treatment.

4. Results

4.1. Regression Model

The experiment examined the 28-day compressive strength, continuous porosity, and pH of the plant-growing ecological concrete specimens, and the test results of each group were obtained by averaging the test data of six specimens. Linear regression analysis was utilized to fit the experimental results with a second-order polynomial, leading to the derivation of a multiple regression equation [28]. The aim is to establish a regression model for the key properties of plant-growing ecological concrete. The experimental results, standard deviations, and model predictions are shown in Table 7, and after eliminating the insignificant terms, the regression equations for compressive strength, continuous porosity, and pH are respectively presented as Equations (2)–(4).

$$Y_{\sigma_{bc}} = 8.13 - 0.090W/B - 0.17F - 2.48R_{\text{void}} - 0.048(W/B) \cdot F + 0.068F \cdot R_{\text{void}} - 0.69(W/B)^2 - 0.25F^2 + 0.23R_{\text{void}}^2 \quad (2)$$

$$Y_P = 24.64 - 0.29W/B - 0.47F + 4.45R_{\text{void}} + 0.23(W/B) \cdot F - 0.22(W/B) \cdot R_{\text{void}} - 0.55(W/B)^2 + 0.22F^2 - 0.61R_{\text{void}}^2 \quad (3)$$

$$Y_{\text{pH}} = 11.24 - 0.065W/B - 0.53F - 0.11R_{\text{void}} - 0.077(W/B)^2 - 0.15F^2 \quad (4)$$

Table 7. Test value and predicted value.

Test	Compressive Strength /MPa			Continuous Porosity /%			pH		
	Test Value	Standard Deviation	Predicted Value	Test Value	Standard Deviation	Predicted Value	Test Value	Standard Deviation	Predicted Value
1	7.43	0.18	7.41	25.23	0.32	25.28	11.60	0.05	11.58
2	7.31	0.11	7.33	24.39	0.33	24.26	11.45	0.06	11.43
3	7.18	0.14	7.16	23.76	0.52	23.9	10.49	0.09	11.51
4	6.87	0.18	6.89	23.83	0.35	23.78	10.38	0.03	10.40
5	10.22	0.29	10.23	19.27	0.61	19.09	11.35	0.04	11.37
6	10.09	0.19	10.07	18.95	0.43	18.96	11.21	0.05	11.23
7	5.27	0.18	5.30	28.45	0.48	28.44	11.15	0.03	11.13
8	5.11	0.14	5.10	27.25	0.38	27.43	11.03	0.03	11.01
9	10.82	0.31	10.83	20.01	0.30	20.13	11.71	0.03	11.71
10	10.34	0.31	10.35	19.42	0.30	19.46	10.76	0.04	10.73
11	5.75	0.14	5.74	29.34	0.46	29.3	11.52	0.05	11.56
12	5.54	0.15	5.53	28.23	0.37	28.11	10.44	0.03	10.44
13	8.14	0.18	8.13	24.65	0.41	24.64	11.25	0.04	11.22
14	8.11	0.19	8.13	24.59	0.32	24.64	11.12	0.05	11.22
15	8.19	0.32	8.13	24.41	0.40	24.64	11.21	0.04	11.22
16	8.08	0.20	8.13	24.81	0.30	24.64	11.27	0.04	11.22
17	8.15	0.30	8.13	24.73	0.47	24.64	11.23	0.03	11.22

In the variance analysis, a smaller p -value indicates higher significance. p -values less than 0.01, p -values less than 0.05, and p -values greater than 0.05 respectively denote extremely significant, significant, and not significant results. As shown in Table 8, the p -values for all three models concerning compressive strength, continuous porosity, and pH are less than 0.01, indicating extremely significant outcomes and validating the experimental judgment of the range of response factors. The p -values for lack-of-fit are greater than 0.05, signifying insignificance, which implies that the model correctly specifies the relationship between the response factors and the response values.

Table 8. Variance analysis of regression model.

Source	Compressive Strength		Continuous Porosity		pH		Significance
	F-Value	p-Value	F-Value	p-Value	F-Value	p-Value	
Model	5156.85	<0.0001	551.10	<0.0001	165.44	<0.0001	significant
W/B	51.61	<0.0001	17.57	0.0030	11.28	0.0064	
F	189.59	<0.0001	46.62	0.0001	739.12	<0.0001	
P	39,028.37	<0.0001	4251.17	<0.0001	33.03	0.0001	
(W/B)·F	7.19	0.0279	5.55	0.0463	-	-	
(W/B)·P	-	-	5.19	0.0522	-	-	
F·P	14.51	0.0052	-	-	-	-	
(W/B) ²	1588.43	<0.0001	34.48	0.0004	8.29	0.0150	
F ²	206.66	<0.0001	5.33	0.0498	33.50	0.0001	
P ²	172.41	<0.0001	41.34	0.0002	-	-	
Lack of fit	0.4516	0.7699	2.23	0.2285	0.8222	0.6159	not significant

The regression equation's error statistical analysis outcomes are presented in Table 9. R^2 is the coefficient of determination, and R^2_{adj} is the adjusted coefficient of determination, which accounts for the degrees of freedom in the context of multiple factors. The closer both are to 1, the better the experimental data fits the model; R^2_{pred} is the predictive coefficient of determination, and the difference between R^2_{adj} and R^2_{pred} is indicative of the significance of factors not included in the experiment. A difference less than 0.2 implies that the regression model can accurately simulate the changes between response factors and response values without omitting any significant response factors; CV stands for the coefficient of variation, and when it is less than 10%, it indicates that the experiment has high reliability and precision; the signal-to-noise ratio represents the ratio of information that can be explained by the model to the information that cannot be explained by the model. When it is greater than 4, the model is considered to be reasonable.

Table 9. Error statistical analysis of regression equations.

Fit Statistics	Compressive Strength	Continuous Porosity	pH
R^2	0.9998	0.9982	0.9869
R^2_{adj}	0.9996	0.9964	0.9809
R^2_{pred}	0.9992	0.9865	0.9696
$R^2_{adj} - R^2_{pred}$	0.0004	0.0099	0.0113
CV	0.45%	0.80%	0.49%
Signal-to-noise ratio	221.86	72.63	40.14

4.2. Alkali Reduction Treatment

4.2.1. Mix Proportion Optimization Results

Based on the established response surface regression model, the mix proportion of plant-growing ecological concrete was optimized. The optimization objectives were to maintain a continuous porosity rate within the range of 20% to 30%, a pH value less than 11, and to maximize compressive strength. The optimized mix design is as follows: a water–binder ratio of 0.30, a fly ash content of 26%, and a designed porosity rate of 22%. The regression model's prediction for this mix is a compressive strength of 10.32 MPa, a continuous porosity rate of 20.00%, and a pH value of 11. Subsequent experimental validation confirmed the optimized mix proportion, yielding a compressive strength of 10.11 MPa, a continuous porosity rate of 20.71%, and a pH value of 10.79. The deviations between the experimental values and the predicted values were 2.03%, 3.55%, and 1.91%, respectively, indicating a high degree of accuracy.

4.2.2. Acid Excitation

An acid excitation experiment was conducted using the optimized mixture proportions described above, aiming to enhance the compressive strength of the plant-growing ecological concrete while also reducing its pH value. The results are shown in Figure 5. As the pH value of the concrete specimens consistently decreased with the increase in acetic acid content, the change in compressive strength was primarily used to assess the effect of acid activation.

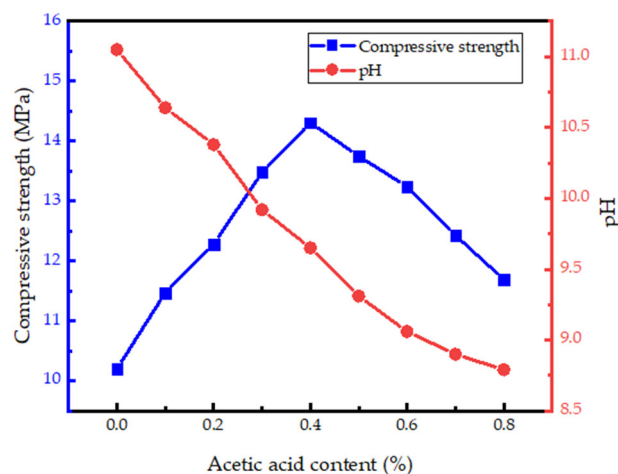


Figure 5. Impact of acetic acid.

After the addition of acetic acid, the compressive strength of the concrete specimens first increased and then decreased with the increase in acetic acid content. When the acetic acid content ranged from 0% to 0.4%, the compressive strength of the specimens increased. Specifically, the groups with 0.1%, 0.2%, 0.3%, and 0.4% acetic acid content showed an increase in compressive strength of 12.45%, 20.39%, 32.16%, and 40.29%, respectively, compared to the blank control group with 0% acetic acid. However, when the acetic acid content was increased from 0.4% to 0.8%, the compressive strength of the specimens decreased. The groups with 0.5%, 0.6%, 0.7%, and 0.8% acetic acid content experienced a reduction in compressive strength by 3.91%, 7.48%, 13.14%, and 18.31%, respectively, compared to the group with 0.4% acetic acid.

Therefore, this article used acetic acid with a concentration of 0.4% of the cementitious material mass to carry out alkali reduction treatment on plant-growing ecological concrete. The compressive strength corresponding to this ratio is 14.31 MPa, with a pH of 9.65.

4.3. Vegetative Experiment

From the fifth to the sixth day after sowing, at this point, the surviving tall fescue seeds had already germinated, and a survival rate statistic was conducted based on the number of seedlings. As shown in Table 10, There was no significant difference in seed germination rate among the three planting methods.

Table 10. Germination rate statistics.

Cultivation Method	Planting Time	Germination Rate
Pure soil planting	5 d	91%
Specimens treated with acid	5 d	87%
Untreated specimens	5 d	85%

The results of the vegetation test are shown in Figure 6. During the 5~7 day period, the plant height of tall fescue in the three experimental groups was similar; from day 7 to 11, the plant height in the blue group developed a significant gap compared to the red and

black groups; from day 11 to 17, this gap widened further; from day 17 to 21, the growth rate of the plants in all three groups slowed down. It is evident that the plant height in the red and black groups remained close throughout, indicating that acid activation can significantly enhance the vegetative performance of plant-growing ecological concrete.

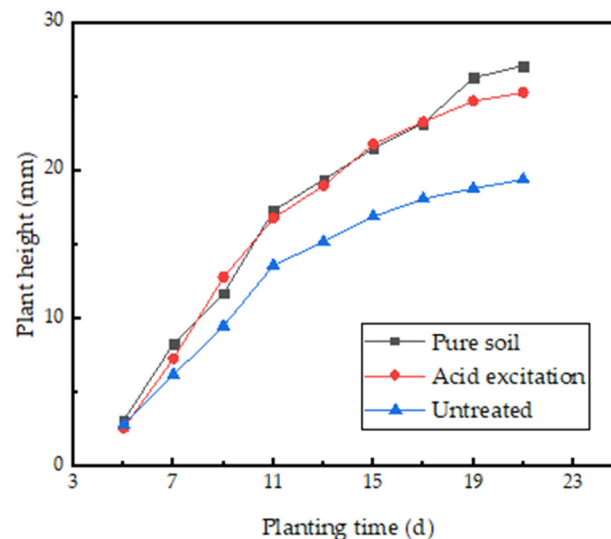


Figure 6. Comparison of growth rates of tall fescue.

As shown in Figure 7, from the side of the concrete, it can be observed that the roots of tall fescue have penetrated into the pores of the concrete, indicating that this proportion of plant-growing ecological concrete can meet the needs of plant growth.



Figure 7. Vegetation performance of ecological concrete.

5. Discussion

The focus of this study was to elucidate the interrelationships among the basic properties of plant-growing ecological concrete, which is beneficial for our in-depth understanding of this sustainable and environmentally friendly material, thereby optimizing the mix ratio. Addressing its shortcomings in strength and alkalinity control, the study utilized acetic acid as an activator to enhance its service life and vegetation effects. This affordable and efficient approach is worth promoting. All research content aims to provide a solution for the issues faced by plant-growing ecological concrete in practical engineering applications, such as the lack of standards, poor performance, and insufficiently low costs.

5.1. The Effect of Different Factors

5.1.1. Analysis of Compressive Strength

The order of influence of 3 response factors on the compressive strength of plant-growing ecological concrete is designed porosity > fly ash content > water–binder ratio. The relationships between the three response factors are shown in Figures 8 and 9, with the response factors not involved in the interaction set to the center-level value.

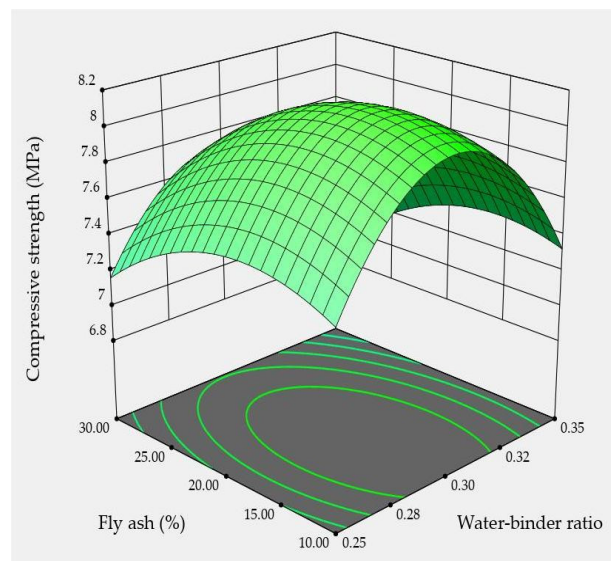


Figure 8. (W/B)·F on compressive strength.

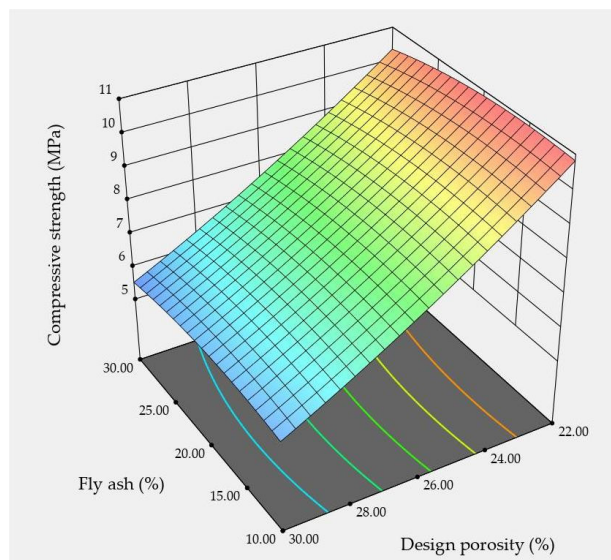


Figure 9. F·P on compressive strength.

The influence of designed porosity on compressive strength plays a dominant role. As designed porosity increases, compressive strength significantly decreases. Chidaprasirtil et al. [29] conducted experiments on ecological concrete with differently designed porosities and found that the compressive strength of ecological concrete decreases linearly with increasing porosity. The increase in designed porosity leads to a decrease in the amount of cementitious material in the concrete, which in turn weakens the support and connection between aggregates, thereby reducing the overall compactness and mechanical properties of the concrete.

The water–binder ratio plays a secondary role in affecting compressive strength. As the water–binder ratio increases, compressive strength first increases and then decreases. At lower water–binder ratios, increasing the water–binder ratio allows for more complete hydration of the cement. Simultaneously, the fluidity of the cement paste is enhanced, which helps to uniformly cover the coarse aggregates, thereby improving the bonding between coarse aggregates. These combined effects lead to an increase in compressive strength. However, at higher water–binder ratios, increasing the water–binder ratio correspondingly reduces the amount of cement used. An overly diluted cement paste cannot form a

sufficiently thick coating, and excessive fluidity causes the cement paste to settle under gravity, resulting in a decrease in the compressive strength of the sample. Luo's research results are consistent with this, and he also believes that an increase in aggregate size lowers the optimal water–binder ratio [30]. For aggregates of 5 mm to 10 mm, the optimal water–binder ratio is close to 0.40, while for aggregates of 10 mm to 20 mm, the optimal water–binder ratio is close to 0.35.

With the increase in fly ash content, the compressive strength first increases and then decreases. Wang studied the effect of fly ash on the compressive strength of pervious concrete and found that increasing the fly ash content from 0% to 20% can increase the compressive strength by 40% [31]. When the fly ash content exceeds 20%, the compressive strength gradually decreases, and when the content reaches 40%, the compressive strength decreases by 20% compared to ordinary pervious concrete. Similar patterns were observed by Maguesvari and Sata [32,33]. Due to the low reactivity of fly ash, its hydration reaction is relatively slow, providing limited strength to concrete during the 28-day curing period. Adding a small amount of fly ash can fill the voids in the cementitious material, increasing the density of the concrete, and thus improving the compressive strength of the sample. However, excessive fly ash significantly reduces the cement content, which provides early compressive strength, leading to a reduction in compressive strength. Additionally, compared to cement, fly ash has a lower water absorption rate, effectively increasing the water–binder ratio. As can be seen from the figure, the peak of the curve shifts to one side, indicating that at higher fly ash content, the water–binder ratio corresponding to the same compressive strength value is lower.

5.1.2. Analysis of Continuous Porosity

The order of influence of the three response factors on the compressive strength of plant-growing ecological concrete is designed porosity > fly ash content > water–binder ratio.

Figure 10 clearly shows that with the increase in designed porosity, the continuous porosity rises. Since it is not possible to completely eliminate the generation of closed pores inside the concrete, the continuous porosity is always less than the designed porosity, and the trend of change is consistent with it. As known from the mix proportion formula, the designed porosity affects the generation of continuous porosity by regulating the amount of binding material used. Compared to the water–binder ratio and fly ash content, the designed porosity plays a dominant role in the change of continuous porosity.

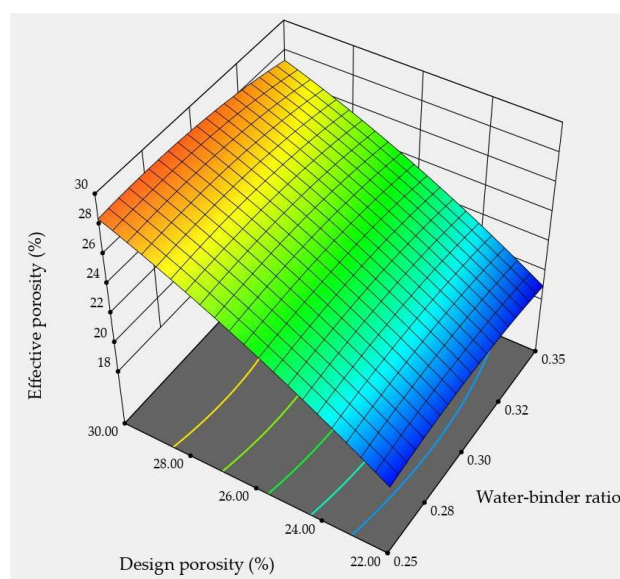


Figure 10. (W/B)·P on continuous porosity.

The trend in Figure 11 also shows that an increase in fly ash content leads to a reduction in continuous porosity. The density of fly ash is less than that of cement, so when using the same mass substitution method, the volume of the same mass of fly ash is greater than that of cement, occupying more space in the concrete specimen, reducing the generation of internal pores, and decreasing the continuous porosity rate. It can be seen from the figure that as the fly ash content increases, the surface change becomes more gradual, this is because the incorporation of fly ash enhances the cohesiveness of the binding materials and workability, making the impact of the water–binder ratio on the continuous porosity less significant. Haji et al. [34] indicated that pervious concrete exhibits better permeability when the fly ash content is 0%–5%; when the fly ash content is 5%–25%, the permeability of pervious concrete shows a declining trend. Considering that the permeability of pervious concrete can well characterize the continuous porosity [35], this experiment obtained the same trend with fly ash content ranging from 10% to 30%.

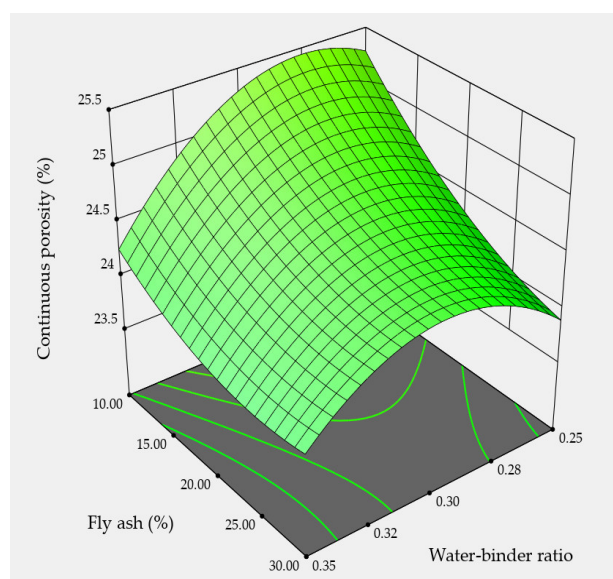


Figure 11. (W/B)·F on continuous porosity.

Figure 11 shows the trend that as the water–binder ratio increases, the continuous porosity first increases and then decreases, which is consistent with the research results of Ling et al. [36]. At low water–binder ratios, the cement paste is extremely viscous and tends to self-bind into lumps, forming a large number of closed pores during the binding process of the coarse aggregate. As the water–binder ratio increases, the fluidity of the cement paste improves, reducing the amount of closed pores generated by the uniform wrapping of the coarse aggregate, thus increasing the continuous porosity. However, once the water–binder ratio reaches a certain level, the fluidity of the cement paste is too great to effectively bind between the coarse aggregates; some of the paste settles and causes bleeding and setting at the bottom of the specimen, which in turn clogs a large number of continuous pores, ultimately leading to a reduction in continuous porosity.

5.1.3. Analysis of pH Value

The order of influence of three response factors on the pH value of vegetation ecological concrete is fly ash content > design porosity > water–binder ratio. It can be understood from the previous variance analysis that the interaction between response factors W/B, F, and P is not statistically significant. For the needs of the analysis, the initial regression equation is used, not discarding the insignificant terms of the polynomial. The interactions (W/B)·P and F·P, which are more significant than (W/B)·F, were selected to generate the response surface plot regarding pH value, with the non-interacting response factors set at the central level.

As shown in Figure 12, with the increase in fly ash content, the pH value of plant-growing ecological concrete decreases. On one hand, fly ash replaces a large amount of cement, reducing the production of alkaline substances. On the other hand, although fly ash has lower activity, a part of the SiO_2 and Al_2O_3 in the fly ash still reacts with the Ca(OH)_2 in the cement to form hydrated calcium silicate (C-S-H) and hydrated calcium aluminate (C-A-H) gels, leading to a decrease in pH value. Whether fly ash participates in the hydration reaction depends on the alkaline environment provided by the alkaline substances produced by the cement hydration reaction. It is foreseeable that the higher the fly ash content, the less cement used, the fewer alkaline substances provided by the cement, the more delayed the hydration reaction of the fly ash, and the lower the final pH value of the concrete. In subsequent experiments, it is necessary to improve the reactivity of fly ash to enhance its hydration utilization rate and to fully utilize the alkali-reducing effect of fly ash. The study by Ganapathy et al. [37] on the effects of fly ash and silica fume on the pH of vegetation porous concrete also corroborates this point.

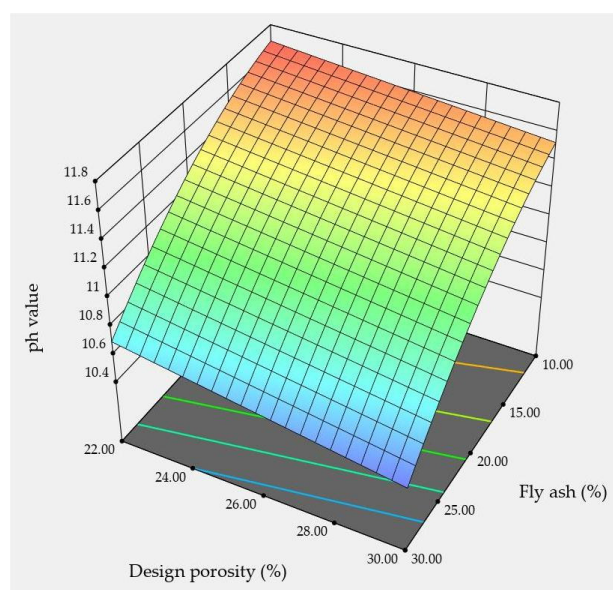


Figure 12. F·P on pH.

As shown in Figure 12, with the increase in the designed porosity, the pH value of the plant-growing ecological concrete decreases. The research results of Tian et al. show that the larger the design porosity of the test block, the lower the initial pH value, and the more significantly it is affected by carbonation [38]. Under the conditions of a fixed water–binder ratio and fly ash content, an increase in designed porosity means more continuous porosity in the plant-growing ecological concrete, and thus a larger contact surface area with CO_2 in the air. The alkaline substances inside the specimen react with CO_2 after being excreted to form carbonates, causing carbonation of the specimen and ultimately a decrease in alkalinity. Additionally, during the daily watering maintenance of the concrete specimens, a higher continuous porosity also allows alkaline substances to be washed away by the maintenance water through the continuous pores, resulting in a decrease in the alkalinity of the concrete.

As can be seen from Figure 13, with the increase in the water–binder ratio, the pH value of the plant-growing ecological concrete first rises and then falls. At a lower water–binder ratio, as it increases, the hydration reaction of the cement becomes more complete, producing more alkaline substances, thus higher alkalinity in the concrete. However, at higher water–binder ratios, excessive water will migrate as free water through the pores of the concrete during the curing process, with alkaline substances precipitating out carried by the water. The highly developed porous structure of the concrete further contributes to this phenomenon, resulting in a decrease in the alkalinity of the specimens.

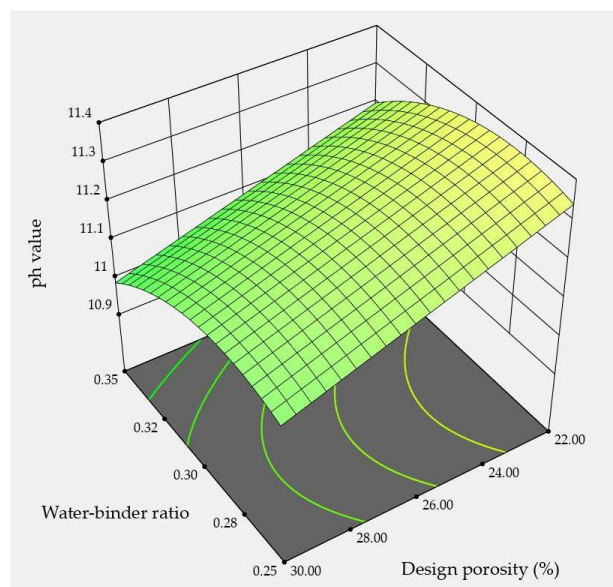


Figure 13. (W/B)·P on pH.

5.2. Acid Activation

5.2.1. Influence of Acetic Acid Content on Concrete

In terms of compressive strength, there are some materials with low reactivity present in hydraulic cementitious materials that participate minimally in hydration reactions, resulting in subpar early strength of concrete. Activators can provide a more suitable reaction environment for these substances, facilitating their involvement in the reaction and enhancing the utilization rate of cementitious materials. Compared to alkali activation, acid activation is a less common method, with typical acid activators including sulfuric acid, hydrochloric acid, phosphoric acid, and others. Yan [39] used different acid solutions to activate the reactivity of cement-based materials, finding that 4% concentration vinegar at a dosage of 5% by the mass of cement showed the maximum increase in compressive strength of specimens, reaching 37.31%. This paper achieved results consistent with Yan regarding the relationship between acetic acid dosage and compressive strength change (as shown in Figure 1), but differed in the optimal dosage. This discrepancy could be due to the use of glacial acetic acid rather than an aqueous solution of vinegar, as different dosages of acetic acid did not alter the water-to-cement ratio of the concrete. Upon adding water to cement, particles attract each other to form a flocculated structure in the paste, which is unfavorable for the progression of hydration reactions. Acetic acid reacts with cement to prevent the formation of this flocculated structure, breaking up large cement flocs, which increases the contact area between cement and water, thus promoting the hydration reaction. When the dosage of acetic acid is too high, the acidic environment it creates inhibits the hydration reaction of cement, leading to a decrease in compressive strength.

Regarding the control of alkalinity, concrete with high alkalinity affects the growth of plants, especially when plant roots penetrate the soil layer and reach the concrete. Although the alkalinity of plant-growing ecological concrete can be reduced through water cycling, plant absorption, natural carbonation, and other processes in practical applications, this prolongs the vegetative cycle, which is not conducive to the application in engineering practice. By testing and identifying effective measures to reduce alkalinity, the initial alkalinity of concrete can be lowered, which is beneficial for quicker plant growth to meet coverage rate standards, thus reducing the construction period of projects. Gil and others [40] used aqueous solutions of acetic acid and other dilute acids to soak concrete specimens for alkali reduction treatment. The study found that this operation effectively neutralized the alkalinity of the concrete, lowering the pH value of concrete blocks from 12 to below 8, providing favorable conditions for plant growth. The considerations for

using vinegar to reduce alkalinity in this paper are largely based on this, but acetic acid was used as an activator instead. Although the alkali-reducing effect of vinegar soaking is significant and suitable for small-scale projects using concrete block assembly, it is evidently not feasible for large-scale projects involving extensive concrete pouring. When acetic acid is added to cementitious materials, its molecules decompose into CH_3COO^- and H^+ , with these ions reacting with alkaline substances in the concrete. Taking calcium hydroxide as an example, H^+ combines with OH^- to form water, while CH_3COO^- forms a relatively stable salt with Ca^+ . Such reactions result in a reduction of alkaline substances in pervious concrete, thereby lowering its alkalinity.

Overall, compared to some other chemical activators, acetic acid is relatively inexpensive and readily available, with minimal impact on the environment and human health. This aligns with the sustainable development requirements of plant-growing ecological concrete for green, environmentally friendly, energy-saving, and emission-reducing properties, giving it certain economic and safety advantages in engineering applications.

5.2.2. Discussion on Planting Performance

Tall fescue is a perennial herbaceous plant that grows quickly and has good cold resistance, drought tolerance, and salinity tolerance, making it suitable for planting under a variety of environmental conditions. Most plants grow best in soil with a pH range of about 6.0 to 7.5, but tall fescue can thrive in soil with a pH of up to 9. Even though the pH of concrete blocks treated with acetic acid in experiments was 9.65, tall fescue still showed growth comparable to that in pure soil. This is because the alkalinity of the leachate from concrete is much lower than that of the concrete itself, and the alkali reduction treatment in practical applications does not require reducing the pH of the concrete to neutral.

The germination rate (about 90%) and growth speed of tall fescue obtained from vegetation experiments did not align with the results of similar environmental studies conducted by other scholars (about 80% or lower) [41–43]. Upon comparison, it was found that the sowing density used in this study was approximately $6 \text{ g}\cdot\text{m}^{-2}$, while that used by other scholars was generally over $10 \text{ g}\cdot\text{m}^{-2}$. Clearly, the population density of tall fescue in this experiment was set too low, allowing for more available resources (such as sunlight, water, nutrients, habitat, etc.) and thus reducing interspecific competition, which in turn increased the germination rate and growth speed. Therefore, the results of this vegetation test are only applicable under conditions of lower planting density. In practical applications, adjustments to plant population density should be made according to the species and the local climate environment.

6. Conclusions

To address the issues of unclear standards, poor applicability, and high cost that plant-growing ecological concrete faces in practical engineering applications, this paper proposes a low-cost, effective, and simple process solution. Initially, with the water-to-binder ratio, the fly ash content, and the design porosity as the response factors, and compressive strength, continuous porosity rate, and pH value as the response values, response surface design experiments were carried out. A regression model concerning the basic properties of plant-growing ecological concrete was established. Subsequently, based on the regression model, the mix proportion was optimized. To address the issues of lower compressive strength and insufficient control of alkalinity in the optimized mix, acetic acid was used as an activator to improve the performance of plant-growing ecological concrete. Lastly, specimens activated with acetic acid underwent vegetative performance tests to verify the effectiveness of the alkali reduction treatment. The main research conclusions are as follows:

- (1) The optimized mix proportion obtained by the regression model established through the response surface method is as follows: water-to-binder ratio of 0.30, fly ash content of 26%, and designed porosity rate of 22%. The predicted performance is a compressive strength of 10.32 MPa, continuous porosity rate of 20.00%, and pH

value of 11. Further experimental validation showed that this mix proportion had a compressive strength of 10.11 MPa, a continuous porosity rate of 20.71%, and a pH value of 10.79. The errors were 2.03%, 3.55%, and 1.91%, respectively, all less than the 5% error range, indicating that the regression model about the basic properties of plant-growing ecological concrete established by the response surface method experiment is accurate and effective;

- (2) Acetic acid, as an activator, can significantly enhance the compressive strength of plant-growing ecological concrete and reduce its alkalinity. An acetic acid content of 0.4% of the weight of the cementitious materials is optimal for improving the performance of plant-growing ecological concrete with the optimized mix. The test results show that the compressive strength increased by 40.29%, and the pH value decreased by 6.33%;
- (3) Acetic acid can improve the plant-growing performance of plant-growing ecological concrete. The plant-growing ecological concrete specimens treated with the abovementioned alkali reduction showed similar vegetative performance when tested with tall fescue compared to pure soil planting and were significantly better than the concrete specimens without alkali reduction treatment.

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