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Research Article

Performance of Ecological Pervious Concrete Prepared with Sandstone/Limestone-Mixed Aggregates

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To understand the performance of ecological pervious concrete prepared with mixed sandstone/limestone aggregates, limestone and sandstone were used as two aggregates. The sandstone-to-limestone volume ratio was calculated in 0 : 1, 0.25 : 0.75, 0.5 : 0.5, 0.75 : 0.25, and 1 : 0 in coarse aggregate to prepare ecological pervious concrete specimens. The compressive test, water permeability test, cooling test, evaporation test, alkaline test, and scanning electron microscope (SEM) tests were carried out with qualified compressive strength as the indicator to determine the optimum sandstone-to-limestone volume ratio for the ecological pervious concrete. The results show that the water permeability, cooling property, and evaporation property of the ecological pervious concrete increase with the sandstone content. When the sandstone-to-limestone volume ratio is less than 0.32 : 0.68 (the substitution rate of sandstone for limestone in ecological pervious concrete is 32%), the strength of ecological pervious concrete meets the requirements of 5 MPa and achieves the best permeability coefficient of 9 mm/s. This realizes the full use of net water storage and cooling capacity of the ecological pervious concrete and makes the ecological pervious concrete meet the construction requirement of slope protection in sponge cities in the south.

1. Introduction

Concrete is the most widely used construction material in the world and the second most consumed product on earth after water [1], whose use reaches 300 million tons per year [2]. A widespread use of concrete implies a rapid development of the construction sector, with outstanding achievements in infrastructure construction. Along with the development of infrastructure, a clearing or excavator of the original landscape is inevitable, which will inevitably destroy its vegetation and ecological balance. A survey of the construction industry in the last 80 years found [3] that there were two main problems to be solved, namely, the consumption of natural resources required for the construction of infrastructure and the impact of urban environmental issues. Much research has been done to produce concrete more environmentally friendly, and finding the more sustainable and economical processing solutions has become an important topic. For example, the search for alternative green building materials (which must be renewable, local, and abundant) and the production of low-technology methods are some practices that have produced good results in this context [4–6]. These dense and impermeable concrete structures bring convenience to our lives while destroying the urban water environment and water ecosystems [7]. Although the rank system of these artificially hardened cement stones ensures a high strength and durability of the material, it loses most of its permeability. And in recent years, urban flooding has become more frequent, widespread, and severe [8]. To address this issue, China has launched the "sponge city" policy to pursue the dual implementation of increasingly complex sustainable urban stormwater management and the use of ecological pervious concrete. Ecological pervious concrete can reduce natural disasters and has excellent permeability, water retention, and cooling performance [9]. It can be mass produced as a substitute for conventional concrete, using only the locally available materials, construction technology, and skills, and the design of simple [10] can be applied to many ecological engineering, such as permeable pavement materials, plant growth substrate, road and river dike slope protection of vegetation, and other regions, to realize the sustainable development of environment protection and infrastructure construction.

South China is rich in mineral resources and has made important contributions to energy security and economic development. Likewise, due to its special topography, the natural environment is fragile and highly susceptible to external influences that can cause geological disasters, like landslides, floods, and other mountain disasters that combine geological and hydrological factors, as well as ground subsidence due to mining [11], posing a serious threat to human life and development [12]. Old landslides are highly susceptible to reactivation by infiltrated rainwater [13], causing considerable damage to critical infrastructure, farmland, housing, public and private infrastructure, and assets [13], such as the Huangjialing and Tuanbao landslides induced by large-scale excavation and continuous heavy rainfall [12, 14], as well as heavy rainfall and landslides from typhoon strikes. The proper understanding of mine vulnerability will facilitate more effective emergency management and the development of disaster preparedness activities [15]. Ecological pervious concrete is very effective in preventing geohazards due to its unique ability to infiltrate rainwater into the ground. Moreover, the geohazard prevention process generates a large amount of earth and rock materials [16], which in turn can be utilized in ecological pervious concrete, forming a circular chain. Aggregate is the volumetric filler of ecological pervious concrete, accounting for 70-75% of the volume of concrete [17]; therefore, the construction process requires an adequate supply of aggregate, so places with abundant sources of aggregate are highly potential for producing ecological pervious concrete. The climate in southern China is mild, with plentiful rainfall, sunshine, heat, long summers and short winters, four distinct seasons, and the same rainy and hot seasons, often with short periods of intense or continuous rainfall. The ecological pervious concrete can cope with natural disasters induced by rain [16, 18]. In addition, due to its high specific surface area and multiconnected pores [19], air can be quickly circulated in continuous channels [20]. Water can be runoff into the ecological pervious concrete through a capillary action on the surface of ecological pervious concrete [21], which can bring various environmental benefits, such as the cooling and plant growth [22–24]. As a hydrophilic material, the ecological pervious concrete has become an "infrastructure" for the construction of sponge cities in the south.

The coarse aggregate of ecological pervious concrete is generally selected from a single particle size of 10 mm to 20 mm of high-quality basalt or limestone [25]. Therefore, the Upper Devonian Rongxian Group ((D_{3r}) limestone was selected to ensure its strength. But the limestone has a low permeability coefficient and cannot achieve a good permeability performance, and the sandstone aggregate of the Middle Devonian Xindu Group (D_{2x}) was selected by its characteristics, using the sandstone with its sizeable internal porosity, relatively high permeability coefficient, low density, low softening coefficient, low modulus of elasticity, and high water absorption to increase the water permeability and water retention of sandstone. The engineering characteristics of sandstone make it not a high-quality aggregate source. Still, due to its unique aggregate properties, the ecological pervious concrete can more effectively ensure the environmental impact caused by excessive rainfall and sufficient sunlight in southern regions and mitigate the effects of temperature and humidity changes. To combine the advantages of the two coarse aggregates, the ecological pervious concrete with limestone and sandstone as the coarse aggregates was developed. Sandstone accounted for 0%, 25%, 50%, 75%, and 100% in aggregate, and coarse aggregate was prepared according to the volume ratio of sandstone-to-limestone 0 : 1, 0.25 : 0.75, 0.5 : 0.5, 0.5 : 0.25, and 1 : 0. The ecological pervious concrete was formulated according to specified porosity, and comparisons of compressive strength, permeability, water retention, and evaporation properties between all the samples were carried out. This paper combines the advantages of the two aggregates to produce ecological pervious concrete in line with the climate characteristics of South China. The results indicated that while ensuring the stability, ecological pervious concrete played a more significant role as the main force of slope protection in the sponge city construction in the south. This experiment is conducive to the supplementation of technical achievements in the field of building materials and the improvement of the academic system and has a theoretical significance to some academic research results in this field.

2. Materials

The engineering properties of the planted ecological pervious concrete were studied based on its proportion. The component of the phytosanitary ecological pervious concrete includes cement, water, coarse aggregate (limestone+sandstone), and admixtures. The detailed properties are as follows.

(1) *P.O42.5 Silicate Cement.* The P.O42.5 silicate cement was selected. Its physical and mechanical properties are shown in Table 1

(2) *Coarse Aggregate.* The limestone and sandstone in the Guilin region were selected as the coarse aggregate. Limestone is an important industrial raw material in the fields of metallurgy, building materials, and construction. In the development of the concrete industry, limestone is the primary target. The advantages of sandstone such as moisture resistance, sound absorption, and light absorption make it possible to go beyond its role as a basic aggregate. The coarse aggregate and cement paste were cemented into porous concrete. The larger the aggregate size, the smaller the stacking density is. More skeletal voids were formed, and the mechanical properties are poor. To ensure that the ecological pervious concrete has a large number of pores and achieves the water permeability and water retention property, its aggregates should be applied to a particle size of similar single-grain aggregates. Thus, according to the source of raw materials, coarse aggregates (sandstone+limestone) with particle sizes of 15-20 mm were selected in this test, and physical properties

Table 1: Physical and mechanical properties of the P.O42.5 silicate cement.

Density/(kg/m^3)	Specific surface area/(m^2/kg)	Coagulation time/min		Flexural strength/MPa		Compressive strength/MPa		Adequacy
		Initial condensation	Final condensation	3 d	28 d	3 d	28 d	
3125	352	209	291	5.5	8.5	26.6	57.2	Qualified

(a) Limestone

(b) Sandstone

Figure 1: Macroscopic morphology of limestone and sandstone.

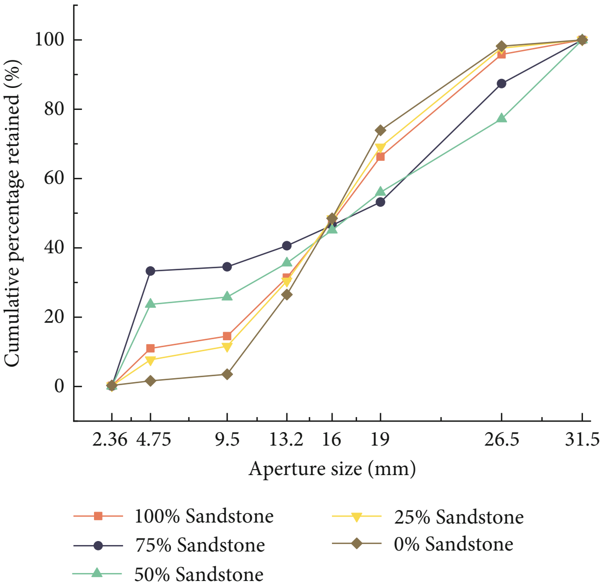


Figure 2: Aggregate grading diagram of ecological pervious concrete.

were tested according to SL/T352-2020 [26]. The aggregates used were crushed, sieved, washed, and dried from the rock body. The apparent density of limestone aggregate is 2.705 g/cm^3, the compact bulk density ρ_G is 1535 kg/m3, and the loose size density ρ_G is 1457.6 kg/m^3. The apparent density of sandstone aggregate ρ is 2.078 g/cm^3, the compact bulk density ρ_G is 1041 kg/m^3, and the loose packing density ρ_G is 972.4 kg/m^3. Figure 1 shows the macroscopic morphology of limestone and sandstone. Figure 2 shows the gradation curve measured by the intermixing of limestone and sandstone in ecological pervious concrete

(3) *Mineral Additive.* To improve the concrete strength, appropriate amount of fly ash [27] was added to concrete specimens at 8% cementitious material, to improve the mixture compatibility and reduce the alkalinity of the concrete without affecting the strength, mainly consisting of the coal ash and slag, with the solid adsorption, and specific gravity between 1.95 and 2.36. The loose dry density ranges from 450 kg/m^3 to 700 kg/m^3, the specific surface area is between 220 kg/m^3 and 588 kg/m^3, and it mainly contains SiO_2, Al_2O_3, and Fe_2O_3. Table 2 shows the performance of fly ash. Table 3 shows the chemical composition content of fly ash

Table 2: The performance of fly ash.

	Fineness/%	Ratio of absorption/%	Burned content/%	Moisture content/%
Index	8.0	80	2.0	0.1

(4) *Mixing water.* Distilled water was used

(5) *Admixture.* High-efficiency water was used to reduce the agent of the polycarboxylic acid. White flowable powder with a bulk density of 565 (g/L) can be observed; the pH value is 7.2; water content is 2.3 (%); the water reduction rate is 20%, and the addition amount is 2% of rubber material, no corrosion to steel bar

3. Methods

3.1. Concrete Mix Proportion. In this experiment, the water-to-cement ratio of the ecological pervious concrete is 0.3, and the target porosity is 25%. The water-reducing agent is determined as 2%. In this case, graded ecological pervious concrete with 15-20 mm particles was prepared with sandstone/limestone volume ratios of 0 : 1, 0.25 : 0.75, 0.5 : 0.5, 0.75 : 0.25, and 1 : 0 volume ratio calculation, namely, 0%, 25%, 50%, 75%, and 100% production of sandstone-to-limestone replacement specimens. The optimum ratio was calculated using the absolute volume method [28], that is, the volume of cemented material slurry + volume of coarse aggregates + volume of target pores = 1 m^3, and the volume of fly ash admixture is included in the volume of cemented material according to the admixture conversion. This test was conditioned on the substitution rate of sandstone for limestone. The coarse aggregate for the test consisted of sandstone and limestone. The volume of coarse aggregate was calculated first with all the coarse aggregate as

Table 3: The chemical composition content of fly ash.

Component	SiO_2/%	Al_2O_3/%	Fe_2O_3/%	MgO/%	CaO/%	K_2O/%	SO_2/%	Na_2O/%
Content	51.3	26.8	7.15	1.29	2.86	1.47	0.45	0.64

Table 4: Proportion of the ecological pervious concrete.

Number	Sandstone dosage (proportion in coarse aggregate)	Coarse aggregates (kg/m^3)		Cement (kg/m^3)	Water (kg/m^3)	Admixture (kg/m^3)	Additive (kg/m^3)
		Sandstone	Limestone				
I	0%	0	1504.3	306.7	92.0	32.8	8.2
II	25%	254.9	1128.2	332.7	99.8	30.8	7.7
III	50%	509.9	752.2	358.3	107.5	28.7	7.2
IV	75%	764.8	376.1	384.3	115.3	26.6	6.7
V	100%	1019.7	0	410.3	123.1	24.5	6.1

limestone, then with all sandstone, and, finally, with sandstone replacing 25%, 50%, and 75% of limestone, respectively. The target porosity was substituted into the calculation according to the specific steps in the following formulas. The optimal proportion of the limestone and sandstone in the coarse aggregate of ecological concrete was determined by a series of tests.

The calculation of the unit volume of coarse aggregate dosage is obtained from the formula $W_G = \alpha \bullet \rho_G$; W_G is the unit cubic meter coarse aggregate dosage (kg/m^3); ρ_G is the correction factor, and we take 0.98 in this paper.

Calculation of unit cubic meter of cementitious material slurry volume, formula $V_P = [1 - \alpha \bullet (1 - V_C) - R\text{void}] \bullet 1000$; V_P is the cement slurry volume (L/m^3); V_C is the aggregate tightly packed void ratio (%); Rvoid is the design target porosity (%).

The calculation of the amount of unit cubic meters of cementing material (including the external admixture) was obtained from the following equation: $W = V_P / R_{W/C} + 1 - \beta_1 / \rho_C + \beta_1 / \rho_S$, $W_C = (1 - \beta_1) \bullet W$, $W_S = \beta_1 \bullet W$; W is the cementitious material slurry volume unit cubic meters of adhesive material dosage (kg/m^3); W_C is the unit cubic meters of cement dosage (kg/m^3); W_S is the design target porosity (kg/m^3); $R_{W/C}$ is the water-to-cement ratio; ρ_C is the density of cement (kg/m^3); ρ_C is the density of external admixture (kg/m^3); β_1 is the mass percentage admixture of external admixture (%).

The calculation of the unit cubic meter water dosage is obtained from $W_W = W \bullet R_{W/C}$; W_W is the unit cubic meter water dosage (kg/m^3).

The calculation of the additive dosage per unit cubic meter was obtained from the formula $W_t = \beta_2 \bullet W$; W_t is the additive dosage per m^3 (kg/m^3); β_2 is the additive mass percentage reference (%).

Following the procedure described above, the trial ratio dose for each group was designed and calculated separately, and the results are given in Table 4.

3.2. Concrete Preparation and Mixing Process.

Firstly, coarse aggregate and half of the water were put into the multifunctional mixer for 30 s, so that impurities such as the stone powder on the surface of coarse aggregate are mixed with the cement paste to improve the interface connection between cement and aggregate and to increase the concrete strength. Secondly, 50% of cement was added and combined for 60 s. The cement and water were combined into a cement paste with good fluidity and were evenly wrapped around the aggregate to reduce the resistance during mixing. Finally, the remaining cement, water, and admixture were thrown into the mixer for 2 min, and the components of the ecological pervious concrete were mixed evenly. The cement slurry continued to cover the aggregate evenly under an action of mixer stirring and, mostly, was connected by points and lines. This makes the ecological planting concrete a high connected porosity and maximizes its strength. The mixed materials were put into a mold to prepare 100 mm × 100 mm × 100 mm specimens. These specimens were maintained in a curing room at a temperature of (20 ± 2) °C and a relative humidity of 96% for 7 days and 28 days. The test was performed with reference to GB/T 50081-2019 [29].

3.3. Molding Process.

The amount of cement paste used to encase the aggregate particles in ecological pervious concrete is small, and strong vibration should be avoided to prevent cement flow from accumulating into the voids and bottom of the concrete, resulting in reduced strength and water permeability. The strength of the specimen formed by pounding is higher than that of the specimen by inserted pounding. The void rate is slightly lower, whereas the difference is insignificant. Considering the strength requirement, it is appropriate to use pounding. The surface of the concrete was rolled flatly to ensure a relatively high porosity and compressive strength of the ecological pervious concrete.

3.4. Actual Porosity.

The type of pore space in the ecological pervious concrete determines its porosity, mechanical properties, and production and construction methods [30]. The effective porosity is the ultimate indicator that determines whether plants can grow or not. The void ratio of the vegetated concrete allows plants to grow in it. The larger the porosity ratio is, the more water and nutrients in the vegetated ecological pervious concrete can promote plant growth

Table 5: Actual porosity of the ecological pervious concrete.

Type	0% sandstone aggregate	25% sandstone aggregate	50% sandstone aggregate	75% sandstone aggregate	100% sandstone aggregate
Porosity (%)	30.64	29.59	30.94	29.68	31.12

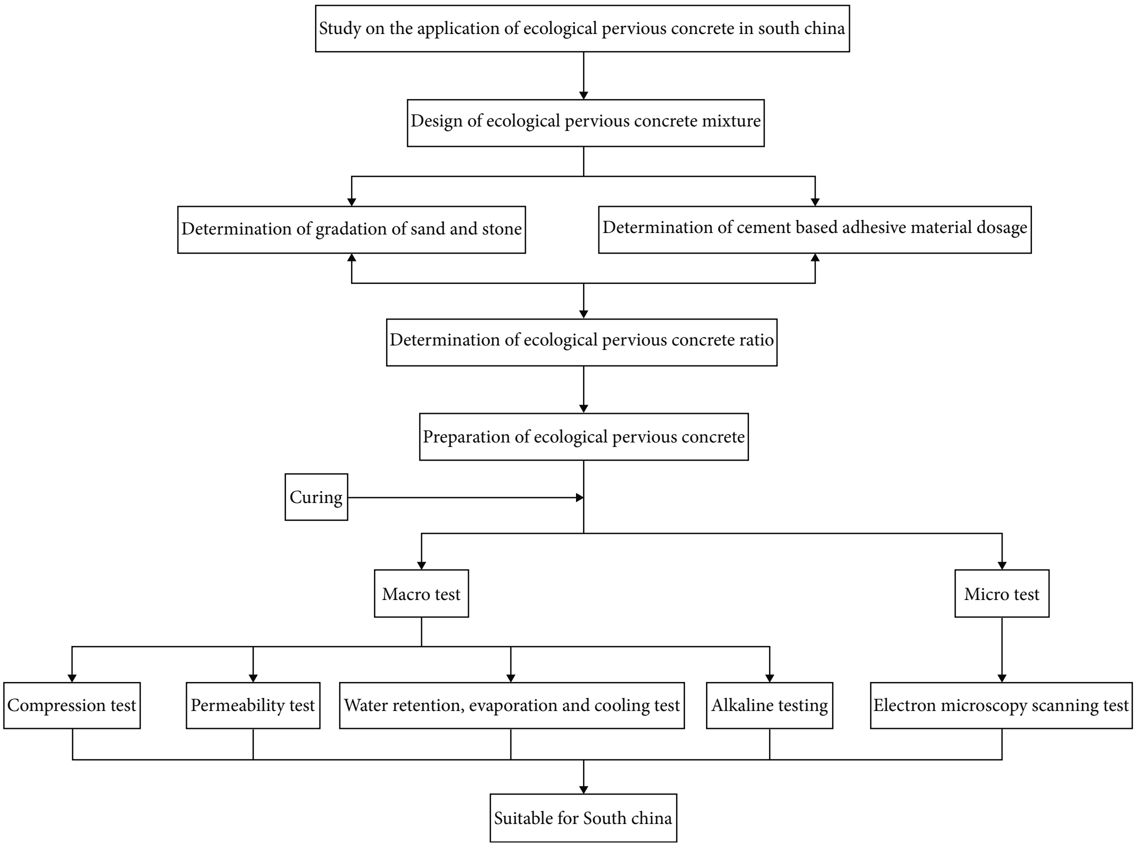


Figure 3: Experimental process diagram of ecological pervious concrete.

[31, 32]. A determination of the effective porosity of the ecological pervious concrete was selected from "Ecological Concrete Slope Protection Technology and Application [33]." Because of the variability of the construction process in each link during the experiment, the final porosity of the ecological pervious concrete differs from the specified porosity. To better study the correlation between the porosity and other properties, the measured porosity is shown in Table 5. The test procedures are as follows:

(1) Use vernier calipers to measure and calculate the appearance volume of the test piece and record as V_1

(2) Submerge the test piece in water until saturation and then weigh the test piece in water with a hydrostatic balance and recorded as W_1

(3) Remove the test piece from the water, drain the internal water, dry the surface water, weigh the test piece in the air after the weight is constant and recorded as W_2

(4) Calculate the effective porosity according to the following formula: $P_0 = 1 - (W_{2-} W_1)/V_1 \times 100(\%)$

It can be found that all of them have a porosity greater than 25%. In addition to the difference in the production process, when mixing concrete, water tends to accumulate in the lower part of the total and form water pockets, resulting in a weaker bond between the cement paste and the aggregate in the interface transition zone. Thus, greater water-cement ratio and porosity were found than the set values.

Figure 3 shows the flow diagram of the whole experiment in this paper.

4. Results and Discussion

4.1. Mechanical Properties of Vegetated Ecological Pervious Concrete. The strength of vegetated ecological pervious concrete is an essential mechanical indicator. Ensuring the stability, it is possible to study other physical properties. The

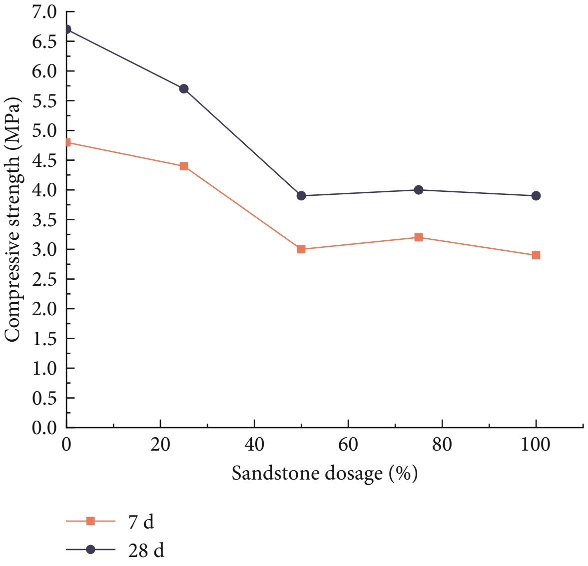


Figure 4: Compressive strength of the ecological pervious concrete.

vegetated ecological pervious concrete material studied in this experiment can be used in the future for road rift and slopes, river and lake bank slopes, residential communities, walls, pavements, and parking lots. Its strength is required to be greater than 5 MPa [34] according to technical specification for application of CECS 361-2013 [35]. Coarse aggregates were converted to sandstone/limestone according to a 0 : 1, 0 : 25 : 0.75, 0 : 5 : 0.5, 0 : 75 : 0.25, and 1 : 0 volume ratio calculation, namely, 0%, 25%, 50%, 75%, and 100% production of sandstone-to-limestone replacement specimens.

In this experiment, the effects of age (7 days and 28 days) and the ratio of limestone-sandstone on the compressive strength of vegetation-type ecological pervious concrete were investigated. Currently, there is no formal standard for the performance index and measurement method of concrete ecological material. The "Concrete Research Committee for Reducing Concrete Burden" under the Japan Concrete Association proposed the "Draft Test Method for Porous Concrete Performance" in 1998 [22]. Nowadays, for the macroporous concrete or permeable concrete, most of the tests are carried out with reference to the test method for ordinary concrete, and 100 mm × 100 mm × 100 mm square test blocks are taken, according to the Chinese national standard GB-T 50081-2019 [29]. The test results are shown in Figure 4. Figure 4 shows a plot of the compressive strength versus the sandstone dose, showing that this is the plot of the compressive strength of the specimen versus the replacement rate of the coarse aggregate of the sandstone.

In Table 6, it can be found that the 28 d strength of concrete made from limestone as coarse aggregate is up to 7.2 MPa, and the strength of concrete specimens made from sandstone as coarse aggregate is up to 4.2 MPa. For the 28 d strength of 0% sandstone aggregate specimens (all limestone), the highest strength is 7.2 MPa, and the lowest strength is 6.3 MPa, with a difference of 0.9 MPa, indicating that the strength is not only related to the aggregate but also due to the differences in the production process: the speed of loading the ecological pervious concrete into the mold and the degree of vibrating will affect its strength.

From the graph of the relationship between compressive strength and sandstone dosage in Figure 4, it can be seen that the compressive strength decreases with the increase of sandstone-to-limestone ratio, and there is a certain rule that the compressive strength of phytolithic ecological concrete decreases with the increase of sandstone content under the same porosity. Based on the relationship curve between compressive strength and sandstone dosage, it can be speculated that at the critical value of 5 MPa, 0% sandstone aggregate specimens and 25% sandstone aggregate specimens meet and exceed their requirements, and when the sandstone-to-limestone ratio is 0.32 : 0.68 (the substitution rate of sandstone for limestone in ecological pervious concrete is 32%), the strength of the specimens can exactly meet the compressive strength requirement of 5 MPa for ecological concrete. If the amount of sandstone is further increased to enhance water retention and reduce the evaporation capacity of the concrete, it will be beneficial to optimize the concrete performance. However, if the sandstone dosage exceeds 0.32/0.68 (the substitution rate of sandstone for limestone in ecological pervious concrete is 32%), the mechanical properties and other important properties of the concrete may be affected. This requirement is not met when the ratio of sandstone-to-limestone continues to increase. When the ratio of sandstone-to-limestone is greater than 0.5/0.5 and the ratio of sandstone-to-limestone is 50%, the compressive strength remains essentially the same and is less affected by test error.

From the analysis of 0% sandstone aggregate specimens and 100% sandstone aggregate specimens, the fracture surface of the 0% sandstone aggregate ecological pervious concrete specimens was mostly located at the junction of cement paste and limestone aggregate when the compression damage occurred, indicating that the limestone itself has a higher strength and has less influence on the strength of ecological pervious concrete, and the limestone in the aggregate plays a full role in its skeletal support. In contrast, fracture in all-sandstone preconcrete occurs primarily at the aggregate when compressive damage occurs, suggesting that the strength of the sandstone in the aggregate has a greater influence on the strength of the specimen. Therefore, the low strength of the concrete test blocks and the poor integration of the cement paste with the aggregate, due to the large porosity of the sandstone, the strong water absorption, and the easy destruction of the aggregate itself at a certain value of the sandstone replacement rate, result in a lower compressive strength.

4.2. Permeability of the Vegetated Ecological Pervious Concrete.

To study the permeability performance of the vegetated ecological pervious concrete, the test was conducted using the relevant provisions of CJJ/T 135-2009 [36] technical specification for permeable cement concrete pavement. Specimens were tested according to its recommended standard head method, which means that the inlet and the outlet have a constant head difference. The test apparatus for

Table 6: Individual strength of each ecological pervious concrete sample.

	7 d strength 1	7 d strength 2	7 d strength 3	7 d mean strength	28 d strength 1	28 d strength 2	28 d strength 3	28 d mean strength
0% sandstone aggregate	4.9	4.5	5.1	4.8	6.3	6.5	7.2	6.7
25% sandstone aggregate	4.4	4.2	4.5	4.4	5.2	6.1	5.9	5.7
50% sandstone aggregate	3.5	3.2	2.3	3.0	4.3	4.2	3.2	3.9
75% sandstone aggregate	3.7	3	2.8	3.2	3.8	4.2	4.0	4.0
100% sandstone aggregate	3.5	2.8	2.3	2.9	3.6	3.9	4.2	3.9

Figure 5: Ecological pervious concrete permeability test process.

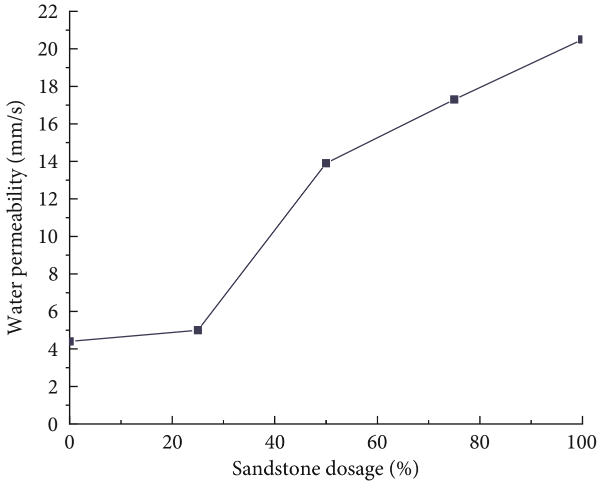


Figure 6: Permeability of the ecological pervious concrete.

determining the permeability coefficient by the standard head method is shown in Figure 5.

Figure 6 shows the testing process, and Figure 6 shows that all-sandstone ecological pervious concrete has the most incredible permeability and all-limestone ecological pervious concrete has a poorer permeability. It is strongly related to the permeability of the aggregate itself. In Figure 6, when the critical sandstone/limestone value of 0.32/0.68 satisfies 5 MPa strength of the ecological pervious concrete, the critical optimum permeability energy of 9 mm/s is reached. Sandstone, as a widespread species in ores, has a high water content and water absorption through its porous and lightweight. Its permeability performance is found to be better than that of the ecological pervious concrete with 0% sandstone under the same water-to-cement ratio. It can be seen that the permeability performance meets the standard with the maintenance of large porosity.

In this test, the specific steps for testing the permeability coefficient are as follows.

(1) Take 3 pieces of pervious ecological concrete with dimensions of 100 mm × 100 mm × 100 mm, wipe up the surface, measure the length, width, and thickness with a steel ruler, measure them 2 times, take the average value, and calculate the cross-sectional area (A).

(2) Seal the test pieces with PVC adhesive to ensure that the water only infiltrates from the top to bottom surface of the test piece

(3) Soak the sealed test pieces in water, after there is no bubbles emerge, take them out and put them into the water permeability measurement test device, then put the device into the water sink, open the water valve, fill the device with water until the water in the sink starts to overflow, and adjust the water intake to maintain a certain head (about 150 mm) in the water permeability cylinder. After the overflow of the sink and the cylinder is stabilized, use a measuring cylinder to collect water from the overflow port of the sink, record the water output within 5 min (Q), measure 3 times, and take the average value

(4) Use a straightedge to measure the head difference between the permeable cylinder and the overflow sink, accurate to 1 mm

(5) use a thermometer to measure the temperature of the water in the overflow tank in the test (T), accurate to 0.5°C

The formula for calculating the permeability coefficient measured by the normal head method is as follows

$$K_T = \frac{\mathrm{QL}}{\mathrm{AH}t} \times \frac{\eta_T}{\eta_{15}}, \tag{1}$$

where K is the water permeability coefficient at the temperature of T °C and constant head; Q is the water volume that comes out in t seconds; L is the thickness of the test piece; A

Table 7: Water retention of the ecological pervious concrete.

Test blocks	After drying/kg	After immersion in water/kg	Soak dry/kg	Water absorption per unit mass
0% sandstone aggregate	1.6517	1.6710	0.0193	0.0117
25% sandstone aggregate	1.6035	1.6316	0.0281	0.0175
50% sandstone aggregate	1.3641	1.4243	0.0602	0.0441
75% sandstone aggregate	1.3362	1.3962	0.0600	0.0449
100% sandstone aggregate	1.3085	1.3676	0.0591	0.0452

is the top surface area of the specimen; H is the water level difference; t is the time of the test; η_T is the coefficient of dynamic viscosity of water at T °C; η_{15} is the coefficient of dynamic viscosity of water at 15°C.

4.3. Water Retention Properties of Vegetated Ecological Pervious Concrete. To study the water retention properties of environmental concrete, concrete ecological specimens with different sandstone-to-limestone ratios and concrete ecological models with 0% sandstone and 100% sandstone were formed for a comparison. After the models were formed and cured for 7 days, they were put into an oven and dried at 60°C for 24 hours, and then were soaked for 24 hours. The specimens were removed and weighed.

Because of its good water retention and thermal conductivity, the ecological pervious concrete can speed up the discharge of standing water and reduce the pressure of drainage channels when rainfall is concentrated. The evaporation of stored water in hot weather can reduce the temperature of road surface, so that it can carry out robust temperature self-regulation and balance in high temperatures. To a certain extent, it can act as a natural vegetation and play an excellent environmental protection effect, so that high temperatures usually do not occur. The sandstone aggregate has a solid ability to absorb and lock water, as shown in Table 7. The higher the sandstone-to-limestone ratio is, the stronger the water retention capacity of the ecological pervious concrete is, and the more it can reduce the road temperature in hot weather. The more substantial water retention capacity means more water in the pores of the test block, which is more conducive to the survival of organisms.

4.4. Cooling Performance of Vegetated Ecological Pervious Concrete. Grabois et al. showed [37] that the self-compacting lightweight concrete has better thermal insulation properties than the normal self-compacting concrete due to the presence of porous aggregates. To investigate the cooling performance of porous concrete [38], concrete ecological specimens with individual sandstone and limestone proportions were used for a comparative study. After the models were wholly immersed in water for 24 hours, the surface temperature of the models was tested using an infrared thermometer under natural outdoor conditions. The temperature was measured using the infrared thermometer per hour from 10:00 a.m. to 4:00 p.m. under natural outdoor conditions. Three sets of experimental data were measured each time and were averaged. The test results are shown in Figure 7.

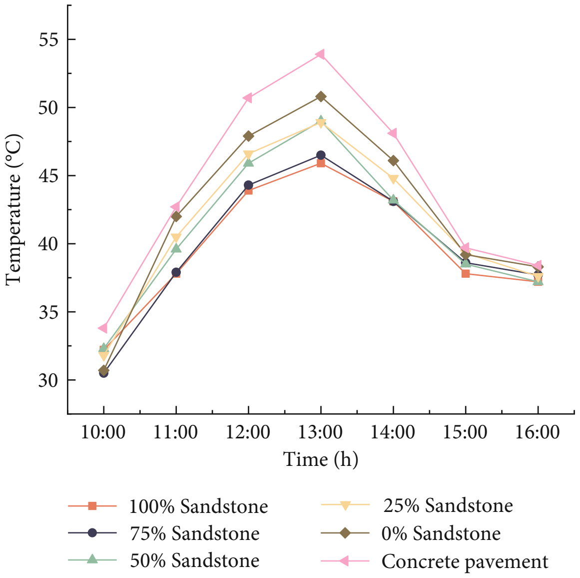
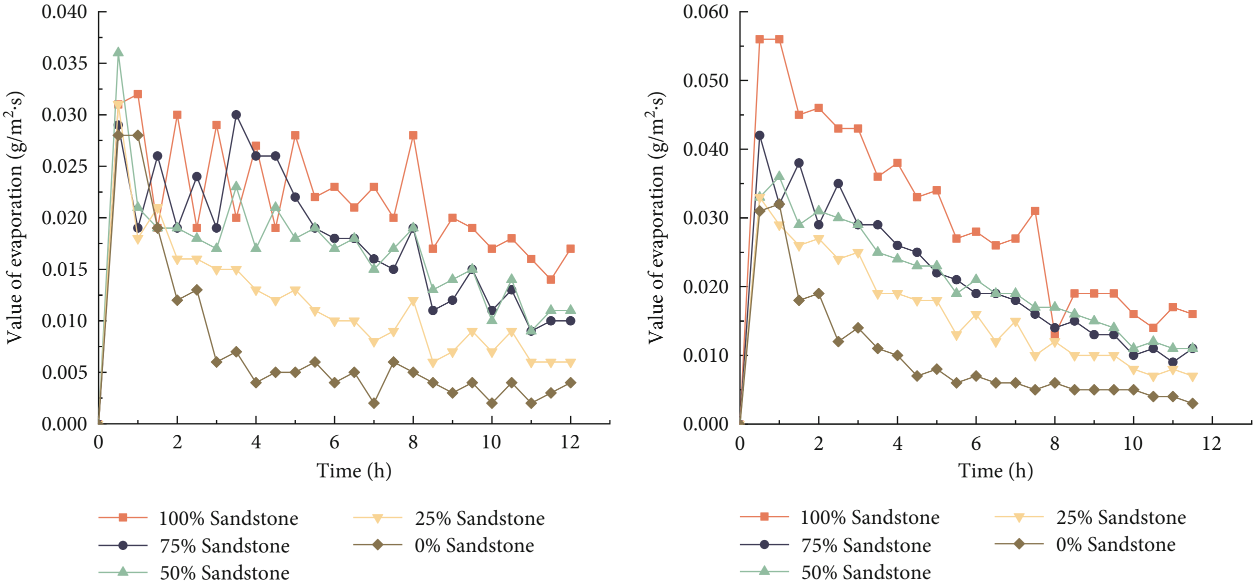


Figure 7: Temperature history of the ecological pervious concrete.

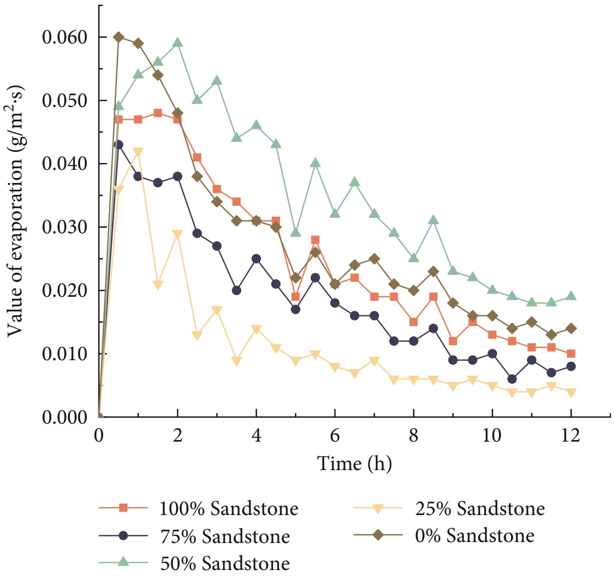
As shown in Figure 7, a lower temperature of the ecological pervious concrete was found compared with that of the normal above-ground concrete. This is because the ecological pervious concrete structure has good heat transfer channels, which allows a strong temperature self-regulation and equilibrium. Numerous connected voids allow heat to be transferred through the voids. The water stored in sandstone in ecological pervious concrete is more than that stored in limestone. Under long-term sunlight, by absorbing a lot of heat, water evaporates and dissipates through gaps. Therefore, the higher the replacement rate of sandstone, the lower the temperature measured. Repeating this process in hot summer days takes away a lot of heat from the pavement and stores the heat inside the concrete. The surface usually does not get hot, thus achieving a cooling effect. Therefore, such concrete is suitable for hot areas.

4.5. Evaporative Properties of Vegetated Ecological Pervious Concrete. To study the evaporative properties of porous concrete models [38], several groups of formed porous concrete specimens and plain concrete specimens were used for comparative studies. After a 28-day curing, the specimens were wholly immersed in water for 24 hours and then dried in an oven at 40°C, 50°C, and 60°C, and they were weighed every 30 minutes for twelve hours. The test results are shown in Figure 8.



(a) Average water evaporation at 40°C

(b) Average water evaporation at 50°C



(c) Average water evaporation at 60°C

Figure 8: Average water evaporation per ecological pervious concrete and hour under different working conditions: (a) 40°C, (b) 50°C, and (c) 60°C.

From the above test results, it can be seen that the evaporation rate of all specimens decreased overall during the 12 hours of testing, with a larger decrease from 0 to 3 hours, a smaller decrease from 3 to 9 hours, and a slight decrease after 9 hours, which was almost insignificant. The higher the temperature is, the greater the evaporation rate and evaporative property are. In other words, the ecological concrete can maintain a high evaporation rate in the first 3 hours, and the evaporation effect gradually decreases from 3 to 9 hours. After 9 hours, almost no evaporation effect occurs. In addition, in the models containing sandstone, the higher the sandstone admixture is, the better the evaporation effect is. The higher the temperature is, the stronger the evaporation effect is, and the more significant the decrease in evaporation rate is, at the same sandstone-to-limestone ratio. In the all-limestone specimen, the decline is unchanged because water absorption is weak. Then, when the sandstone admixture increases, the evaporative effect of the ecological pervious concrete prolongs. This finding indicates that the specimens with more sandstone content absorb more water, and thus, more water is available for evaporation.

4.6. Suitability of Concrete Ecological Planting Organisms. The pH value of vegetative ecological pervious concrete has always been an important indicator of the performance of vegetation. The strong alkaline substances inside the ecological pervious concrete are detrimental to plant growth and

Table 8: pH values of the ecological pervious concrete.

Type	0% sandstone aggregate	25% sandstone aggregate	50% sandstone aggregate	75% sandstone aggregate	100% sandstone aggregate
7 d	11.50	11.62	11.34	11.53	11.25
28 d	9.86	9.87	9.44	9.64	9.56

development [8], resulting in the inability of plants to survive. Therefore, while ensuring the compressive strength of ecological pervious concrete, the lower the internal pH value, the more suitable for plant growth. The phytogenic ecological pervious concrete has large porosity and permeable and breathable properties. The growth and development of vegetation require specific space and nutrition, which can provide a suitable living space for animals, plants, and microorganisms [39, 40] to carry out normal physiological activities as long as the pH value is lower than 10 [41]. In this experiment, the soluble alkali of the designed planted concrete was mainly precipitated by the cement slurry, so testing the external water value of the cement slurry can reflect the condition of large pore alkali environment for plant growth in planted concrete [42]. Further, after the models were formed and raised to 7 days and 28 days, the models were taken as roughly 20 mm × 20 mm × 20 mm cubic specimens after measuring the mechanical properties and being placed in a wide-mouth bottle containing 2500 mL distilled water in a wide-mouth bottle. The pH value of the aqueous solution after immersion was tested to evaluate the effect of exotropia alkali on the plant growth environment of the planted concrete [43].

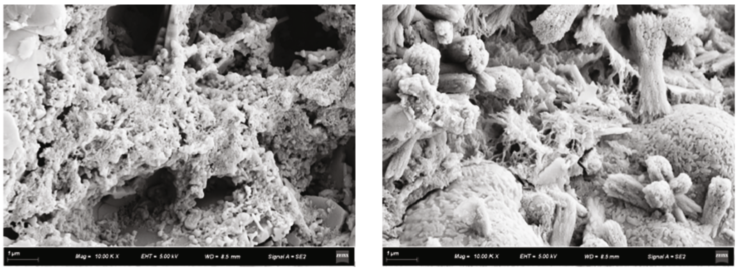
As can be seen in Table 8, with 8% of the fly ash admixture, the pH value is basically around 11 at 7 days. After 28 days, the pH value has dropped to around 9. It can be found that the pH value of the ecological pervious concrete test blocks decreases with the proportion of admixture of fly ash. The main reason for fly ash to achieve the effect of alkali control is because a large amount of SiO_2 is contained in it. The release of hydroxyl ions during the hydration of cement creates a high alkaline environment, making it difficult for plants to grow on the surface. Fly ash contains a large amount of SiO_2, which can consume a large amount of $Ca(OH)_2$ to reduce alkalinity, thus creating a favorable growth environment for plants. Therefore, fly ash is used to replace the cement in ecological pervious concrete to reduce alkalinity. The alkalinity of ordinary concrete is generally above 12 for a demand of high strength, while the ecological pervious concrete by reducing alkalinity achieves the pH conditions required for plant growth.

4.7. Microanalytical Study of Vegetated Ecological Pervious Concrete. This test is aimed at analyzing the microstructure morphology of ecological pervious concrete, qualitatively analyzing the formation mechanism of macroscopic strength through microstructure, and comparing the consistency between microscopic analysis results and macroscopic strength test results. The ecological pervious concrete was taken out after 28 days of standard curing and was left in the natural environment for 1 day. Tiny concrete fragments were randomly cut in the center of the specimen. Then, the slices were soaked in anhydrous alcohol for 1 day to terminate hydration and were dried to constant weight at 60°C. The part of the concrete cement paste junction with aggregate was selected as much as possible and folded into small pieces of about 1 cm^3. The new sections were coated, and microscopic observation was performed with the Zeiss.

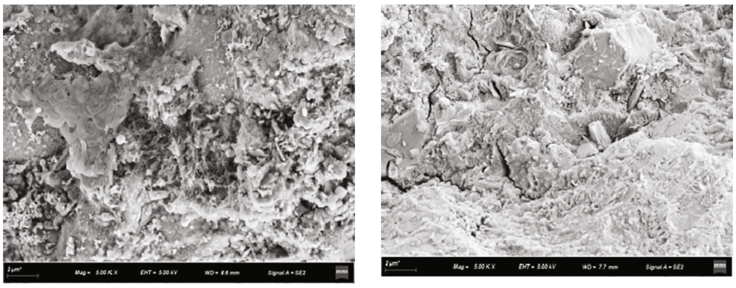
The 7-day all-limestone ecological pervious concrete aggregate on the interface transition zone with the all-sandstone ecological pervious concrete aggregate was selected for electron microscopy scanning. The results are shown in Figure 9.

Due to a difference in the nature of limestone and sandstone aggregates, water absorption of sandstone and limestone has other effects on the transition zone of the ecological pervious concrete interface. The water absorption of the sandstone is 10.56%, and that of the limestone is 0.252%, resulting in a much small water-to-cement ratio and a more minor porosity than the actual water-to-cement ratio when the sandstone is used as coarse aggregate. The hydration products can be observed after further magnification, such as the flaky $Ca(OH)_2$ crystals, the needle-like calcium aluminate crystals, and the fibrous C-S-H gels (Figure 9(a)). Due to a presence of more pores on the aggregate surface, the all-sandstone specimens can absorb moisture easily (Figures 9(a) and 9(b)). It can be seen that some of the cement particles were plunged into the interior of the aggregate and underwent hydration reactions, generating a large amount of calcium alumina, C-S-H, and $Ca(OH)_2$ and forming a dense shell that hindered the entry of humidity. With further reactions, the moisture decreased, and an interfacial transition zone with a relatively loose structure was formed. Compared with the all-sandstone ecological pervious concrete, the denseness of the interfacial transition zone (Figures 9(c) and 9(d)) between the aggregates of the all-limestone specimens is much better. No acicular $Ca(OH)_2$ crystals are found, and the whole cementite matrix is dense and slab-like. However, the structural denseness is poor, and there are more significant gaps in the interfacial transition zone.

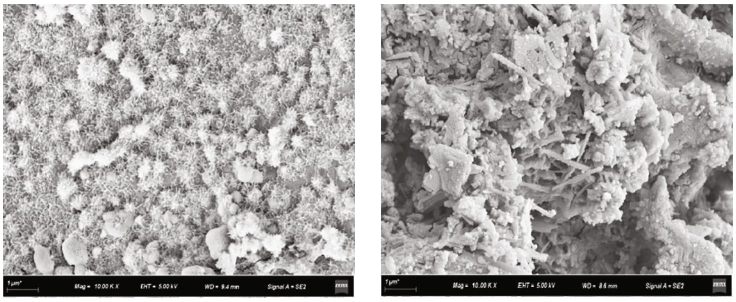
The 28 d all-limestone ecological pervious concrete aggregate on the new cement surface with the all-sandstone ecological pervious concrete aggregate was selected for an electron microscopy scanning, as shown in Figures 9(e) and 9(f). The all-limestone specimens were already very well hydrated, basically dendritic calcium alumina and network-like and coral-like hydrated calcium silicate gel. While the water-to-cement ratio of all-sandstone specimen is more minor, and hydration products were mostly fibrous crystals. The shell prevented the hydration reaction from proceeding further, and cement paste dosage was reduced accordingly. In terms of cement film thickness,



(a) Sandstone 7 days (b) Sandstone 7 days



(c) Limestone 7 days (d) Limestone 7 days



(e) Limestone 28 days (f) Sandstone 28 days

Figure 9: Microscopic morphology of the transition zone of the interface between different aggregates of the ecological pervious concrete curing for 7 days and 28 days.

a thinner cement film is conducive to promoting the hydration reaction more thoroughly. The cement film is denser. This large pore structure is relatively thick, and microscopic cracks are more easily formed. The sandstone aggregates due to water absorption, so the all-sandstone specimen water-to-cement ratio is smaller, the hydration is not sufficient, and the reticular gel particles are rather larger. The 28-day all-limestone specimen interface transition zone denseness is relatively good, and the transition zone gap is also relatively small. The compressive strength is higher than that of the sandstone specimen, which is consistent with the microscopic analysis.

5. Conclusion

To produce the vegetated ecological pervious concrete, the compressive strength, alkalinity, water permeability, water retention, evaporation, and cooling properties of the vegetated ecological pervious concrete were combined with the weather and climate of South China. Limestone is replaced by sandstone in gradual proportion, and the permeability, water retention, evaporation, and cooling properties significantly increased. In summary, it had a potential application in ensuring various types of performance in vegetated ecological pervious concrete. The main conclusions are as follows:

(1) Limestone and sandstone from the Guilin region were used, and two of their coarse aggregates were used to configure the ecological pervious concrete. The 28 d strength of concrete made of limestone as coarse aggregate can be up to 7.2 MPa, and the strength of concrete test block made of sandstone as coarse aggregate can be up to 4.2 MPa. When the sandstone-to-limestone ratio was more significant than 0.32/0.68 (sandstone replacement rate is 32%), the test block strength was 5 MPa and met the requirements of the ecological pervious concrete. When the sandstone-to-limestone ratio was more significant than 0.5/0.5 (sandstone replacement rate is 50%), the strength was basically unchanged, and the strength of sandstone in the aggregate plays a controlling role in the strength of the ecological pervious concrete due to a lower strength of the sandstone and a higher strength of the limestone in aggregate itself

(2) Due to a strong water absorption and pores, the sandstone aggregate achieved the optimal permeability of the ecological pervious concrete of 9 mm/s when the 5 MPa strength was reached

(3) When the sandstone-to-limestone ratio is more extensive, the permeability, water retention, evaporation, and cooling performance of the ecological pervious concrete increase. Therefore, the concrete is favorable for use in areas with hot weather and rainfall, such as southern China

(4) With the effect of admixture fly ash, compared with ordinary concrete, the ecological pervious concrete achieved a low alkali environment required for plant growth with the pH value of less than 10 and as low as 9.44

Data Availability

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

Conflicts of Interest

No potential conflict of interest was reported by the authors.

Acknowledgments

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