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Case study

State-of-the art on preparation, performance, and ecological applications of planting concrete

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ABSTRACT

Planting concrete (PC) is a type of sustainable concrete. It remains challenging to prepare and design a PC by considering complex factors such as voidage and alkalinity. In this paper, preparation and mix design methods of PC are reviewed and compared, with particular emphasis on the influence of various factors on permeability, mechanical properties, durability, and plant compatibility. Alkali reduction measures, vegetation testing, and plant compatibility cannot be ignored in the design of PC. 25~30% voidage and 8–10 pH can ensure the durability of vegetation concrete, physiological characteristics of plants and fertilizer retention performance. In addition, the paper summarizes the application of PC in water purification, slope protection and green roof establishment. The cost and applicable conditions of different slope protection methods are further compared and analyzed. Finally, several essential areas that require further research efforts are suggested based on the current research results, including research direction and challenges of PC.

1. Introduction

As a widely used building material, concrete invisibly changes human living environment. The development of society gradually enhances people's awareness of protecting the natural ecological environment. In this context, making concrete compatible with ecological environments on the premise of satisfying essential functions has posed a new challenge. In the early 1990s, the Japan Concrete Institute (JCI) took the lead in proposing the concept of "eco-concrete" [1]; following that, the concept of "planting concrete (PC)" emerged.

PC, also referred to as vegetated concrete or planting eco-concrete, is an eco-concrete available for planting and greening [2]. As a unique eco-friendly sustainable material, PC is composed of cement, water, and usually a single-gradation coarse aggregate with little fine aggregate [3–9]. PC consists of surface soil, porous concrete, water-retaining materials, and nutrients [2]. Surface soil is generally used to bury plant seeds, providing a suitable environment for their initial germination and growth. Porous concrete serves as the skeleton, while water-retaining materials and nutrients fill the voids to provide growth conditions for plants.

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Researchers have conducted various studies on PC. At present, research on PC mainly includes design methods [2,3], mechanical properties [4,5], permeability [4–6], alkaline environment [6,8], durability [7,9,10], and ecological applications [11–13]. However, most of these studies have mainly been conducted from a single engineering perspective. For example, when designing PCs, many researchers only focus on the target permeability and mechanical properties, often ignoring the alkaline environment of plant growth. The growth conditions of plants require PC to have high voidage and low alkalinity, but the premise of good durability is that PC has excellent mechanical properties and low voidage, which seems contradictory. In addition, when conducting ecological application research, there is a lack of attention to the growth characteristics of plants, especially the compatibility between plants and concrete. Therefore, there are still many issues that need to be further addressed in the preparation methods, durability, and plant compatibility of PC, such as voidage, frost resistance, and high alkalinity.

In fact, the design and ecological application of PC is a multidisciplinary issue, including civil engineering, ecology, botany, landscape architecture, etc. Therefore, this article critically reviews the preparation and performance of PC from a multidisciplinary perspective, and elaborates on the effects of various factors on the permeability, mechanical properties, durability, and plant compatibility of PC. In addition, this paper also summarizes the application of PC in water purification, slope protection, and green roof construction. The cost and applicable conditions of different slope protection methods were compared and analyzed through engineering cases. Finally, several essential areas that require further research were identified, including the research direction and challenges of PC.

2. Design and preparation methods of PC

2.1. Material selection

2.1.1. Cement

Cement is the main component of PC. To produce PC, low-alkalinity cement should be used in terms of cement varieties. Since plants growing in PC need to grow in an alkaline environment with a pH value of 8–10 [14], PC incorporating low-alkalinity cement as binding materials can create a more suitable alkaline environment for plant growth. The cement used for PC mainly includes P·O 42.5, P·O 52.5, sulphoaluminate cement (SAC) and calcium aluminate cement (CAC). Compared with Portland cement, the content of CaO in SAC clinker is lower, and the alkalinity in its system is lower than that in the Portland cement system. The use of SAC can reduce the alkalinity of concrete and is more suitable for plant growth. Chenchen Gong [2] et al. adopted SAC as the binding material and mixed it with different dosages of carbamide. The 28d pH values of the concrete products obtained were all close to 8.31. In a different study, Xiaohua Bao [10] et al. used CAC to improve the survival rate of vegetation. The pore solution pH value of CAC was 8.7–9.9, lower than that of Portland cement (13.5–13.9).

Table 1 shows the effect of different types of cements on the performance of PC. When the water-to-cement ratio is small (i.e. ≤0.22), the strength of the PC with P·O 42.5 cement is higher than that with SAC cement. This may be because fast setting cement (i.e. in this case SAC) hardens faster and despite the addition of some amount of retarder, it still suffers from rapid loss of workability, leading to weakening of the inter-aggregate bond, which has a negative impact on compressive strength. When the water-to-cement ratio increases to 0.30–0.33, the compressive strength decreases substantially with the increase of aggregate ratio. However, the effect of using P·O 52.5, P·O 42.5 and SAC cement on the compressive strength is negligible at a similar aggregate-cement ratio. This is mainly because when the water-to-cement ratio is larger, the slurry fluidity is better and the time loss is low, which greatly reduces the effect of cement variety on the bonding properties of the slurry between the aggregates, so it almost does not affect the compressive strength. However, SAC generally shows fast hardening characteristics, and the workability decreases rapidly during construction, which has higher requirements for construction technology. In addition, the drying shrinkage, frost resistance and sulfate resistance of SAC are relatively poor [15]. In arid and sulfate-corrosive environments, the use of SAC to prepare PC still has many technical challenges.

Table 1
The influence of material selection on the performance of planting concrete.

Cement type	w/c	Aggregate-binder ratio	Aggregate particle size /mm	Voidage /%	pH	Permeation coefficient	Compressive strength /MPa	Reference
P·O 42.5	0.22	4.8–6.3	10–16	24.30–29.07	10.02–10.34	*	11.75–18.99	[16]
		5.3–6.8	16–25	26.15–28.89			9.66–16.22	
		5.3–6.3	10–25	26.14–30.04			11.23–16.25	
	0.33	7.8	16–20	29.78–33.28	12.0–12.5	2.24–2.35	4.75–5.39	[17]
		7.2	20–25	28.83–30.13		2.16–2.36	3.50–3.71	
		6.7	25–30	29.92–31.44		2.22–2.33	2.87–3.15	
P·O 52.5	0.30	4.91–5.47	10–20	25	12–12.14	*	8.5–11.8	[18]
SAC 42.5	0.33	8.0	16–20	29.77–30.81	7.0–7.5	2.39–2.50	4.19–5.17	[17]
		7.4	20–25	29.71–30.80		2.30–2.38	3.48–3.78	
		7.9	25–30	30.84–33.19		2.44–2.71	2.42–2.93	
	0.22	5	26.5–31.5	35.1	8.2	3.65	7.8	[19]
CAC	0.4	5	20	31.9	9.7	*	1.67	[15]

* Note: indicates that relevant data have not been obtained from references.

2.1.2. Coarse aggregate

When selecting coarse aggregates for preparing PC, parameters including particle size, shape, and material should all be considered appropriately. Among them, coarse aggregate particle size significantly affects the planting properties of PC. Single-graded stone gravel coarse aggregate, which is more conducive to the formation of continuous voids. Regarding shape selection, coarse aggregate should meet the requirements of small flake content, a clean surface, and few impurities [20]. For this reason, coarse aggregate should be selected and cleaned before is added to PC mixtures. A wide range of materials is available as coarse aggregates for the preparation of PC, including recycled brick aggregates, waste glass, wood fibres, and ceramsite. In this context, PCs containing different coarse aggregates have been the main focus of researcher in the field of PC [21–25]. Park Seung-Bum [26] et al. discovered that the higher the replacement ratio of recycled aggregates, the smaller the differences in the voidage and strength characteristics of PC made of recycled aggregates compared with PC without recycled aggregates. Considering that plant growth requires a voidage of 20%–30% and a capillary suction of above 20% to retain water, Jeon In-Ki [27] prepared PC with a minimum strength of 3 MPa by taking orchid stones as the aggregates with a cement-to-aggregate ratio of 30% by weight as the basic mix proportion. Sung Chan Yong [28] analyzed the effects of aggregate particle size on voidage and strength characteristics using crushed gravels of 5–10 mm and 5–20 mm in size.

Fig. 1 shows the relationship between PC's compressive strength and aggregates' average particle size under a similar water-binder ratio and voidage. As the average particle size increases, the compressive strength gradually decreases. This is because under the same voidage, the PC prepared with larger particle size aggregates requires less binding material, and the contact bonding area between aggregates is reduced, resulting in lower concrete strength. In addition, the average size of aggregates in the range below 22.5 mm generally ensured a compressive strength of 8 MPa. It can be inferred from the literature that the particle size range corresponding to the average particle size of 15, 17.5 and 22.5 mm is 10–20, 15–20 and 19–26.5 mm, respectively. That is to say, the use of 10–26.5 mm particle size aggregates to prepare porous PC can satisfy the requirements of voidage and compressive strength at the same time for plant growth.

2.1.3. Admixtures

Adding mineral admixtures (i.e. supplementary cementitious materials) such as fly ash (FA), slag (S), limestone powder and silica fume (SF) to binding materials is an important way to reduce the amount of cement. Suitable admixtures can improve the strength of PC and reduce the alkalinity in the pores of vegetation concrete [1,10,16]. Shiqi Cui [33] et al., who observed and analyzed the microstructure, type, and state of PC by scanning electron microscopy and X-ray diffraction, found that slag powders significantly improved the strength and durability of PC. Chenchen Gong [25] et al. prepared a low-alkalinity planting cementitious material (PCM) by adding limestone powders and found that increasing the dosage of limestone powders caused the pH value of PCM to decline significantly. Analysis revealed that $Ca(OH)_2$ activated limestone powders from hydrated clinker, reducing the cementitious material's pH value. The specific reaction can be expressed by Formula (1).

$$3(3CaO\cdot 3Al_2O_3\cdot CaSO_4)+3(CaSO_4\cdot 2H_2O)+2CaCO_3+3Ca(OH)_2+92H_2O\rightarrow 2(3CaO\cdot Al_2O_3\cdot CaSO_4+32H_2O)+2(3CaO\cdot Al_2O_3\cdot CaCO_3\cdot 11H_2O)+5(Al_2O_3\cdot 3H_2O) \tag{1}$$

Fig. 2 shows the relationship between the amount of admixtures and the compressive strength of PC with different types of aggregates. For the PC with ordinary gravel aggregates, although the test data presented in Fig. 2 are under the condition of a water-to-binder ratio of 0.27 and voidage of 25%−30%, the voidage of concrete in different kinds of literature are different, resulting in a large discreteness of the compressive strength results. However, in the same literature test data set, the addition of fly ash and slag within

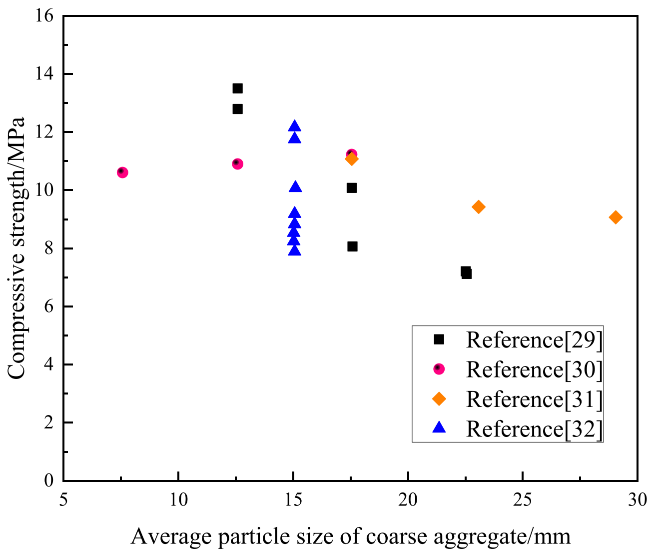

Fig. 1. Variation of compressive strength with the average particle size of aggregates [29-32].

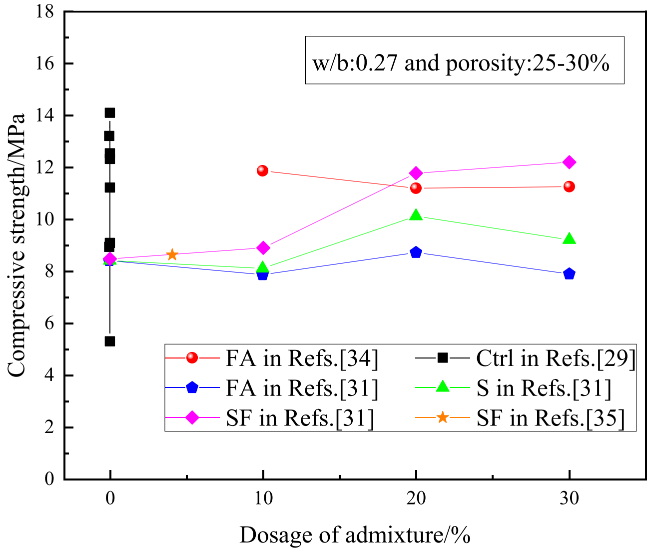

Fig. 2. Compressive strengths of PCs concerning type and content of admixtures [29,31,34,35].

30% by weight of the binding material has little effect on the strength, and the addition of silica fume within 10% by weight has little effect on strength. Adding more than 20% by weight silica fume can greatly improve compressive strength of PC. Compared with ordinary concrete, the effect of adding admixtures in PC is relatively small, especially the strength improvement effect of silica fume is limited. Therefore, using silica fume as an enhancement method is not economical. Although mineral admixtures can have a secondary hydration reaction with $Ca(OH)_2$ to promote the cement matrix densification, the PC has high voidage, and the density of the cement matrix at the micro level cannot effectively improve the overall voidage, so the improvement of the compressive strength is limited. As shown in Fig. 2, for ceramsite lightweight aggregate planting concrete, adding different types or composite admixtures, the overall compressive strength is slightly higher than that of the specimens without admixtures, but the strength improvement effect is not significant.

Therefore, fly ash, limestone powders and slag can be appropriately added to the binding materials of PC to reduce the amount of cement and achieve greater greenness and lower carbon emissions. However, adding a small amount of silicon powders to PC does not effectively improve its strength.

Table 2
Comparison of mixture design methods of PC.

Methods	Steps	Advantages	Disadvantages
Volume method [38,39]	Calculate the mix proportion after the sum of the volume occupied by each constitutive component and the target pore volume equal to the PC's volume.	Effectively control the target voidage and master its characteristics.	When the amount of cement slurry is large, the difference between the measured voidage and the target voidage is significant; it is necessary to measure the density of cement and mineral admixtures and the apparent density of aggregates, which requires slightly higher technical conditions.
Mass method [40]	Assuming that the apparent density of PC is within a certain range, calculate the amount of materials based on the empirical method.	Simple and easy for construction	The difference between the actual voidage and the target voidage can be large.
Specific surface area method [41,42]	Similar to traditional concrete mix design, however, various correction factors are needed to modify the calculation results.	The actual voidage is close to the target voidage.	The correction factor greatly influences the results; the design and calculation process is cumbersome; the requirements for raw materials are high.
Method of surrounding spherical model [43,44]	The ordinary shape aggregates are transformed into a spherical model with the centroid of the aggregate as the centre and the particle diameter as the diameter. The total number of aggregates per unit volume and the total surface area are measured in a tightly packed state, and the coarse aggregate is wrapped with cement slurry. The thickness and water-to-cement ratio determine the amount of cement and water.	It is easy to study the change law of concrete performance from the internal pore structure of the material.	The design and calculation process is cumbersome; the coating slurry's thickness and the coarse aggregate's bulk density have large dispersion.

2.1.4. Other materials

Park Seung-Bum [26] et al. evaluated the effects of the proportion placement level of recycled aggregates and the applicability of porous concrete as planting material in the combined usage of carbon fibres (CFs) and silica fume (SF). In the case of using SF, a 10% by weight mixing ratio of SF exhibited the most effective contribution to obtaining higher strength. When CF was used, a CF mixing ratio of 3% by volume obtained the highest flexural strength, and PAN-derived CF was far better than the Pitch-derived CF. Chan-Yong Sung [36] et al. prepared PC using rice straw ash and found that the voidage, compressive strength, and flexural strength of PC increased with increasing rice straw ash content. Chan-Yong Sung [37] et al. reported the strength evolution of porous polymer concrete using unsaturated polyester resin. The compressive strength of the prepared PC was noted in the range of 17.1–23.2 MPa. The research results showed that compressive strength depended on the dosage of the binder and that, for the same binder dosage, a larger aggregate size led to a higher compressive strength.

2.2. Mix design

Since PC contains no fine aggregates, it cannot be designed according to the mix design methods for traditional concrete. Regarding the properties of PC, commonly used methods for mixture design include the volume method, the mass method, the specific surface area method, and the surrounding spherical model method. The specific mix design methods and their advantages and disadvantages are presented in Table 2. The main parameters used for the mix design of PC include water-to-cement ratio, coarse aggregate particle size and gradation, aggregate-binder ratio, and voidage. These parameters will be discussed and elaborated in detail below.

2.2.1. Voidage

Voidage is the main factor affecting the strength of PC, and it is also the critical factor influencing the growth of vegetation planted in PC. To meet the requirements of plant growth and the service functions of concrete structures, the PC prepared should have a voidage of 25%–30% [45]. If the voidage of PC is too small, it will be inconducive to the growth of plant roots and their capacity of absorption of nutrients to support plant growth. On the other hand, if it is too large, it will affect the strength of the PC. Without special requirements for PC strength, its voidage can be appropriately increased [42]. Xiaobo Yan [46] et al. believed that the thickness of cement paste on coarse aggregate surface determined the pore structure characteristics and performance of PC to some extent. They also found that the pore structure characteristics obtained by the volume fraction and area fraction methods were highly correlated. Xiaokang Liu [47] et al. discovered that the voidage of porous concrete increased with increasing coarse aggregate particle size and that the total voidage and interconnected voidage presented the same evolution trend. The porous concrete prepared with single-gradation coarse aggregate had a higher voidage than that prepared with continuous-gradation coarse aggregates, indicating that single-gradation coarse aggregates should be preferred in the preparation of porous concrete. Guiling Wang [42] et al. identified the bulk density of aggregate as the primary factor affecting the magnitude of the voidage of porous concrete. They stated that the secondary factors dictating the voidage of porous concrete included the moulding process, the wrapping thickness of the cementitious paste, the stirring method, etc. For aggregates with the same performance indexes, stirring methods make little difference to the voidage of the porous concrete prepared.

Fig. 3 reveals the relationship between the compressive strength of PC with water-to-binder ratio of 0.27–0.30 and the change of voidage. As the voidage increases from 20% to 35%, the compressive strength gradually decreases. This is mainly due to the larger the voidage, the larger the gap between the aggregates, the smaller the bonding contact area between the aggregates, the more uneven the

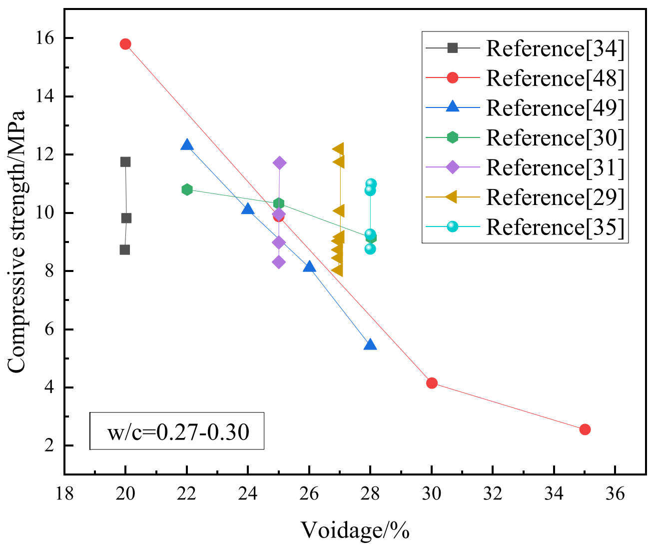

Fig. 3. Effect of voidage on compressive strength [29-31,34,35,48,49].

internal stress distribution during compression, and the strength gradually decreases. Fig. 3 shows that when the voidage is less than 26%, the compressive strength of vegetation concrete is above 8 MPa. Even when the voidage is about 28%, the average compressive strength can reach 8 MPa, which generally meets the strength requirements of PC. In addition, to ensure the compressive strength and plant physiological characteristics of PC, combined with relevant study and standards, it is recommended that the target voidage of planting concrete can be designed to be between 25% and 30%.

2.2.2. Water-to-cement ratio

Water-to-cement ratio plays a decisive role in cement paste's strength and fluidity in the PC mix design. Water-to-cement ratio not only significantly affects the strength of PC but also influences its permeability. Hongzhu Quan [44] et al. found that there is an optimal water-to-cement ratio for the preparation of PC. This is because, for an excessively low water-to-cement ratio, the cement paste on the coarse aggregate surface is minimal, affecting the bonding between coarse aggregates and further compromising the strength of PC. On the other hand, if the water-to-cement ratio is too high, it will lead to more pores in the cementitious material, thereby reducing its compressive strength.

To satisfy the conditions of plant growth, it is generally accepted that the voidage of PC shall be more than 20%. Fig. 4 shows the relationship between the compressive strength of PC prepared with different types of aggregates and the water-to-cement ratio under similar voidage conditions. For the PC with ordinary aggregate, it can be found from Fig. 4(a) that the compressive strength increases and then decreases with the increase of water cement ratio. When the voidage is 25-31%, the compressive strength is higher when the water-to-cement ratio is 0.27–0.33, which is generally above 9 MPa. Even when the water-to-cement ratio increases to 0.35, the compressive strength is still above 8 MPa. For the PC with recycled aggregates, it can be observed from Fig. 4(b) that the test results of different literatures demonstrated certain dispersion. When the voidage is 20%, the compressive strength also shows a trend of increasing and then decreasing. When the water-to-cement ratio is as high as 0.40, the compressive strength is still above 9 MPa. When the voidage is 25% and the water-to-cement ratio is 0.23–0.27, the compressive strength is about 8 MPa. When the water-to-cement ratio is 0.29, the compressive strength measured by Yin [48] is only 4.8 MPa. This may be because the recycled aggregates in their study were obtained by crushing the original concrete, and the strength of the recycled aggregate is ununiform. Moreover, the water absorption of recycled aggregates is large, and the preparation process is different from that of ordinary aggregates, which leads to large dispersion.

In general, the compressive strength of PC required by SL/T 800–2020 [50] is not less than 8 MPa. Therefore, the water-to-cement ratio is recommended as follows: for ordinary aggregates, it is between 0.30 and 0.35water-to-cement ratio; for recycled aggregates, under the condition of ensuring the preparation process and aggregate quality, a water-to-cement ratio of 0.30–0.35 can also be used conservatively.

2.2.3. Amount of coarse aggregates

The particle size and gradation of coarse aggregates directly affect their compacted bulk density ρ_{GC}. The dosages of coarse aggregates and the binding materials per unit volume of PC are determined by the compacted bulk density and target voidage of aggregates. If the difference in voidage between aggregates and PC is too large, the dosage of the binding materials will be increased. It will also make it impossible for the binding materials to evenly wrap aggregates, further reducing effective pore size, increasing concrete alkali content, and lowering interconnected voidage. On the other hand, if the difference in voidage between aggregates and PC is too small, PC strength will be affected. According to Section 2.1.2, the aggregate with a particle size range of 10 ~ 26.5 mm

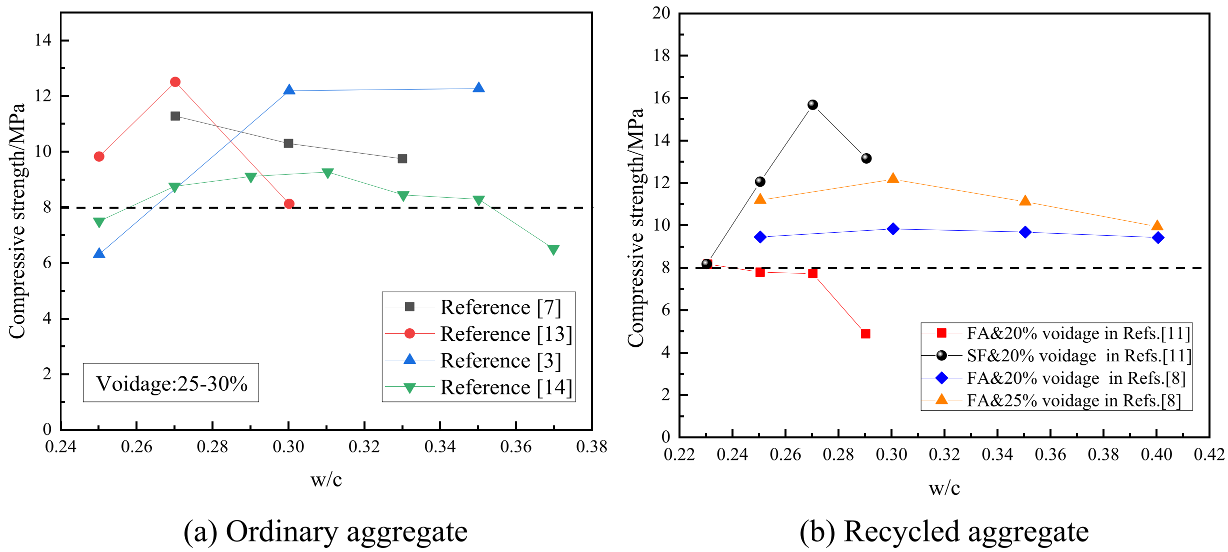

Fig. 4. Variation of compressive strength concerning water-to-binder ratio.

should be selected for planting concrete. When calculating the amount of coarse aggregate, the amount of aggregate per unit volume of PC is calculated according to Eq. (2) [40].

$$W_G = \rho_{GC} \cdot \alpha \tag{2}$$

Where W_G is the dosage of aggregates per unit volume of porous concrete, kg/m^3; ρ_{GC} depicts the compacted bulk density of aggregates, kg/m^3; *and* α represents reduction coefficient, set as 0.98 for crushed gravel coarse aggregates.

2.2.4. Aggregate-binder ratio

The aggregate-binder ratio refers to the mass ratio of aggregate to binding materials in PC, which can reflect the degree of encapsulation of the aggregates by the binding material. Fig. 5 shows the relationship between compressive strength and aggregate-binder ratio. When the water-binder ratio is 0.22, the compressive strength decreases linearly with the increase of the aggregate-binder ratio. The aggregate-binder ratio increases from 4.8 to 6.8, and the compressive strength decreases by about 40% to 9.66 MPa. When the water-binder ratio is 0.30, as the aggregate-binder ratio increases from 4.91 to 5.47, the compressive strength only slightly decreases, but still above 8.3 MPa. This is because under the condition that the water-binder ratio is constant, the aggregate-binder ratio increases, the amount of aggregate increases, the coverage thickness of the cementitious material slurry on the aggregate surface decreases significantly, and the bond strength between aggregates decreases. Moreover, the change is more obvious in the case of a low water-binder ratio, which is manifested by a significant decrease in the compressive strength of vegetation concrete. Combined with the above recommended 0.30 ~ 0.35 water-binder ratio, the initial aggregate-binder ratio of planting coagulation is suggested to be 4.8 ~ 5.4.

2.2.5. Binding materials and water

After determining the aggregate-binder ratio, the amount of binding materials and water can be further calculated. The volume of PC per unit volume includes the volume of binding materials, aggregate volume and target voidage volume [40]. Therefore, the amount of binding materials per unit volume of porous PC can be calculated according to Eq. (3):

$$W_J = \left(1 - \frac{W_G}{\rho_G} - R_{VOID}\right) \times \rho_J \tag{3}$$

Where W_J is the dosage of binding materials per unit volume of porous PC, kg/m^3; ρ_G is the apparent density of aggregate, kg/m^3 ; R_{VOID} is target voidage; and ρ_J is the density of cementitious paste, kg/m^3.

After the water-binder ratio is determined, the dosages of the binding materials and mixing water are calculated according to Formulae (4) and (5), respectively.

$$W_C = \frac{W_J}{(1 + W/B)} \tag{4}$$

Where W_C depicts the dosage of the binding materials per unit volume of porous concrete, kg/m^3; W/B is the water-binder ratio;

$$W_W = W_J \times \frac{W}{B} \tag{5}$$

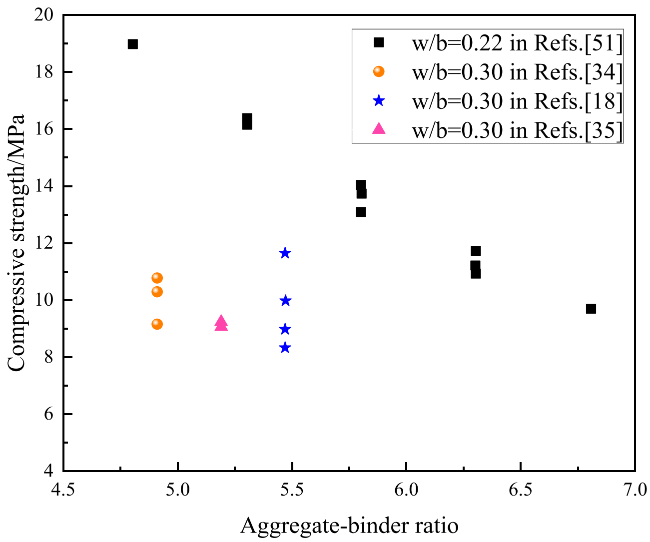

Fig. 5. Variation of compressive strength with aggregate-binder ratio [18,34,35,51].

Where W_W presents the dosage of mixing water per unit volume of porous concrete, kg/m^3.

2.3. Preparation method for PC

Mix design is only a theoretically feasible solution. Both the target voidage and the prepared concrete's ability to meet strength criteria are determined by the PC preparation process. The key lies in whether coarse aggregate is effectively wrapped by cement paste to form continuous voids. Compared with ordinary concrete, PC imposes stricter requirements on the cementitious material's performance, moulding process, and curing process [20]. The main preparation processes for PC are as follows (Table 3).

3. Performance of PC

3.1. Permeability and interconnected voidage

The permeability of PC determines whether plants can access to sufficient water. The void structure of the PC determines the permeability degree of the concrete. First, the permeability of PC is related to interconnected voidage. Suitably interconnected voidage promotes plant growth. The voids in concrete are divided into interconnected voids, semi-connected voids, and unconnected voids. To ensure PC's voidage, the voids should be truly valid interconnected. If the interconnected voidage of the PC is too large, it will be difficult for the PC to withstand rainwater scour. On the other hand, if the interconnected voidage is too small, it will be difficult for plant roots to penetrate through the PC. Generally speaking, PC with an interconnected voidage of 25%–30% [2] and an average pore diameter of 2–3 mm can meet plant growth requirements [54]. A suitable voidage can decelerate the loss of soil and nutrients under the action of running water by ensuring a certain permeability. The magnitude of permeability varies with the particle composition of the concrete base material. PC with a permeability coefficient above 0.11 cm/s can show good permeability [55]. As shown in Fig. 6, the voids should be filled with enough nutrients, providing space for plant roots' growth [10].

The main factors affecting the permeability of PC are voidage, aggregate gradation, and water-to-cement ratio. Given the coarse aggregate of PC, the permeability coefficient has a good linear correlation with voidage. Permeability coefficient increases with increasing voltage. Sandoval [56] deduced the relationship between voidage and permeability coefficient through experiments, as shown in Formula (6):

$$k_c = 0.0591 \bullet p^{1.09} \left(R^2 = 0.98\right) \tag{6}$$

Where k_c denotes permeability coefficient; p denotes voidage.

Zhuang [57] et al., who investigated the effects of three different coarse aggregate gradations on permeability coefficient of PC, concluded that permeability coefficient presents an increasing trend with increasing coarse aggregate gradation for the same cement dosage. In addition, the permeability of PC is also closely related to the water-to-cement ratio. Dongwei Hou [58] et al. revealed that the permeability of PC decreased with increasing water-to-cement ratio. As the material's water-to-cement ratio increased, cement paste's fluidity increased. In the moulding process, cement paste would flow to the lower layer under gravity, causing lower voids to be blocked and thereby reducing the permeability coefficient of concrete.

Chenchen Gong [2] et al. used the permeability coefficient to characterize the interconnectivity of pores in PC. Fig. 7 illustrates the effect of carbamide on the permeability coefficient of PC. The permeability coefficient of the reference sample was 19.1 mm/s. The permeability coefficient of PC first increased and then decreased in line with the increase in carbamide dosage. The concrete with

Table 3
Comparison of preparation processes of PC.

Methods	Steps	Advantages	Disadvantages
Aggregate wetting method [52]	In the mixing, use about 50% of water to wet aggregates, add cement, and finally continuously add the remaining water for mixing until all the aggregate is evenly wrapped in a layer of cement slurry before filling in the mould. When filling in the mould, it is not suitable to vibrate strongly. The insert drill is inserted gently along the mold wall and corner.	The operating procedure significantly enhances the wettability of the cement paste on the aggregate particles, and the voidage is close to the designed voidage value.	It is not suitable for cement slurry to fully and effectively wrap the surfaces of coarse aggregates.
Cover aggregate with cement paste method [53]	First, water and cement are mixed in a cement slurry mixer, then the coarse aggregates and fully mixed cement slurry are poured into the concrete mixer for mixing, and finally filled in the mould.	It is more suitable for cemented material slurry to fully and effectively wrap the surfaces of coarse aggregates.	The slurry will appear at the bottom of the PC. Strength and voidage may differ greatly from design values.
Add aggregate in batches method [20]	Firstly, put 1/3 of coarse aggregates and cement into the concrete mixer for complete mixing. Add 1/2 more water and stir thoroughly. Then add remnant 2/3 of coarse aggregate and 1/2 of water in two batches. Stir well and pour into moulds.	Cement slurry fully and effectively covers the surfaces of coarse aggregates.	The slurry may occur at the bottom of the PC specimen. The strength and voidage may differ significantly from the design values.

Fig. 6. Growth of plant roots in PC [10].

2.5 wt% carbamide had the highest permeability coefficient of reaching 23.2 mm/s, 21.5% higher than the reference sample without carbamide. Controlling carbamide dosage below 2.5 wt% helped improve PC's permeability and pore interconnectivity.

3.2. Mechanical properties

The main indexes measuring the mechanical properties of PC are compressive and flexural strength [59]. Chinese code JC / T 2557–2020 stipulates that the 7d compressive strength of PC should be greater than or equal to 3 MPa, and the 28d compressive strength is greater than or equal to 10 MPa. Japan has published special design indicators. For revetments mainly used for planting, the 28d compressive strength of PC is required to be above 10 MPa. For revetments exposed to serious current scour, the 28d compressive strength of PC must exceed 18 MPa. Many studies have identified a good linear relationship between the compressive and flexural strength of PC. Wenle Zhong [60] analyzed the correlation between the compressive and flexural strength of PC through linear regression. The experiment showed that the relationship between compressive strength f_c and flexural strength f_t could be expressed as f_c=7.08f_t, and $R^2 = 0.998$.

The mechanical properties of PC are affected by many factors, including voidage, water-to-cement ratio, aggregate-cement ratio, aggregate gradation, cementitious material type, and admixtures. The voidage of a PC directly affects its mechanical properties. Sherong Zhang [61] confirmed through experiments that, when the same cementitious material was used, the mechanical properties of porous concrete mainly depended on the amount of internal voidage. With a large set of data on voidage and tested compressive strength, Chunqi Lian [62] proposed a new model using Griffith's fracture theory. Therefore, they concluded that the voidage of PC could be used to predict its compressive strength. The mechanical properties of PC are closely related to the water-to-cement ratio. Shaobiao Zhang [63] et al. found through experiments that, compared with ordinary concrete, PC presents a more complicated relationship between strength and water-to-cement ratio. As shown in Fig. 8, when the voidage of concrete was small, the decreasing trend of concrete strength became evident with the increasing water-to-cement ratio. By contrast, when the voidage of concrete was large, the changing trend of concrete strength tended to be gentle. This is because when the voidage was higher, the wrapping layer was thinner, and the concrete strength mainly depended on the strength of aggregates.

The aggregate-to-cement ratio and aggregate gradation of PC are also the main factors affecting its mechanical properties. Yunxing

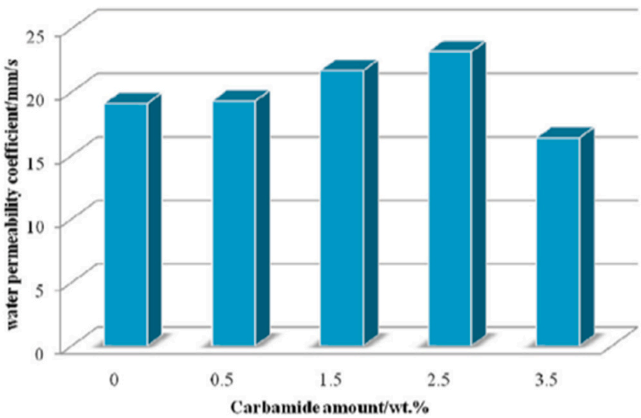

Fig. 7. Permeability coefficient of PC with carbamide [2].

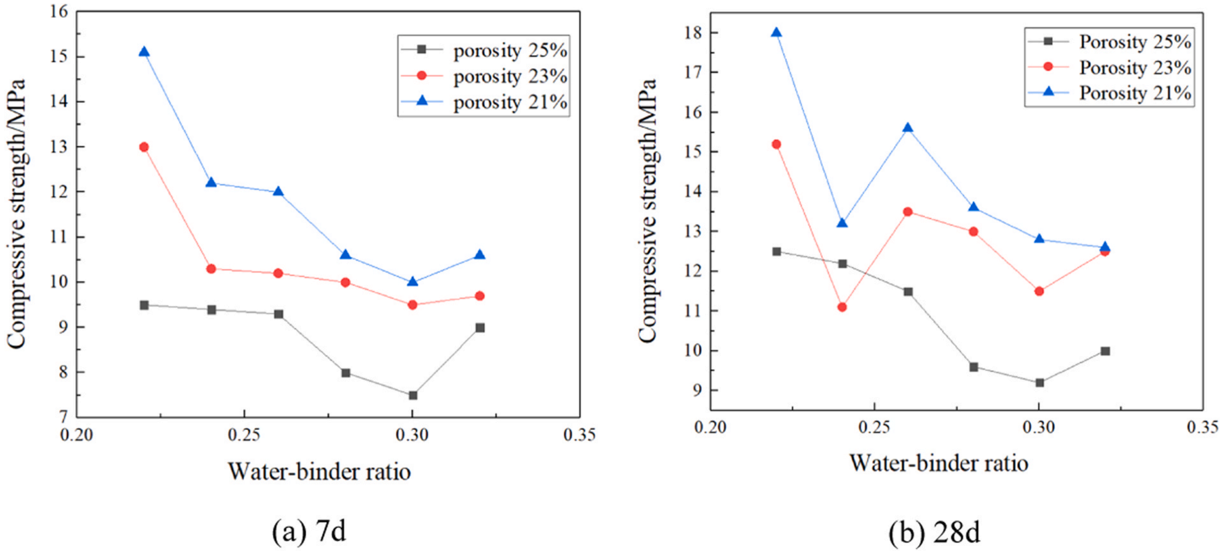

Fig. 8. Relationship between compressive strength and water-to-binder ratio on 7d and 28d strength [63].

Shi [64] found through experiments that, under the same aggregate gradation, increasing aggregate-to-cement ratio led to reduced cementitious material dosage and weakened aggregate binding strength, further lowering PC's compressive and flexural strength. According to Zhengwu Jiang et al. [65], the compressive strength of porous pervious concrete was mainly determined by the occlusal friction between coarse aggregates and the bonding strength between aggregate and cement paste. Therefore, the gradation and particle size of aggregates affect the compressive strength of concrete. Zhuang [57] found through experiments that the compressive strength of porous eco-concrete decreased with increasing coarse aggregate particle size. When coarse aggregate particle size increased from 5–15 mm to 15–25 mm, compressive strength decreased by about 19%. When it increased from 5–15 mm to 25–35 mm, compressive strength decreased by about 35%.

Di Li et al. [13] tested and analyzed PC samples' voidage, alkalinity, and mechanical properties. The results showed that the voidage of large-aggregate concrete (i.e. with an aggregate size of 15–20 mm) was slightly higher than that of small-aggregate concrete (i.e. with an aggregate size of 5–10 mm), and the average porosities of their treatments were 30.5% and 31.9% for each treatment, respectively. In the aggregate group, particle sizes ranged from 5 to 10 mm, and the compressive strength of concrete with smaller particle sizes was 17.5% higher than that of concrete with larger particle sizes. The compressive strength of concrete increased with decreasing aggregate particle size [66]. Sung Chan Yong [28] et al. tested the 7d compressive strength of PC. Their experimental results showed that the compressive strength of PC increased with increasing cementitious material dosage (i.e. in the dosage of 6.5%–9.0% by weight) (Fig. 9). Moreover, there was an opposite relationship between compressive strength and voidage (Fig. 10).

The strength of PC also varies with cementitious material [67]. Lei Lang [68] et al. stated that the previous concrete prepared with

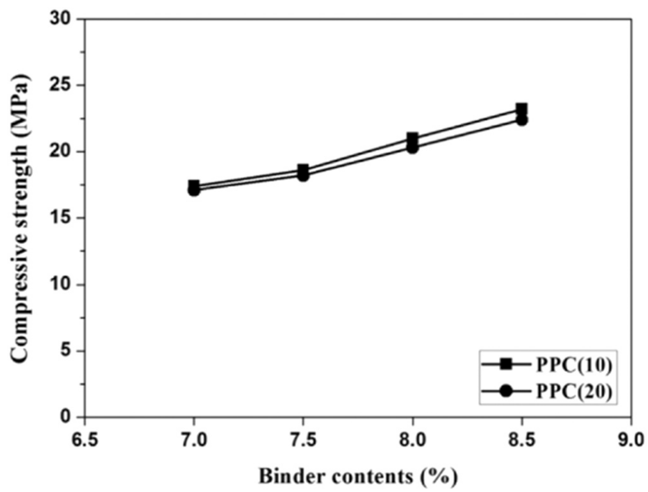

Fig. 9. Compressive strength with binder dosage [28].

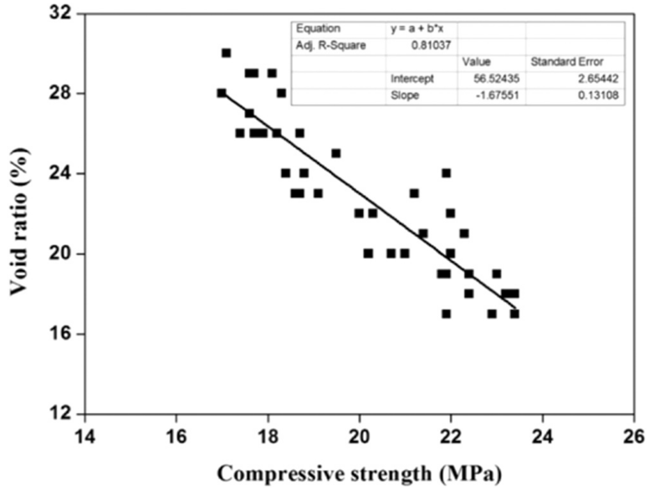

Fig. 10. Correlation between compressive strength and void ratio [28].

magnesium phosphate cement as the cementitious material had a high early strength. With a 28d flexural strength above 5.5 MPa, pervious concrete produced with magnesium phosphate cement exhibited a stronger flexural strength than pervious concrete with Portland cement. In addition to selecting different cementitious materials, Jianming Gao [69] et al. studied the effect of mineral admixtures on PC. The research results indicated that adding mineral powders and silica fume helped improve PC's compressive and flexural strength while adding fly ash did exactly the opposite.

3.3. Alkaline environment

PC has certain requirements for alkalinity. Ordinary concrete is alkaline due to calcium hydroxide generated during cement hydration. The pH value of ordinary concrete is generally as high as 12–13 [70], creating a highly alkaline environment where plants cannot grow. To ensure plants' survival, PC's pH value is usually controlled at 8–10. [14,25] In considerations of PC, the key is to lower the alkalinity of its internal environment. A low-alkalinity environment is beneficial to plant growth but detrimental to the mechanical properties of concrete. In a low-alkalinity environment, the hydration products of cement (such as calcium silicate hydrate and calcium aluminate hydrate) lose their stability and dissolve, resulting in weaker concrete. In addition, changes in the alkaline environment also adversely affect the durability of PC. Microbes survive in a low-alkali environment, and the acidic substances produced by their life activities erode PC. PC is in direct contact with soil, and the large quantities of salts and acidic substances in soil further aggravate the erosion of PC by salts and acids.

Different plants have slightly different alkali tolerance due to their diverse biological characteristics; thus, plant adaptability tests are required before applications. Currently, there is no standard regulation on the pH value tests of PC. The available methods for measuring the alkalinity of PC are shown in Table 4.

To create a suitable growth environment for plants, the alkalinity of PC can be reduced by several methods, including neutralization, changing cement variety or adjusting cement dosage, and surface treatment. These methods and measures are to be discussed and analyzed in detail below.

3.3.1. Changing cement variety or adjusting cement dosage

In preparing PC, low-alkalinity cement or neutral cementitious materials (such as SAC, CAC, phosphate cement, gypsum paste, and unsaturated polyester resin) can be used as a substitute for ordinary cement in reducing alkalinity. Chenchen Gong et al. [2] used SAC combined with carbamide as fertilizer to prepare planting concrete with nitrogen nutrient-releasing effects, and its pH value was 8–9. Kyung-Ho Lee et al. [71] proposed to use α-calcium sulfate hemihydrate as a partial substitute for ordinary Portland cement. α-calcium sulfate hemihydrate is neutral, and an ideal alkalinity reduction effect can be achieved at a low dosage; however, it reduces cement strength. In Japan, type-B and type-C Portland blast-furnace slag cement are used in most cases as cementitious materials. Japanese standard JIS R 5211 has specified the range of blast-furnace slag content for them. Porous concrete prepared with them has a low pH value and is suitable for plant growth.

3.3.2. Add mineral admixtures

By adding mineral admixtures, such as filling acidic soil or adding fly ash(FA), slag(S), silica fume(SF), metakaolin(MK), limestone powder and other admixtures, the SiO_2 will react with a portion of $Ca(OH)_2$ [2,10]. This method is simple, but the amount of admixtures added should be controlled at a moderate level for concrete strength [25]. This technique is frequently used in combination with other measures due to its limited impact on alkalinity reduction. Fig. 11 shows the alkalinity change of PC with different mineral admixtures at 28d [84]. The addition of fly ash(FA) and slag(S) shows that the pH value decreases and then increases, and the pH value

Table 4
Methods for measuring the alkalinity of PC.

Method	Process	Advantage	Disadvantage
Potential Determination	Use a digital pH probe to measure the pH of soil periodically [71]. Refer to ASTM D4972 for specific operations.	This method can keep soil conditions within a favourable range for plant growth and investigate whether the leaching of hydrogen ions from the concrete pore water into soil varies with different concrete mixes [70].	It ignores the difference in pH value between soil and pore water, and there are a few applications of this method.
Solid-liquid extraction [72]	Crush samples, and suspend the powders with a particle size of less than 0.08 mm in distilled water with a solid–to–liquid ratio of 0.1. Use a pH meter for measurement [25,73].	It's a common method to acquire the pH value of pore water.	The powders tested are too little to ensure their representativeness. Moreover, the grinding process may accelerate the hydration of the non-hydrated cement particles, and the added water will cause secondary hydration. Both factors will make the pH value higher. [74]
Pore solution extraction [75,76]	Put the concrete cylindrical pieces into a pressure chamber, collect the pore solution [77], and measure its pH value [78].	It is the most common way to measure a pore solution's pH value accurately.	Special equipment is needed to extract the solution, which is not easy to operate. The components of pore solutions obtained under different pressures may be different. It is hard to acquire sufficient pore solutions, especially for samples with a low water-binder ratio, higher age, or more aggregates [79].
In situ leaching	Drill a hole with a diameter of 3–5 mm and a depth of 25–35 mm on the surface of the saturated sample, add a known amount of deionized water into the hole, seal the hole with a rubber plug, and measure the pH value of the solution in the cave when it becomes stable. [80]	The sample is directly operated to reduce the effects of external factors.	The operation is complex. Since the sample is saturated, the condensation of water on the surface will lead to alkali leaching, resulting in a reduced pH value [81]. In addition, carbonation will also affect the final determination results because it takes a long time for the solution to reach equilibrium.
Ex-situ leaching	Prepare 20 mm-size cement paste cubic samples, cure them for 7 days or longer after forming, and soak them in a certain amount of distilled water in a sealed environment. Test the pH value of the water solution after soaking [82].	It is easy to operate.	It can only reflect the effect of alkali reduction measures on the cement paste but cannot evaluate other alkali reduction measures.
X-ray diffraction	Use the intensity of $Ca(OH)_2$ crystal peak in XRD as the index to characterize the alkalinity of the sample [10].	The effect of alkali reduction measures on the cement paste can be reflected accurately.	The results without accurate pH values can only be compared.
Fiber optic sensors	Combine the optical fiber and the sensing material, and display different absorbance or fluorescence using the sensing material according to the pH value of the environment [83].	The optical fibre sensor can be directly embedded in the sample in the casting process or drilled and filled with water on the existing structure and inserted into the optical fibre.	Whether the sensor is based on the absorbance or it is a fluorescent sensor, its signal shall be calibrated with the sensor in different pH value solutions.

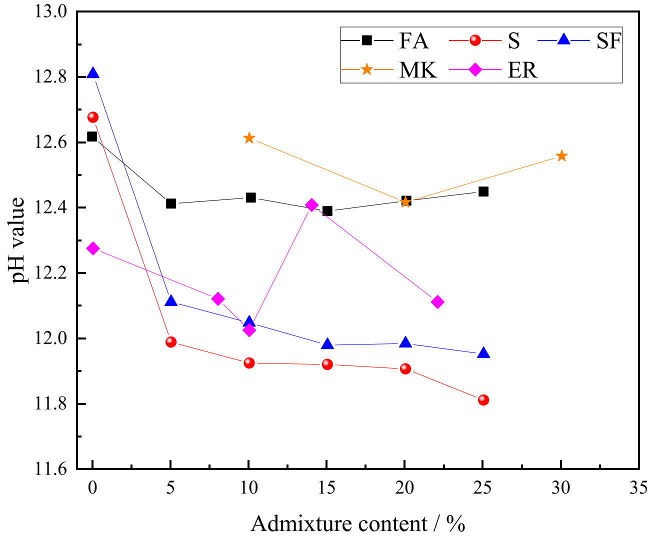

Fig. 11. Effect of the addition of mineral admixtures on pH value of PC at 28d [84].

is still as high as 12.3 or higher. However, when adding MK and SF, the pH value gradually decreases with the increase of dosage. The pH value can be reduced by about 0.6 at 4 wt% dosage, but when the dosage reaches 25 wt%, the pH value is still 11.8, which cannot meet the needs of plant growth. The content of active silica in SF is more than 90%, and its pozzolanic effect is more significant, which will consume more $Ca(OH)_2$, not only reducing the alkalinity of cement matrix, but also making its microstructure denser. However, the excessive amount of SF will lead to the increase of viscosity of cement paste, which will affect the strength and water permeability. The appropriate amount of silica fume is generally 5~10% by weight of cement [85].

Therefore, among these admixtures, SF and MK have better alkali reduction effect, while FA and S have relatively low alkali reduction effect. However, although the addition of SF and MK can reduce the alkalinity of PC to a certain extent, it is not enough to meet the alkalinity conditions for planting by adding admixtures alone, and other composite alkali reduction methods still need to be considered.

3.3.3. Neutralization

At present, in addition to the above alkali reduction methods, some chemical alkali reduction methods are often used, such as weak acid chemical solution spraying or soaking. Fig. 12 shows the process of alkalinity changes in PC treated with different alkali reducing methods. After treatment, the initial alkalinity gradually decreases. As the treatment time increases, $Ca(OH)_2$ inside the PC gradually dissolves and diffuses, and the pore alkalinity gradually increases. The method of reducing alkalinity with ammonium bicarbonate

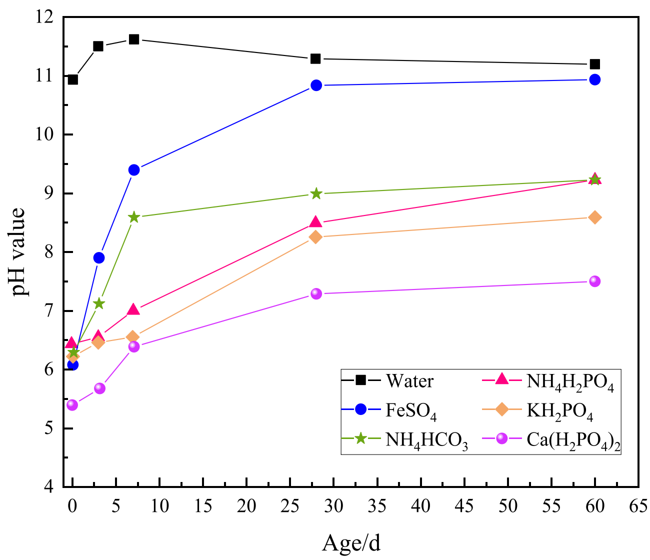

Fig. 12. Effects of weak acid solution soaking treatment methods on the pH value of PC.

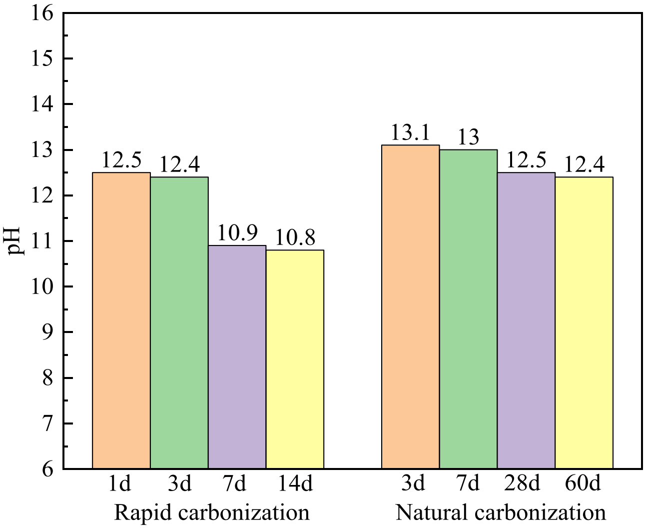

Fig. 13. Effects of carbonization on the pH value of PC.

(NH_4HCO_3) may result in a certain degree of loss of concrete strength. The alkali-reducing capacity of phosphate alkali reducing method can be sorted in order as superphosphate ($Ca(H_2PO_4)_2$)>potassium dihydrogen phosphate(KH_2PO_4)>ammonium dihydrogen phosphate($NH_4H_2PO_4$), and this alkali reducing method has little effect on the strength of concrete [86]. However, phosphate is generally rich in phosphorus and nitrogen. If it is used for bank and slope protection in rivers and lakes, it may have an impact on water quality.

3.3.4. Carbonization treatment

After carbonation treatment, a dense layer of $CaCO_3$ can be formed on the surface of the PC, which hinders the diffusion of internal $Ca(OH)_2$ into the pores, thereby reducing the alkalinity of the pore environment. Fig. 13 reveals the effect of different carbonization treatments on the alkalinity of PC [19]. After rapid carbonization for 7–28 d, the alkalinity of concrete can be reduced by 1.2–1.4 in terms of pH value, and the increase of alkalinity is significantly reduced after rapid carbonization for more than 7 d. However, the pH value is still as high as 12.3 after 60 days of outdoor natural carbonization, only decreasing by 0.7 in pH value. It can be seen that rapid carbonization for more than 7 days can effectively reduce the alkalinity of PC, but it still needs a long carbonization time to reduce the pH value to below 9.5 to meet the requirements of plant growth. However, rapid carbonization requires special equipment, and it is difficult to be widely applied to engineering practice.

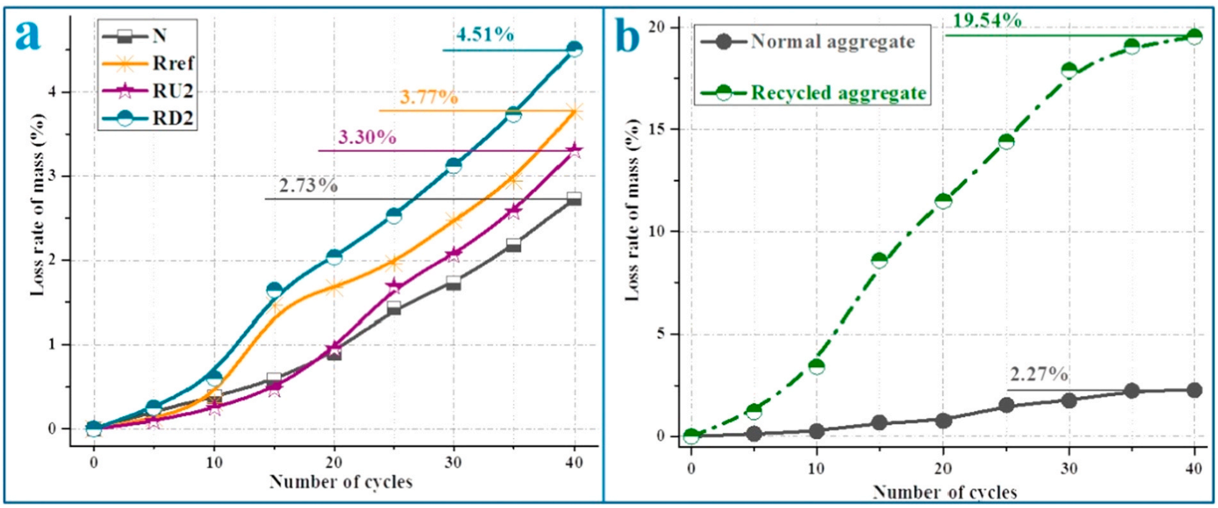

Fig. 14. Frost resistance (i.e., mass loss) of PC [89].

3.4. Durability

Concrete durability refers to the ability of concrete to resist the damage caused by the combined action of external and internal factors. Due to factors, including a low-alkalinity environment, high voidage, planting, and direct contact with various fillers, higher requirements are raised for the durability of PC than ordinary concrete. Durability of PC mainly concerns the following aspects:

3.4.1. Frost resistance

Compared with ordinary concrete, PC is more likely to suffer from the growth of plant roots. Due to its multi-porosity and low-alkalinity nature, PC is more vulnerable to erosion by running water, acids, salts, microbes, etc. The entry of water also makes it susceptible to freeze-thaw attack. This explains why engineering applications impose higher requirements for durability of PC. Many studies have shown that due to its high voidage, low strength, and poor frost resistance, PC is also vulnerable to frost-heaving damage in cold areas. Taking mass loss rate, strength, and effective voidage as evaluation indexes, Dongli Wang et al. [87] investigated the frost resistance of seashell waste pervious concrete from the microstructure perspective based on the slow-freezing method and proved the feasibility of applying seashell waste pervious concrete in the cold areas of northern China. Currently, the frost resistance of PC is evaluated mainly by using the test methods for ordinary concrete. That is, the slow or quick-freezing method depends on the environments of engineering applications and frost resistance is graded based on the maximum number of freeze-thaw cycles. Specifically, the slow-freezing method is adopted in projects where the PC is not in long-term contact with water or is not directly soaked in water. By contrast, the quick-freezing method is employed in hydraulic and port projects.

To some extent, admixtures affect the frost resistance of PC. Hwang-Hee Kim et al. [88] tested the residual compressive strength of PC after 100 freeze-thaw cycles to conforming to ASTM C666/C666M-15, aiming to assess its frost resistance. The test results revealed that blast-furnace slag, natural jute fibre, and latex could improve the frost resistance of concrete. Laibo Li et al. [89] prepared PC with recycled aggregate from demolished concrete (RADC) and found that the frost resistance improved by 12.4% and the drying shrinkage rate decreased by 20.5% after adding carbamide as a fertilizer (Fig. 14). By contrast, adding diammonium phosphate (DP, $(NH_4)_2HPO_4$) would cause a higher mass loss rate. Thus, it is inadvisable to adopt DP as a fertilizer in PC. The frost resistance of PC prepared with recycled concrete aggregates was inferior to that of PC prepared with natural aggregates. The possible reason is that the inherent frost resistance of recycled aggregates is much lower than that of natural aggregates (Fig. 14b), which is attributable to its high water absorption. As a result, the weight loss rate of PC prepared with recycled aggregates was higher than that of PC prepared with natural aggregates. Furthermore, adding carbamide improved the frost resistance of PC prepared with recycled aggregates, while DP demonstrated the opposite effect. This may be because carbamide is beneficial to the hydration and hardening of SAC [90], while DP can react with CH to produce insoluble phosphates ($CaHPO_4$ and $Ca_3(PO_4)_2$). The cementing effect of DP is undesirable [91], which obstructs the hardening of SAC.

3.4.2. Resistance to soft water attack and scour

PC is in direct contact with the natural environment and is often used in water conservancy, seaport, and other engineering projects, which makes it susceptible to erosion and scour by running water. Erosion by running water mainly refers to soft water attack. Soft water attack is a type of dissolution erosion. The $Ca(OH)_2$ in concrete is continuously dissolved, resulting in the decomposition and dissolution of hydration products. Scour is a type of physical erosion that occurs mainly in areas frequented attacked by running water.

Due to its low $Ca(OH)_2$ concentration and high porosity, PC has a large contact area with water. Under soft water attack, its hydration products are easily dissolved and separated. For this reason, PC should strongly resist soft water attacks. The anti-scour ability

Fig. 15. Measurement of stem and root lengths [2].

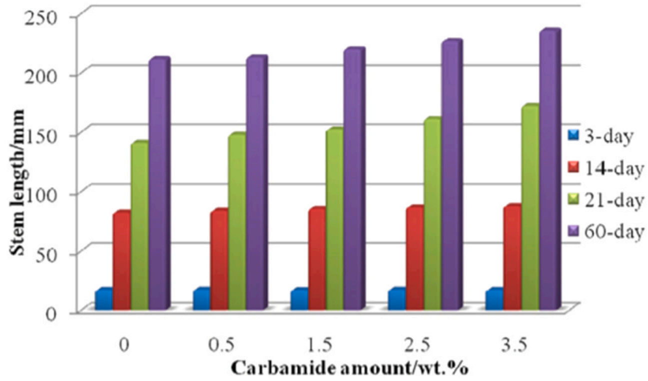

Fig. 16. Stem length of plants in PC with carbamide [2].

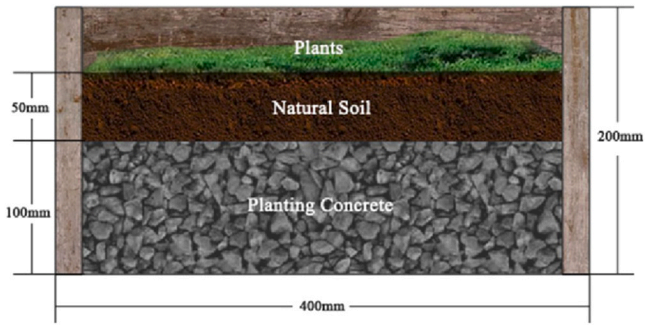

Fig. 17. Sketch of PC sample used for the vegetation test [13].

of PC is also crucial, especially in river bank projects. The porous sea sand concrete mixtures (PSSCM) prepared by Sheng Li et al. [92] demonstrated a strong anti-scour ability and can effectively reduce the damage to plants and soil caused by water scour. Because of the single aggregate gradation of PC, there is poor binding between aggregates. To prevent soil and the nutrients filled in the pores from being washed away by running water, PC must have strong anti-scour ability. Min Zhao et al. [93] used biochar as a modifier for eco-concrete. After being bound with the cementitious material, biochar not only filled the voids of vegetated concrete but also increased the connection area of aggregates, thereby improving the mechanical properties of vegetated concrete. Laibo Li et al. [94], who carried out scour resistance of soil (SRS) tests [95], proved that filling eco-concrete with SAP-modified soil can also enhance its anti-scour ability.

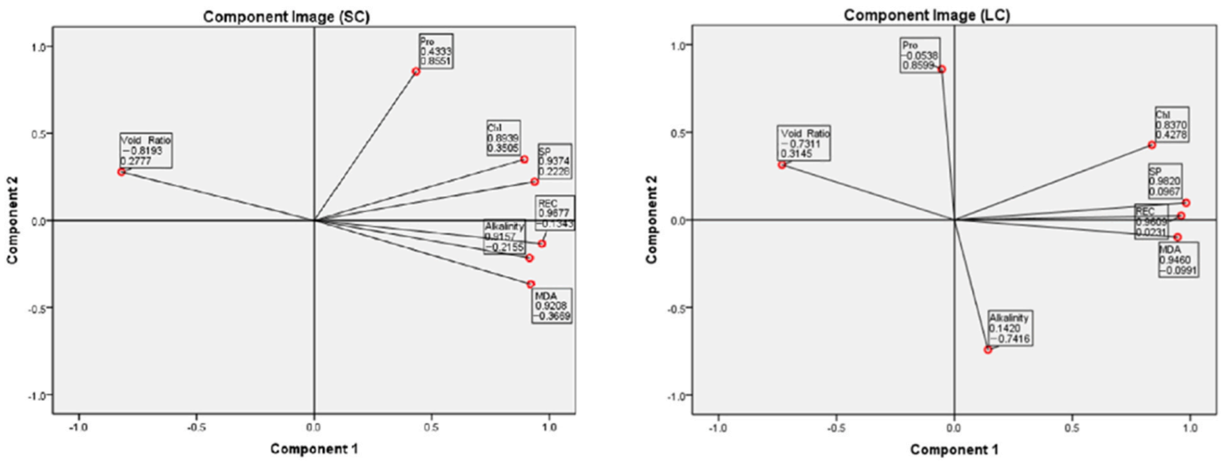

Fig. 18. Weight distribution for various indices in the first and second principal components in the SC and LC groups [13].

Fig. 19. Planting block view in plastic house [28].

3.4.3. Resistance to acid erosion

The filling soil in PC is weakly acidic. Its acidity resulted from the organic acids in humus, the redox reactions of microbes in soil, and the acidic inorganic salts and polymers added to adjust soil pH and fertility. The acidic substances in the soil dissociate H^+ in the soil solution and engage in a neutralization reaction with the $Ca(OH)_2$ dissolved from cement stones [96]. On the one hand, this abruptly reduces the alkalinity of cement stones and causes calcium silicate hydrate and calcium aluminate hydrate to lose their stability and be hydrolyzed and dissolved, resulting in a continuous decline in concrete strength. On the other hand, the corrosion products have poor stability and are susceptible to dissolution, accelerating the corrosion process. In this sense, under the premise of a pH suitable for plant growth, how to ensure the stability of PC is also a major consideration.

3.4.4. Resistance to microbial attack

The main microbes that cause damage to concrete are transported from rainwater, river water, and sewage. The pore environment of porous vegetated concrete is slightly alkaline, which provides a necessary condition for the survival and proliferation of microbes. The corrosion and damage of porous vegetated concrete by microbes are realized mainly through microbial metabolites [97]. The aerobic heterotrophic bacteria and fungi that metabolize organic carbides cause damage to concrete by producing acids based on organics. The denitrifying and nitrifying bacteria involved in nitrogen metabolism produce nitrous acid and nitric acid, which accelerate the neutralization of concrete. The sulfate-reducing bacteria involved in the sulfur cycle reduce the sulfates in water to sulfides, which are then oxidized by sulfur bacteria to produce sulfuric acid, thereby damaging the concrete.

3.4.5. Resistance to salt erosion

Concrete is deteriorated by the high concentrations of sulfates, chlorides, and magnesium salts found in soil. The concentrations of Mg^{2+}, SO_4^{2-}, and Cl^- in soil solutions are generally above 0.001 mol/L, and may even reach 0.1–1.0 mol/L in some cases. In a salt-

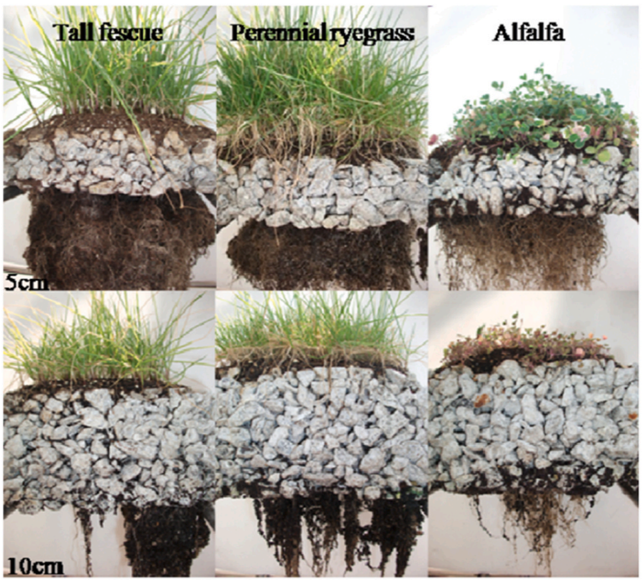

Fig. 20. Roots growing through PC blocks of 5 and 10 deep in 20 weeks after sowing [37].

corrosion environment, various components of cement stones are unstable and can undergo related physical and chemical reactions with harmful ions, resulting in concrete deterioration and damage [98–101]. In addition, the dry-wet alternation action of salt solutions accelerates the penetration of harmful ions in the cementitious material layer, exacerbating the damage caused by salt erosion.

3.5. Plant compatibility

3.5.1. Plant physiological characteristics

PC provides a basic environment for plant growth. However, plant growth is affected by many factors. Low-voidage PC offers minimal growth space for plant roots, and excessively high pH affects the uptake of ions by plants. Under low voidage and excessively high pH conditions, roots cannot normally absorb nutrients. For this reason, plants under such conditions are lagged far behind plants in the natural growth environment and may even die. Therefore, plant physiological characteristics cannot be ignored.

Chenchen Gong et al. [2] found that, after three days of curing under standard conditions, concrete was covered with a 2 cm-thick layer of wet soil with seeds. The mass ratio of soil/water/seeds was 1000:3:100. Soil was covered with a layer of plastic sheeting until seed germination. When the specified planting age was reached, the concrete sample grown with plants inside was removed from the foundation soil, and the roots were kept as intact and undisturbed as possible. Then the concrete sample was washed with water to remove soil. Finally, the concrete sample was broken up, and the plants were taken out to measure the stem and root lengths. Fig. 15 shows the PC sample taken out from the soil and washed with water and the measurement of stem and root lengths. Chenchen Gong et al. [2] planted tall fescue seeds in SAC concrete to explore the compatibility of carbamide-affected concrete with plant physiological characteristics (Fig. 16). The research results indicated that, in the same growth period, stem length presented an increasing trend with increasing carbamide dosage, and the increase rate of stem length in carbamide-affected concrete was higher than that in concrete without carbamide. The 21d stem length of tall fescue in concrete with 3.5 wt% carbamide reached 172.1 mm, which is 22.1% longer than that in concrete without carbamide.

Di Li et al. [13] poured PC into a wooden mould of 400 mm × 400 mm × 200 mm in size and placed a natural soil layer of 50 mm on it to retain water and fertility (Fig. 17). Then plant seeds were sown evenly in the soil at a concentration of 10–12 g/m^2 and covered with a thin layer of natural soil (5 mm). Throughout a 12-week observation period, Di Li et al. [13] recorded and analyzed the growth statuses and heights of plants in small-grained concrete (SC), large-grained concrete (LC), and non-concrete (NC). The physiological indexes of plants, including free proline (Pro), malondialdehyde (MDA), chlorophyll (Chl), relative electrical conductivity (REC), and soluble protein (SP), were studied. The main variables affecting plant growth were determined using principal component analysis (PCA). According to the findings, the main factors affecting SC groups other than the control group were SP, REC, MDA, and alkalinity, as shown in Fig. 18. It must be emphasized that plants were under stress during growth in the PC groups. Therefore, plants grown on PC or in pores require more careful care, such as fertilization.

Before sowing seeds in PC, Sung Chan Yong et al. [28] impacted culture soil with a vibrator to enable the plant roots could provide nutrients and water after entering the ground. The culture soil on the impacted block was embedded by 1 cm to prevent seeds' loss in sowing, increase water content, and achieve smooth germination. To analyze the growth characteristics of plants in vegetated concrete, germination rate, vegetation coverage, and growth increment were measured within six weeks after sowing, as shown in Fig. 19. Germination rate and vegetation coverage were observed with naked eye, followed by an analysis of the aggregate size and plant species' growth characteristics. Growth increment directly measures the grass growth of the above-ground parts caused by plant growth and makes a qualitative evaluation. The experimental results showed that regardless of PC mix design and vegetation type, the initial germination point appeared 4–7 days after sowing. About 2 weeks after sowing, the germination rate was above 80%. Further, about 4 weeks after sowing, PC showed a vegetation cover of 8–9 cm.

Chan-Yong Sung et al. [37] measured the coverage rates and root lengths of plants 12 and 20 weeks after sowing to analyze their growth characteristics in planting polymer blocks (Fig. 20). After sowing, the coverage rates of planting polymer blocks were measured every four weeks using a visual rating system. The growth length was quantitatively assessed by directly measuring the length of underground roots of the plants. The test results showed that, 12 weeks after sowing, the coverage rate of each planting polymer block exceeded seven points. 20 weeks after sowing, it was observed that the roots of plants in planting polymer blocks completely

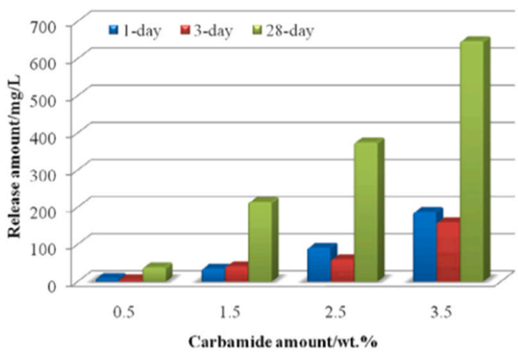

Fig. 21. Release amount of nitrogen nutrient [2].

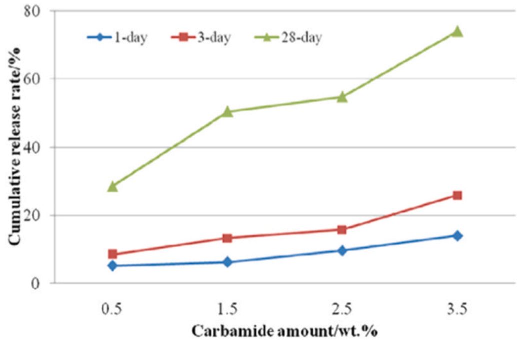

Fig. 22. Cumulative release rate of nitrogen nutrient [2].

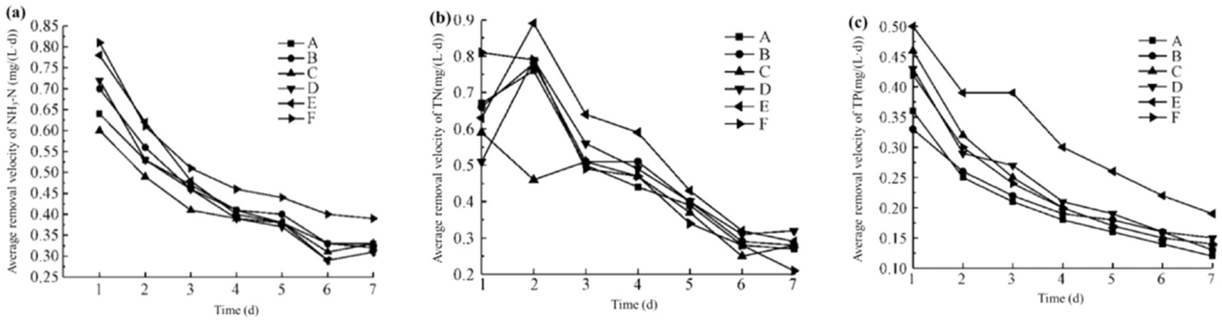

Fig. 23. Variances of average removal velocity of NH_3-N(a), TN(b), and TP(c) over time [110].

Table 5
EMC (mg/L) and UPLRs of storm runoff in experimental plots (kg/hm^2·a) [111].

Experimental plots	Parameter	Water quality index					
		TN	TP	DN	DP	TSS	COD
CK	EMC	14.98	2.81	2.41	0.15	2157.7	377.3
	UPLRs	105.19	19.72	9.89	1.02	15,147.2	2648.6
T1	EMC	18.56	2.42	4.08	0.061	2390.1	344.3
	UPLRs	91.67	11.96	10.11	0.30	11,807.1	1700.7
T2	EMC	13.20	2.22	1.94	0.053	1770.5	268.9
	UPLRs	49.78	8.38	7.30	0.20	6674.6	1013.9
T3	EMC	15.46	2.34	2.15	0.098	1718.9	255.9
	UPLRs	62.34	9.44	8.68	0.40	6927.3	1031.4

penetrated not only the 5 cm-deep PC samples but also the 10 cm-deep ones.

3.5.2. Fertilizer retention performance

As regards the fertilization of PC, due to the scarcity of nutrients (such as nitrogen and phosphorus) required for plant growth in Portland cement concrete (PCC), it is necessary to provide solid or liquid fertilizers regularly [94,102,103]. According to the theory of "fertilizer movement with water" [104,105], the nitrogen and phosphorus in fertilizers are more susceptible to loss in PCC. This suggests that fertilizers should be continuously supplied to meet the nutrient demands of plant growth, which is laborious and cost-ineffective. The high alkalinity of PCC (pH = 13.5) is extremely harmful. Due to the formation of C-S-H gel and calcium hydroxide [106,107], alkali leaching has a negative effect on plant growth. SAC can alleviate two shortcomings: inadequate fertilizer retention and alkali leaching. Some existing studies have shown that the fertilizer release rate in hardened SAC paste is much lower than that in Portland cement [90,94,103]. Therefore, SAC is an excellent candidate for a substitute for Portland cement in developing PC and improving its fertilizer retention.

The release amount and cumulative release rate of nitrogen are parameters measuring PC's fertilization performance. Chenchen Gong et al. [2] found that, under the same dosage of carbamide, the release amount and cumulative release rate of nitrogen nutrients continuously increased with the extension of curing age to 28d (Figs. 21 and 22). At 3d, the cumulative release rates of nitrogen nutrients in PC with 1.5 wt% carbamide and PC with 3.5 wt% carbamide were noted as 57.3% and 205.7%, respectively, higher than the cumulative release rate of nitrogen in PC with 0.5 wt% carbamide. The results indicated that increasing the dosage of carbamide in

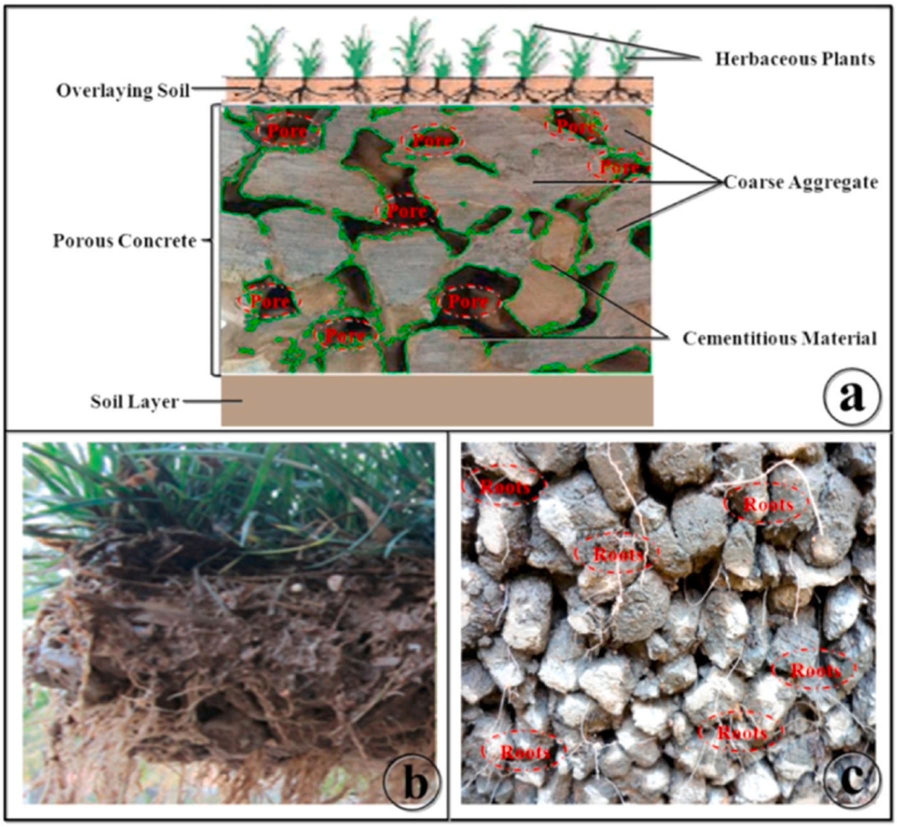

Fig. 24. (a) Sketch illustration of PC [90,94]; (b) real pictures of PC [3,119]; (c) real pictures of plant roots through concrete [46,94].

PC facilitated the release of nitrogen nutrient.

4. Applications of PC

Recently, as scientific researchers pay increasingly close attention to the ecological environment, porous concrete has soon shown its potential for application in planting infrastructure. Porous concrete, by combining greening with concrete, attempts to enhance the landscape while restoring ecosystems by growing plants in concrete. The pores in this type of concrete contain soil, water-retaining agents, fertilizers, alkaline buffers, etc. Relying on this design, the roots of the plants grown in concrete can protrude inside, thus allowing microbes and tiny organisms in the soil to grow. Currently, some commercial products are already available. They include porous concrete sprayed with plant seed materials, frame-shaped blocks lined with porous concrete on the bottom and sides, large porous concrete river walls with natural stone patterns, and porous concrete for succulents [108].

4.1. Water purification

PC is a new type of concrete material that combines plant and concrete, which takes into account both ecological benefits and structural functions. Many researchers have studied the water purification mechanism of PC, mainly through a series of physical, chemical and biological effects inside the PC to remove pollutants such as nitrogen and phosphorus. The relevant principles are shown in the following aspects: (1) PC has become a filter material due to its porous structure, which can filter and adsorb pollutants; (2) In the process of contact with sewage, the components of PC will release Ca^{2+} and Mg^{2+} ions, which can produce chemical reactions with NH_4^+ and PO_4^{3-} ions in the wastewater, forming flocculation and precipitation to purify the water; (3) Aggregate and filler soil of PC can provide carriers for microorganisms, which makes the microorganism abundance value inside the PC higher; microorganisms can utilize the nutrients in the sewage to grow and multiply, which can degrade the pollutants.

Lee Heung-Soo et al. [109] prepared porous concrete and PC, and applied them to the revetment. The test results showed that the water purification efficiency of PC was 4.3%, 1%, 6%, 18%, and 11% more than that of porous concrete, BOD, COD, T–N, and T–P, respectively. It can be judged on this basis that PC is a more effective contact medium for water purification than porous concrete. Kim, Jeong-Hwan et al. [36] conducted planting monitoring over six months using porous concrete plates. The test results showed that plants grew vigorously, and PC could restore the environment of the stream area.

Taking six groups of 90 d composite-aggregate Bahia grass PC potted plants as the research object, Xiongfeng Yan [110] et al.

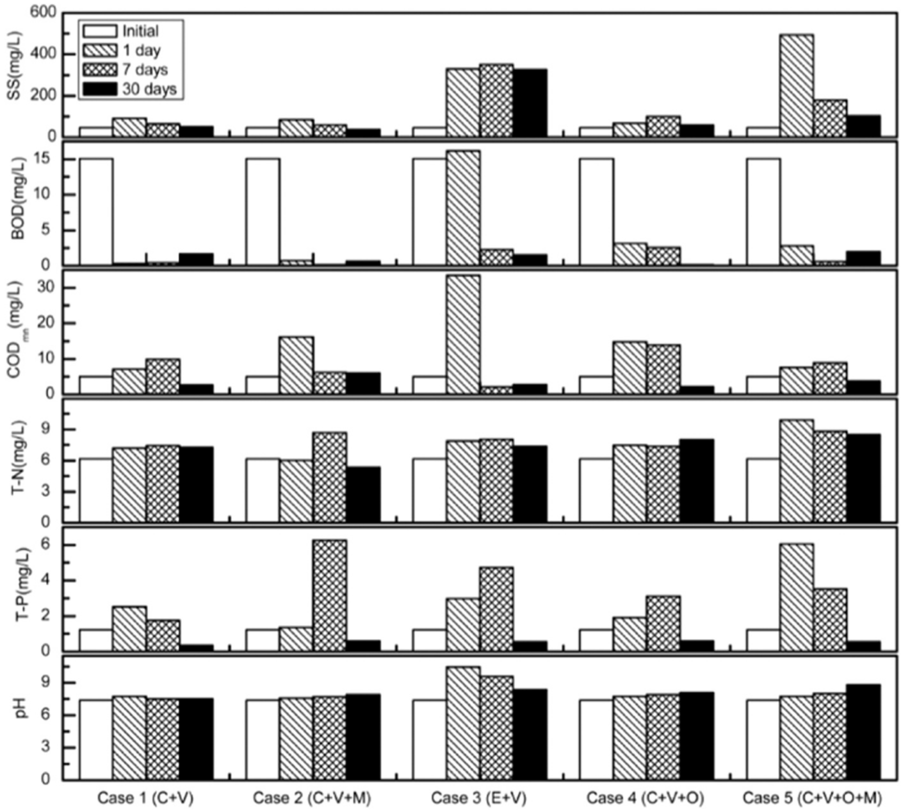

Fig. 25. Variations of concentration rate for 1–30 d [102].

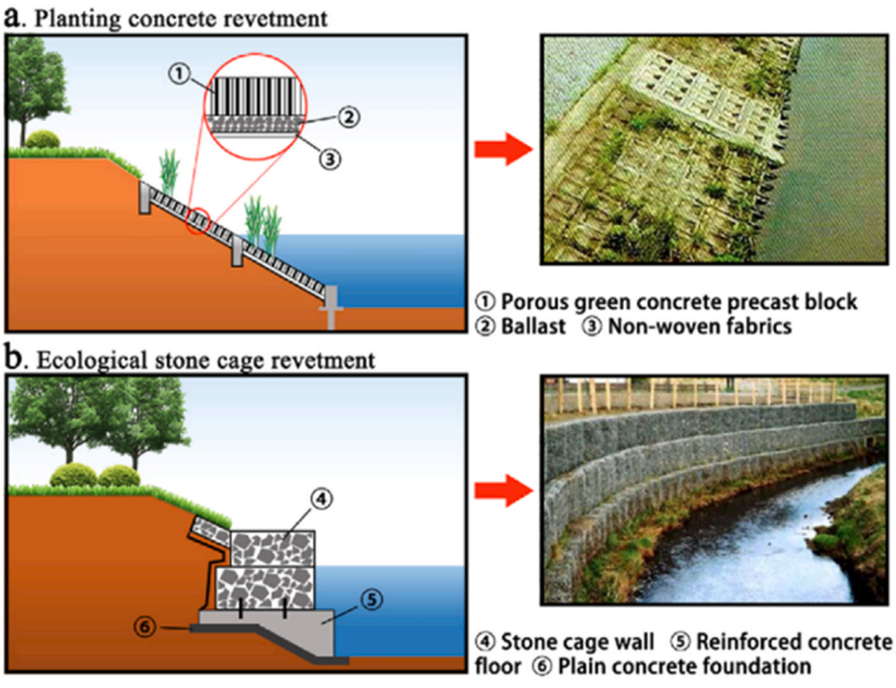

Fig. 26. Profiles of ecological (flexible) revetments, including PC revetments (a) and ecological stone cage revetments (b) [123].

adopted the method of preparing solutions for static culture and selected ammonia nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP) as the main indices. The purpose was to examine the pollutant removal effects of PC based on two types of composite aggregates, i.e., zeolite & steel slag, and zeolite & pumice (Fig. 23). The research results indicated that the Bahia grass PC based on the mixture of zeolite and pumice by 1:1–1:3 produced desirable good denitrification and dephosphorization effects.

Qingfeng Chen et al. [111] found that, compared with the bare land (CK) and the improved soil plot (T1), the PC test plot (T2) reduced runoff by 48% and 24%, TN unit pollution loading rates (UPLRs) by 53%, and 45%, dissolved nitrogen (DN) by 26% and 28%, TP by 57% and 30%, dissolved phosphorus (DP) by 80% and 33%, COD by 62% and 40%, and TSS by 56% and 43%, respectively. Besides, it produced significantly lagged runoff time and flow peak (Table 5). Therefore, PC changed the hydrological process of rainwater on the slope, played a vital role in delaying runoff, and effectively reduced the output load of pollutants. Compared with CK and T1, T2 produced lower average output loads of pollutants yet exhibited similar behaviour to T3. This is mainly because PC not only enhances the infiltration capacity of rainwater and reduces runoff but also has a robust anti-scour ability and reduces soil erosion. In addition, studies have shown that vegetation also plays a stable role in controlling the pollution of hillside rainstorm runoff [111]. However, vegetation has low strength and anti-scour ability, making it difficult to plant on steep banks and slopes. Therefore, using PC for slope protection can reduce the event mean concentration (EMC) of pollutants and UPLRs. PC also has a remarkable anti-scour ability and can be used in a variety of applications.

4.2. Slope protection

PC can be used as a substitute for conventional concrete to develop sustainable, multi-functional, and intelligent materials rapidly and realize modern civil infrastructure's environmental protection and sustainable development [89]. By its huge advantages, such as excellent permeability, good thermal insulation performance, and light weight [112,113], PC offers a realistic solution to the problems caused by erosion and flooding. Relying on impervious land development, it also meets the biocompatibility and plant growth characteristics as a substrate for PC [114–117], as shown in Fig. 24a [90,94]. It is also widely used in permeable ditches, conduits, drains [118], noise barriers, etc. [114,117]. PC is a porous eco-concrete that, compared with ordinary concrete, is more effective in soil erosion protection for river bank slopes and roadbeds (Fig. 24b) [3,119], thereby preventing soil erosion and degradation [46,94]. The roots of plants can penetrate PC through the pore structure and absorb nutrients from underground (Fig. 24c).

Qing Xia et al. [120] found that when the total dosage of the cementitious material is greater than 526 kg/m^3 or its dry specific gravity is greater than 1700 kg/m^3, porous vegetation concrete can meet the ecological revetment strength and plant growth requirements of small and medium rivers. Hui Jiang et al. [121] proposed an innovatively designed prefabricated porous vegetation concrete block suitable for ecological revetments of small and medium rivers. The block was designed by adopting a random concave-convex structure made of porous concrete material. The results showed that the scour reduction rates of different prefabricated blocks placed on the slope ranged from 35% to 43%. Tae Woong Ahn et al. [122] compared and analyzed the slope contact between porous concrete filter mediums and PC. The results showed that the removal efficiency of PC (SS 5%, BOD 3%, COD 6%, T-N

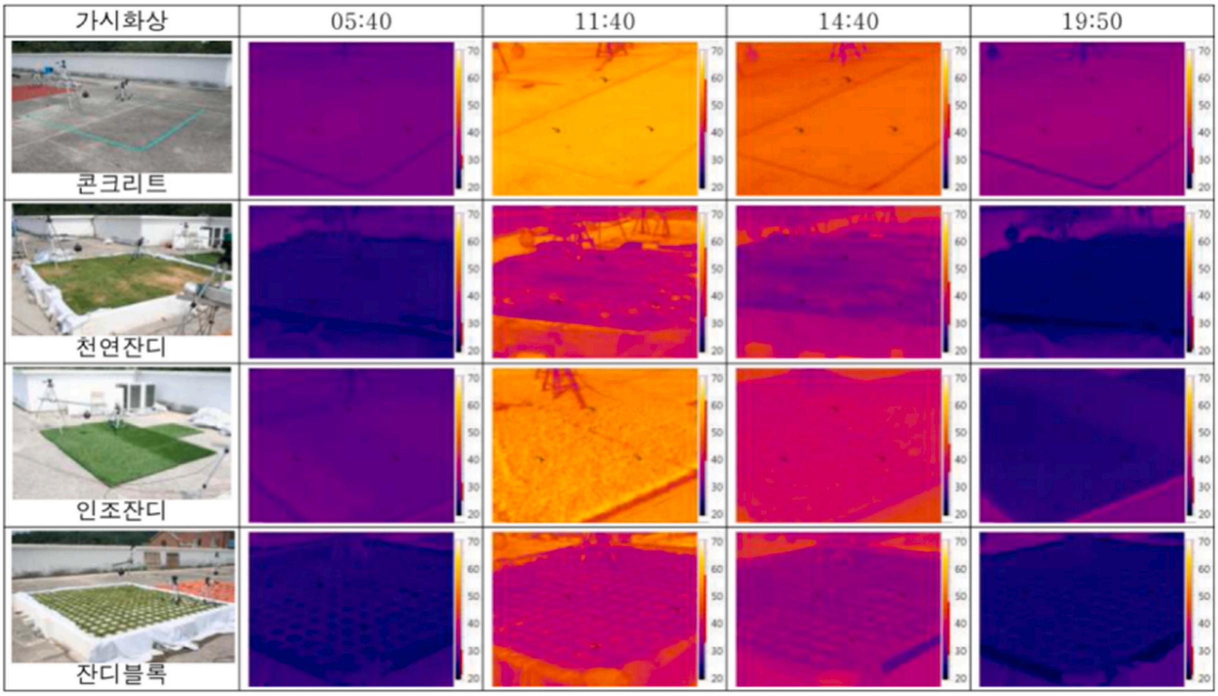

Fig. 27. Thermal images of various roof gardens [101].

Table 6
Costs and application conditions of different slope protection methods.

Slope protection method	Cost (yuan/ m^3)	Application conditions	Advantage	Limitations
Pulp masonry rubble	670–690	The slope is between 1:1 and 1:2, or the bank and embankment slope where the main flow erosion is strong.	Good durability, reduce the land occupancy area, hard texture, strong ability to resist wind and waves.	The consumption of boulders is large and the transportation cost is high. Poor sense, lack of vitality.
Ordinary concrete	745–785	High and steep slopes with a slope greater than 1:1, or river bank slopes with a flow rate of 4–8 m/s.	High strength, good integrity.	High project cost. Isolate the material connection between land and water, water self-purification ability is weak.
Planting concrete	589	The slope is slower than 1:1, and the river flow rate is 3–5 m/s.	Good adaptability and high stability. Soil and water conservation ability is strong, reduce surface runoff. Improve water quality, regulate microclimate, and have significant ecological effects.	The construction efficiency is low. The construction process is easily affected by weather and the service environment.

9%, T-P 10%) was higher than that of porous concrete. Compared with porous concrete, PC has a higher purification and filtration efficiency. By improving plain concrete, higher water quality is expected to enhance its self-purification ability and refine the waterfront and PC landscape. Jeon In-Ki et al. [27] prepared economic PC blocks suitable to all kinds of slopes (40ß–75ß), which can be extruded and continuously produced. By planting the polymer blocks of tall fescue, perennial ryegrass, and alfalfa, Chan-Yong Sung et al. [37] revealed that this approach would benefit environment-friendly projects, such as slope and revetment greening.

Kim Young Ik et al. [102] analyzed water purification effects by PC through collecting the initial inflow samples of five revetment blocks on the first, seventh, and 30th days (Fig. 25). Vegetation blocks containing oyster shells and vegetation blocks were tested with useful microbes and oyster shells simultaneously. The test results showed that the 30 d SS, BOD, COD, and T–P values were all lower than the initial values, indicating effective water purification of PC.

Recently, PC has been used as ecological (flexible) revetments [123]. For instance, PC and ecological stone cage revetments have been used to restore the ecological functions of riparian zones in Chongming of Shanghai, China (Fig. 26). These two revetment measures are characterized by good flexibility, high permeability, and porous structure and are beneficial to biological habitats and plant growth.

4.3. Green roof establishment

Large cities often conflict over land resources between housing and the urban landscape. Roof gardens have been recommended as a greening solution in this context [124]. In 1996, Hoyano and Horiguchi proposed a roof planting system based on porous concrete and described a novel roof planting system without a soil layer on porous concrete [125]. Yoshitaka Ishikawa et al. [125] discussed the recycling of wastes (fly ash from coal-burning power stations and aggregate made of ALC panel wastes) to configure the newly proposed thin roof planting system. In addition, the outline and utility of an outdoor experimental setup used for measuring the water/heat balance of a roof planting system were described.

Lee Sang- Taey et al. [15] ranked several systems in the descending order of temperature control effect: concrete planting system with grass, concrete grassless planting system, mixed soil system, and existing roof system. The results showed that PC could be placed on building roof, instead of ordinary concrete slabs to produce a series of beneficial effects, such as improving environmental factors, lowering construction costs, conserving energy, and reducing environmental loads. To establish urban rooftop gardening in summer, Takahiro Sendo et al. [101] evaluated the effects of ten ornamental plants on buildings using factors including growth rate, extra-foliaceous photosynthetic capacity, attached leaves' stomatal conductance, soil surface, and canopy air temperature. It was found that Thymus, Evolvulus, Petunia, and Fragaria were excellent plant species for roof gardening, as could be seen from their rapid green coverage and high growth rate. On summer nights, the soil surface temperature of all vegetation was 6–8°C lower than that of concrete roofs. Roof greening significantly affects building cooling and air conditioning energy conservation in the summer. Choi Dong-Ho et al. [126] tested the passive cooling effect of plantings (natural grass, grass blocks, concrete slabs, and artificial grass) on building roofs (Fig. 27). The research results showed that the surface temperature difference between artificial grass and concrete was minimal and that artificial turfs alleviated the temperature rise of the slab surface.

Table 7
Mix proportions of vegetation concrete (kg/m^3).

Natural aggregate (NA)	Recycled aggregate (RA)	Water	Cement	Slag	Metakaolin (MK)	Latex powder (LP)	Aluminum potassium sulfate(APS)	Water reducing agent (WRA)
799	748	78	131	46	23	18	11	0.78

(a) Frame and lattice beam casting (b) Left bank planting concrete laying effect (c) The overall effect of vegetation growth after 2 months

Fig. 28. Construction progress of river slope protection.

Table 8
The basic cost of the main project of slope protection.

Charge items	Cost details (yuan)										Total (yuan)
Material costs	NA 13426	RA 4041	Cement 9420	Slag 2200	MK 1428	LP 8800	APS 1339	WRA 1600	Vegetation 9600	Other materials 2147	54001
Machinery usage fee	Concrete loading truck 2430						Mixer equipment 840				3270
Labor costs	Construction 11000						Maintenance 2425				13425
Total (yuan)											70696

5. Cost analysis of PC

5.1. Analysis of factors affecting the cost of PC

The cost of planting concrete mainly includes components such as cement, admixtures, crushed stones, and water. Li [127] optimized the mix design by defining design variables, objective functions, and design constraints, and proposed a cost calculation formula for unit volume of planting concrete, as shown in formula (7).

$$F(x) = C_1x_1 + C_2x_2 + C_3x_3 + C_4x_4 + C_5x_5 + C_6x_6 \tag{7}$$

In the formula:
$F(x)$—objective function, the cost calculation formula of PC per unit volume;
x_1、x_2、x_3、x_4、x_5、x_6—the amount of water, admixture, stone powder, gravel, sand and cement, respectively, (in kg);
C_1、C_2、C_3、C_4、C_5、C_6—the cost of water, admixture, stone powder, gravel, sand and cement per unit weight, respectively.

Researchers have come to different conclusions about the cost of PC. Zhang [128] concludes that the production cost of single block of PC is 12.26 yuan, which was 20.8% higher than that of ordinary concrete (10.15 yuan). Li [129] believes that the construction cost of PC is higher than that of traditional concrete, but the engineering cost(including materials and construction cost, etc.) is lower. Table 6 lists the slope revetment structure and construction methods, and summarizes the cost and characteristics. Compared with mortar rubble and traditional ordinary concrete, the project cost is reduced by 14%-33%. In general, the ecological slope protection technology of PC has certain advantages in economy, slope protection strength and water erosion resistance. Improving the construction method of PC and optimizing its mix ratio will help reduce engineering the cost of PC.

5.2. Engineering cases

5.2.1. Project overview

Hongyu Li [129] designed and prepared PC, which was applied in river slope protection. The mix proportion of PC is shown in Table 7. The 28-day compressive strength of the prepared PC is 10.8 MPa, the continuous voidage is 26.9%, the sand permeability is 61.3%, and the pH of the concrete pore environment is 10.43. Fig. 28 shows the construction process of river slope protection.

5.2.2. Cost analysis of river slope protection engineering

Table 8 shows the basic cost of the main slope protection project, mainly including material costs, machinery usage costs, and labor costs. The material cost is 54001 yuan, accounting for 76.38% of the total cost, which means that the material cost is the largest cost of the project. According to the cost calculation formula for planting concrete per unit volume, as shown in formula (7), the raw materials for PC can be changed and optimized to control costs. Section 2.1 discusses the selection of raw materials for PC. The sum of aggregate and cement costs accounts for 49.79% of the material cost. The use of alternative and environmentally friendly aggregates (such as recycled aggregates) and cementitious materials (slag, fly ash, steel slag powder, etc.) can significantly reduce material costs. Adopting PC automatic mixing and transportation methods, and improving the construction method of PC, which will help to reduce the mechanical usage cost of PC. The labor cost mainly includes construction and maintenance costs. The use of efficient fertilizer applicators can reduce construction costs. PC with high porosity and excellent permeability is prone to blockage or accumulation of impurities. Therefore, regular maintenance and cleaning of debris are necessary. In addition, timely watering and maintenance of PC are required during long-term drought periods. The use of automatic irrigation facilities is beneficial for saving maintenance costs in the later stage.

6. Conclusions and outlook

6.1. Conclusions

Extensive research in recent years has dramatically improved people's understanding of PC. To prepare PC, suitable raw materials should be selected, including low-alkalinity cement, single-gradation coarse aggregates, and admixtures that can reduce alkalinity. The main factors affecting PC design are the water-to-cement ratio, coarse aggregate particle size and gradation, aggregate-to-cement ratio, and voidage. In this paper, planting concrete is prepared and designed by considering all these complex factors, and the water permeability, mechanical properties and alkali environment of planting concrete are further discussed. In addition, the paper also focuses on the durability, plant compatibility, application and economic costs of PC. The main conclusions are as follows:

(1) In terms of material selection, the PC with low alkaline cement as cementitious material is easier to provide a suitable alkaline environment for the growth of plants. 10–26.5 mm is a more suitable aggregate size range for PC. Compared with fly ash and slag, silica fume and metakaolin have better alkali reduction effect.
(2) In the aspect of mix proportion design, the volume method, mass method, specific surface area method and ball model wrapping method can be used to design the target PC. It is suggested that the target void ratio of PC can be designed to be 25%-30%, and the water-to-cement ratio is set in the range of 0.30–0.35, and the aggregate-binder ratio is suggested to be 4.8–5.4.
(3) For the alkali environment of PC, to ensure the survival of plants, the pH value of PC is recommended to be controlled at 8–10. Changing the type of cement or adjusting the amount of cement, adding mineral admixtures, neutralization method and carbonization treatment method can reduce the alkalinity of PC.
(4) In terms of durability, adding blast furnace slag, natural jute fibre or adding urea as fertilizer can improve the frost resistance of PC. Acid corrosion resistance, microbial corrosion resistance and salt corrosion resistance are the problems that cannot be ignored in the durability of PC.
(5) For the plant compatibility of PC, further attention should be paid to the root system, height and other physiological indexes of plants. The use of SAC can alleviate the problems of poor fertilizer retention and alkali leaching. The increase of urea or DP dosage is beneficial to the release of nitrogen and phosphorus nutrients, which can improve the fertilizer retention performance of PC.
(6) PC can be used in water purification, slope protection and green roof establishment. In general, the PC has certain advantages in terms of cost, slope protection strength and resistance to water erosion.

6.2. Outlook

As a type of sustainable concrete with great potential and value to the environment, PC provides an attractive and feasible solution for low-carbon and sustainable concrete. However, there are still many problems to be solved through research for PC. In the future, more in-depth research needs to be conducted in the following aspects:

(1) The PC preparation procedure assesses whether the required voidage can be accomplished and whether the prepared concrete meets the requirement for strength. In this regard, efficient and economical preparation methods are in urgent need.
(2) More research should focus on improving the durability of PC, including their resistance to weathering, acid and salt attacks, and microbial attacks.
(3) The selection and compatibility of alkalinity reduction measures and plants should consider economic efficiency sufficiently. A suitable alkalinity reduction plan and excellent fertilizer retention performance are important factors contributing to plants' healthy growth.
(4) Novel ecological PC based on auxiliary cementitious materials and recycled aggregate should be developed. In this regard, exploring the appropriate replacement ratios of auxiliary cementitious materials and recycled aggregate will benefit PC's economic efficiency and environmental friendliness.
(5) The post-maintenance of PC including repairing PC measures constitute a major research direction.

CRediT authorship contribution statement

Yingjie Ning: Methodology, Investigation. **Yang Zhou:** Investigation, Data curation. **Xiangming Zhou:** Writing – review & editing, Supervision, Investigation. **Jie Yu:** Data curation, Investigation. **Yujian Fan:** Data curation, Formal analysis, Investigation.

Tao Shi: Resources, Supervision, Writing – review & editing. **Yanming Liu:** Writing – original draft, Methodology, Investigation. **Zhuohao Qian:** Investigation, Conceptualization. **Bin Wang:** Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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