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Original Research

Performance Evaluation and Field Application of Prefabricated Grass-Planting Concrete Blocks with Concave-Convex Construction for Mid-Sized and Small River Revetment Projects

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Abstract

As a kind of material used in river revetments, the revetment concrete blocks are required to have satisfactory strength, scouring resistance, and good vegetation coverage. In this paper, prefabricated grass-planting concrete blocks that are suitable for the ecological revetment of medium and small-sized rivers are proposed and innovatively designed. The blocks are made with concave and convex structures of random porous concrete material, which can be jointed and inlaid to form a three-dimensional slope with vegetation function. The performances and advantages of prefabricated grass-planting concrete are evaluated. Four kinds of precast blocks are proposed. The flow velocity reduction, soil conservation, and scouring resistance of these blocks are analyzed quantitatively through physical modeling and field application. The results show that the four blocks can effectively reduce the near-shore flow velocity and decrease the level of scouring on the slope surface. The rate of scouring reduction of the different prefabricated blocks placed on the slope was in the range of 35%-43%; thus, the results were similar. Through application on a riverbank, this concave-convex revetment structure shows excellent improvement in scouring resistance and soil conservation, with average vegetation coverage up to 95%. Prefabricated grass-planting concrete blocks can be used as riverbank revetment materials.

Keywords: prefabricated grass-planting concrete, ecological revetment, scouring resistance, soil conservation, river

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Introduction

Rigid materials such as masonry, cast-in-place concrete, and blank concrete walls, which can effectively resist floods and protect the riverbank, are typically used in river revetments. However, the rigid material and material structure are compact, and make it difficult for plants to grow, which blocks the exchange between the river and the riparian zone. The river ecosystem is destroyed with a rigid material slope, and the river fails in its role as an ecological corridor. Grass-planting concrete, e.g., porous concrete with a planting function [1], is of particular interest and has found practical application as a river revetment material. Its performance can strengthen the growing conditions for plants. The plant roots can freely pass through its continuous voids, and water, fertilizer soil, air, and space for growth are provided in the void [2]. The effective porosity of grass-planting concrete is usually more than 20% [3]. Some researchers have carried out an impact analysis of the components and mix ratio, the basic mechanical properties, and void and alkaline testing of grass-planting concrete [4-7]. It has been found that the strength viability of porous concrete depends not only on the void, but also on the size of the coarse aggregate and the water-cement ratio [8-10]. To meet void requirements, the strength of concrete may be reduced by using less mortar [11], and other materials such as limestone powder, ganister powder, and fly ash are used to replace cement and achieve high compressive and tensile strength of the concrete [12-14]. Polymer may be added to porous grass-planting concrete and paving materials [15, 16]. The alkalinity of concrete comes from the cement, and it increases with an increased content of cement. The high alkalinity of concrete is unfit for growing plants [17, 18]. A 40-60% by weight replacement of cement with fine-powder blast furnace slag effectively reduces the cement content and alkalinity of concrete [19]. Calcium aluminate cement with a lower pH than ordinary Portland cement was used [20]. These studies facilitate the application of grass-planting concrete. However, there are some problems. Although a thin covering of soil on the surface of grass-planting concrete can provide plants with water, air, and nutrients, it can be scoured off under flood conditions, especially if plant roots have not passed through the concrete to reach the bank foundation. Recently, grass-planting concrete revetments have been mostly in the form of concrete outer frames with cast-in-place grass-planting concrete. It is easy for large concrete blocks to crack because of the uneven settlement of the bank foundation and the low strength of concrete. At the same time, it is difficult to control the pouring quality onsite, due to unsteady temperature and humidity during the curing period. The stability of the riverbank slope and the growth of planting are directly affected by these factors, which significantly restricts the production and application of grass-planting concrete in rivers.

In this study, new types of prefabricated grass-planting concrete blocks with concave-convex construction are put forward, and the revetment performances are tested. Different from common prefabricated concrete [21, 22], prefabricated grass-planting concrete is a small member that uses random porous concrete as the skeleton, which is a mosaic spliced to form a three-dimensional slope. The concrete voids are filled with suitable soil mixed with grass seeds. The roots of herbaceous plants grow in the concrete and reach the shore foundation, unifying the herbaceous plants, concrete, and shore foundation. Optimization of the structural design and physical model testing of prefabricated grass-planting concrete blocks was carried out, flow velocity was reduced, and soil conservation and scouring resistance were evaluated. Furthermore, the physical properties and vegetational performance of the concrete were applied and validated *in situ.*

Material and Methods

Materials and Specimens

Materials

Commercial ordinary Portland cement P.O 42.5 [23] and ganister powder were selected as the cementitious materials for preparing prefabricated revetment concrete blocks, and its properties are listed in Table 1. Coarse aggregates with gradations of 10-20 mm, 15-30 mm, and 20-40 mm were tested for making concrete, and their physical properties are presented in Table 2. Natural river sand was used as a fine aggregate, with an apparent density of 2650 kg/m^3, a bulk density of 1530 kg/m^3, and a fineness modulus of 2.15. The eco-concrete additive used was SR-4 which is liquid, and its main ingredients were $CaCO_3$, SiO_2, and other inorganic materials. The SR-4 additive, which has a density of

Table 1. Properties of Portland cement P.O 42.5.

Properties	P.O 42.5
Density (kg/m^3)	3085
Blaine fineness (m^2/kg)	358.2
Setting time(min)	
Initial	195
Final	235
Compressive strength (MPa)	
3d	27.7
28d	49.8
Flexural strength (MPa)	
3d	5.9
28d	8.8

Table 2. Properties of coarse aggregate.

Properties	Coarse aggregate		
Aggregate gradation (mm)	10-20	15-30	20-40
Apparent density (kg/m^3)	2750	2755	2760
Compact packing density (kg/m^3)	1460	1510	1560
Sand content (%)	0.91	0.80	0.45
Needle flake content (%)	11.00	10.50	1.00
Water absorption (%)	13.50	11.30	10.55
Crushing value (%)	9.50	6.28	6.85

1.045 kg/L, can efficiently improve the compressive strength and durability of the formed blocks. Ganister powder with an average size of 0.13 µm and specific surface area of 19.0 m^2/g was selected to increase the strength property of the prefabricated revetment concrete blocks.

Specimens

The target compressive strength of blocks was 7 MPa or higher, the target void ratio was more than 20%, and the target pH value was less than 9 for mid-sized and small rivers. To achieve the voids in the grass-planting concrete, a gap-graded aggregate was used. The design mix proportion of the grass-planting concrete was optimized by orthogonal testing. Key testing factors were analyzed, such as crushed stone grades of 10-20 mm, 15-30 mm, and 20-40 mm, design porosities of 20% and 25%, liquid-solid ratios of 0.20, 0.25, 0.30 with liquid components including water and SR-4 and solid components including cement, sand, and ganister, and 3 L/m^3 of eco-concrete additive SR-4 and 15 g/m^3 of Ganister powder. Component contents of grass-planting concrete were computed by the volume method [24]. The design mix proportions of prefabricated grass-planting concrete are shown in Table 3.

Methods

Structural Design

To evaluate the physical and mechanical properties of concrete blocks, different types of prefabricated grass-planting concrete blocks were innovatively designed. The design and calculation of the structure types, sizes, and embedding shapes of the specimens were carried out, and detailed structures were considered on the basis of structural analysis and engineering experience.

Table 3. Mix proportions of grass-planting concrete.

No.	Coarse aggregate grade (mm)	Target voids (vol%)	Liquid-solid ratio	Crushed stone content (kg/m^3)	Water (L/m^3)	Cement content (kg/m^3)	Sand content (kg/m^3)	SR-4 (L/m^3)	Ganister powder (kg/m^3)
1	10~20	20	0.2	1430	101	253	253	3	15
2		25			83	208	208	3	15
3		20	0.25	1430	117	232	232	3	15
4		25			96	190	190	3	15
5		20	0.3	1430	132	218	218	3	15
6		25			109	179	179	3	15
7	15~30	20	0.2	1480	95	237	237	3	15
8		25			77	192	192	3	15
9		20	0.25	1480	109	218	218	3	15
10		25			89	176	176	3	15
11		20	0.3	1480	124	204	204	3	15
12		25			101	166	166	3	15
13	20~40	20	0.2	1530	89	222	222	3	15
14		25			71	177	177	3	15
15		20	0.25	1530	102	203	203	3	15
16		25			82	162	162	3	15
17		20	0.3	1530	116	191	191	3	15
18		25			93	152	152	3	15

The size, length, and minimum thickness of the prefabricated block structures are mainly related to the flow velocity and slope. The minimum thickness of the prefabricated blocks is given by Eq. (1), and the detailed structural design was carried out in combination with engineering experience and the stability of the inlay.

$$t = K\frac{0.11(2h)}{(\gamma_c - \gamma_w)\cos\alpha\sqrt{b}} \tag{1}$$

...where t is the thickness of the prefabricated blocks (m), K is the safety factor, which can be determined to be 1.10 based on the safety factor of a general slope according to the GB 550286 standard [25], $2h$ is the design wave height (m), γ_c is the bulk density of concrete (t/m^3), γ_w is the bulk density of water (t/m^3), b is the length of blocks along the bank slope (m), and α is the angle between the bank slope and a horizontal line; α is equal to 28.6° when the slope of the riverbank is 1:2.

It is difficult to provide sufficient water and soil until the grass has grown in riverbanks; therefore, concave-convex construction is proposed in this study for the near-shore side of the slope to decrease flow velocity and prevent flow-down of the soil.

In the design process, the following steps are required. First, the concave-convex height difference must be set according to the hydraulic conditions of the river and the requirement of grass growth, while the thickness of the concave structure should be ensured to meet the requirements of the minimum thickness of revetment blocks; the thicker the concrete, the more difficult the growth of grass. Second, it is necessary to design different shapes for the concrete blocks to be sufficiently embedded, and some bayonets should be designed; the more stably the blocks are embedded with each other, the more conducive to the stability of the riverbank. Third, structural design cannot be too complex, as the production and construction of components of complex structures are not favorable. Moreover, the concrete section cannot be too large or too small, because the concrete could easily break during the construction process. Therefore, it is necessary to optimize and improve the components via practice. For example, the shape of the built-in blocks was a cross, the middle regular part of which was designed to be convex. Though built-in cross blocks have a simple structure and are easy to make, the blocks can be firmly inlaid with each other. Different types of blocks were designed to help the grass to settle easily and flourish until its roots could pass through the member. Assembled grass-planting concrete test blocks are manufactured according to the design size, as follows: The concrete mixed from raw materials was poured into a wooden mold and manufactured by tamping via the use of steel chisels and a manual layering method, then cured at the standard condition of 20±2ºC and relative humidity above 95%. Member production was complete after 28 days.

Fig. 1 shows the design of four types of prefabricated grass-planting concrete blocks, which are, respectively, built-in I-shaped blocks (type I), built-in regular hexagon blocks (type II), built-in cross blocks (type III), and built-in square blocks (type IV). Types I, II, and IV have prefabricated blocks of two different thicknesses. The thickness of the tall member is 10 cm, and that of the short member is 8 cm, thus the surface of the concave-convex structure forms a quincunx with a 2 cm height difference. Type III is a single concave-convex cross member with a 5 cm height difference. In order to further strengthen the stability of the blocks on the riverbank, holes with a 7.5 cm square are designed in the middle of type II and IV blocks for planting grass with strong roots, such as *Vetiveria*, which plays a role in plant reinforcement [26].

Strength

Specimens were prepared in a cube steel mold of 150×150×150 mm for compressive strength testing, and 100×100×400 mm for flexural strength testing [27], and then cured at the standard condition of 20±2ºC and relative humidity above 95% for 28 d. In order for the surface of the specimens to be in close contact with the equipment, the super-surface and undersurface were smoothed by the mortar before the test. Each of the three specimens were manufactured corresponding to each set of compressive or flexural data, and the average values of strength were calculated for each dataset.

Void ratio

Voids are the main property of grass-planting concrete that helps the grass to grow. Void ratio (P_e) is the rating of accessible voids, which can be evaluated with Eq. (2) on the 28th day using the volume difference [28]. The volume of cube specimens of 150×150×150 mm (V_0) is computed, a certain amount of water is added to the water container, and the volume (V_1) of the water is calculated. Thereafter, the test specimen is slowly placed into the water container. When the water surface is stable, the water surface value is measured and the volume (V_2) is calculated.

$$P_e = (1 - \frac{V_2 - V_1}{V_0}) \times 100\% \tag{2}$$

The specimens were prepared such that the pores were saturated with water as much as possible. After water curing for 1 d before the test, the water-cured specimens were dried for 24 h to ensure that they were absolutely dry, and the void ratios were then measured.

Alkalinity

The alkalinity of grass-planting concrete was tested according to a previously reported method [29]. Concrete specimens with a volume of 150×150×150 mm were constructed for alkalinity testing at a temperature of 20±2ºC for 28 d. The concrete specimens were placed

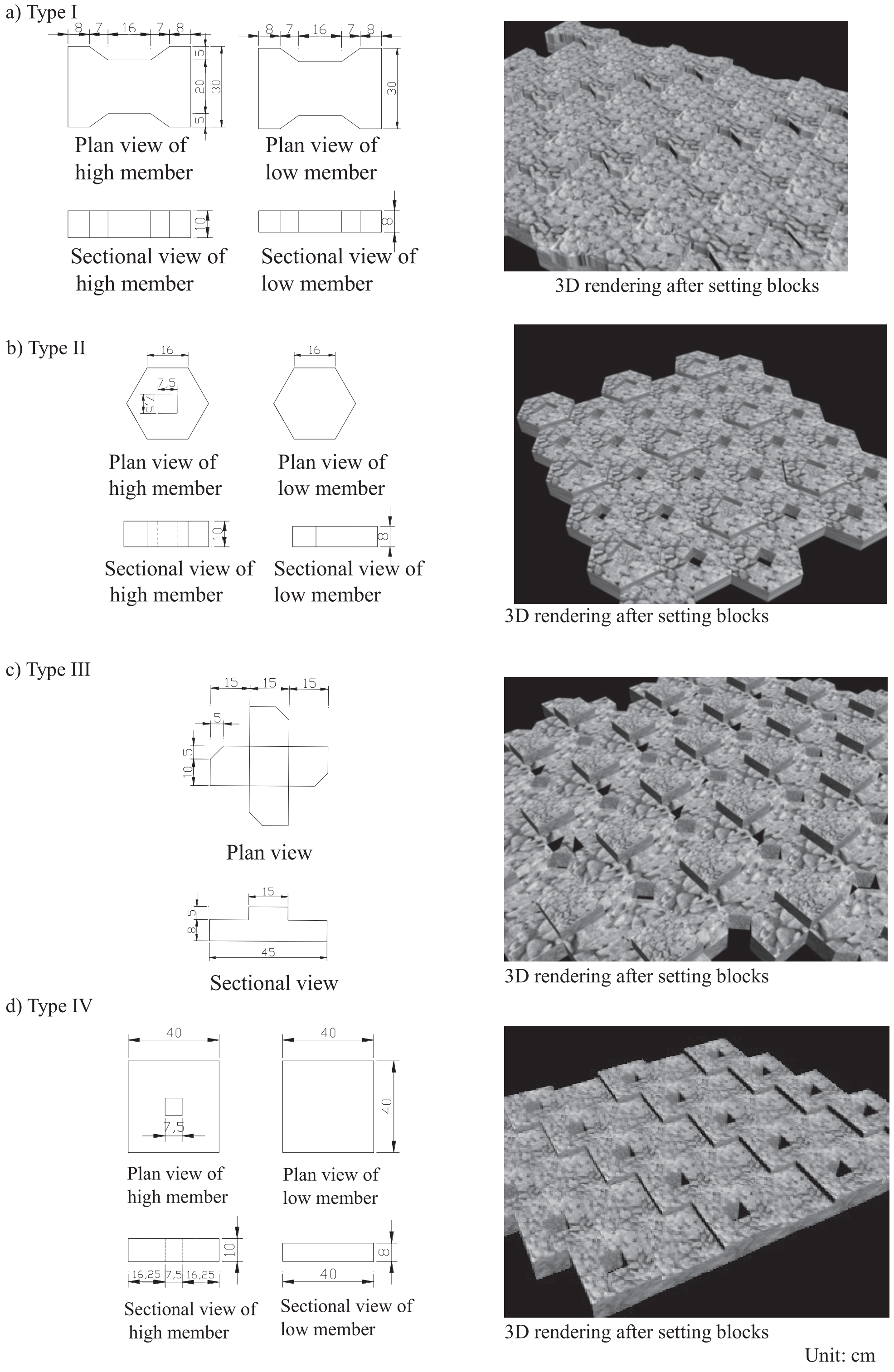

Fig. 1. Structural design diagram of prefabricated grass-planting concrete blocks.

in water containers, and 3 L of distilled water was added into these containers to immerse the specimens. After immersion for 24 h, the test water was retrieved with a small cup, and the pH value was measured with a pH meter. The pH value of the soaking solution was measured using a laboratory-grade pH meter (PHS-3E, China). The container was refilled with 3 L of pure deionized water after each test.

Flow Velocity Difference

The concave and convex surfaces of the concrete blocks can guide the flow of water and change the turbulent status of the flow to reduce the scouring of water on the surface soil and the presence of soil in the voids of the concrete. The flow velocity difference is an expression of key dynamic parameters as well as the flow resistance and Reynolds number. The flow velocity difference denotes subtraction between the flow velocity of the convex and concave area of the blocks. In this experiment, flow velocity was measured on the convex and concave area of the blocks before the concrete was filled and poured with soil, and the mean flow velocity difference was the mean value of three measuring positions on each frame of the tested blocks. The positions of the measurement points are shown in Fig. 1. The velocity was measured with the flow velocity meter.

Scouring Resistance

The slope of a bank (*i*), which is the ratio of elevation difference and horizontal distance of the slope, is usually in the range of 1:2 to 1:3 in ecological projects of mid-sized and small rivers. Soil is easily lost when the slope is less than 1:2, so slopes of 1:2 or 1:3 were set in the experiment. Flow velocity was measured during the research of mid-sized and small rivers, and was usually less than 3.0 m/s, so scouring models were set with a flow velocity (*V*) of 0.7 m/s, 1.2 m/s, and 2.0 m/s. The blocks were placed in constant water level in the rivers, and scouring models were tested with a water depth (*H*) of 0.5 m or 1.0 m, as well as a water depth between the top of the wooden frame and the water surface (see Fig. 2).

To implement the scouring experiments, slope equipment with a 1 m^2 custom-made wooden frame was designed and prefabricated. The prefabricated blocks were assembled into a wooden frame. The farmland soil with the flow was poured into the revetment concrete blocks, and the soil cover with the humidity of 21% was filled and manually compacted by rammer to the level of the convex surface of the concrete. The experimental design is shown in Fig. 2.

Scouring tests were carried out on the four types of assembled blocks and a cast-in-place concrete block. Cast-in-place concrete test was a comparison with that of concave convex structures blocks. It directly poured the porous concrete into the testing frame, and a grass-planting smoothing concrete block without concave convex surface was formed by flapping and flattening process. The water flowing through the surface of the wooden frame was even and smooth without obvious local disturbance. The scouring level of different blocks, which varied with the scouring time under the same test conditions, was measured. The soil scouring level was measured at 10, 20, and 40 min, and the amount of scoured soil was measured by weighing method. Before the test, the soil was saturated by adding water, and the total weight of wood frame, concrete and soil was measured as the initial total weight. After each scouring test, the total weight is measured under the soil saturation condition. the amount of cumulative scoured soil was computed with the difference between the initial total weight and the total weight of each test.

The experiment scheme for scouring resistance was planned with the factors of water level, flow velocity, and slope. Nine test cases are shown in Table 4.

Results and Discussion

Strength

Fig. 3 shows that the average 28 d compressive strength of specimens with a 20-40 mm coarse aggregate grade is less than 6.00 MPa, and the maximum value is 7.10 MPa; the average 28 d flexural strength is 2.70 MPa, and the maximum value is 3.10 MPa. Compared with specimens using small and medium grade aggregate, the strength of the specimens decreases mainly because the larger the aggregate grade and the smaller the specific surface area, the smaller the total cementing area, and the strength cannot meet

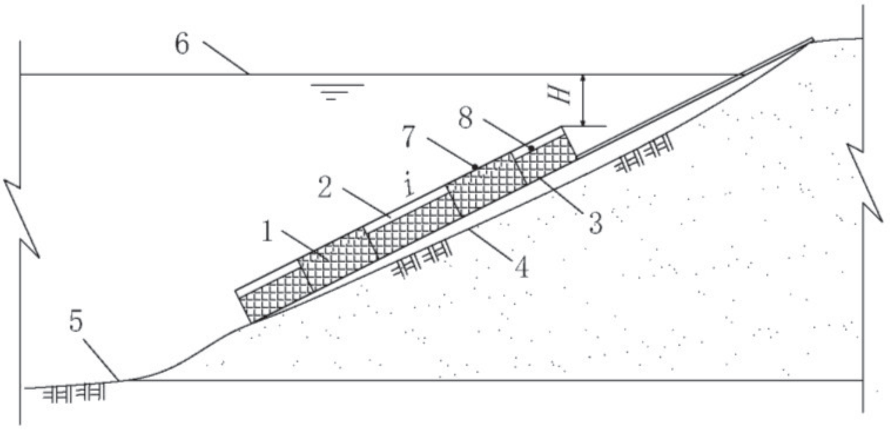

Fig. 2. Test design of scouring resistance. 1. Prefabricated grass planting concrete; 2. Casing soil; 3. Wooden frame; 4. bank-based; 5. Riverbed; 6. Water surface; 7. The measurement point of the flow velocity in the convex surface of the concrete blocks before the concrete was filled and poured with soil; 8. The measurement point of the flow velocity in the concave surface of the concrete blocks before the concrete was filled and poured with soil. H: The height from the water surface to the top of the wooden frame

Table 4. Test cases of scouring resistance.

Case	Member types	Water level (m)	Flow velocity (m/s)	Slope
Case 1	Type I	0.5	1.2	1:2
Case 2	Type II	0.5	1.2	1:2
Case 3	Type III	0.5	1.2	1:2
Case 4	Type IV	0.5	1.2	1:2
Case 5	Cast-in-place concrete	0.5	1.2	1:2
Case 6	Type II	1.0	1.2	1:2
Case 7	Type II	0.5	0.7	1:2
Case 8	Type II	0.5	2.0	1:2
Case 9	Type I	0.5	1.2	1:3

the basic target requirements for the compressive strength of mid-sized and small rivers. The average 28 d compressive strength and 28 d flexural strength of the specimens with a small aggregate grade reached 8.40 MPa and 3.10 MPa, respectively, and their maximum values were 12.90 MPa and 4.10 MPa, respectively. Therefore, a coarse aggregate grade of 15-30 mm is suitable for grass-planting concrete with the goal of obtaining a compressive strength of more than 7 MPa in mid-sized and small rivers.

Void Ratio

Fig. 4 shows that the void ranges of all test specimens vary from 19.0% to 20.4%, with an average of 19.8%, which is close to the target void of 20%. The void ranges from 23.2% to 24.8%, with an average of 24.2%, which is close to the target void of 25%. The compressive strength of concrete decreases with an increase in void. The results show that the void is closely related to the compressive strength.

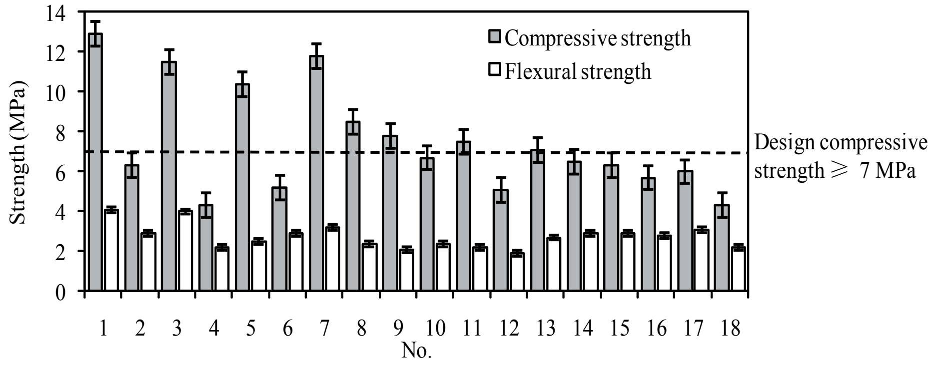

Fig. 3. Strength of grass-planting concrete specimens.

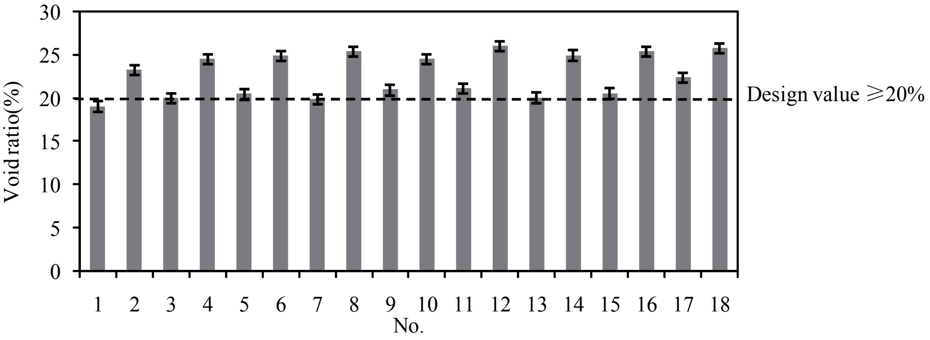

Fig. 4.Void ratio of grass-planting concrete specimens.

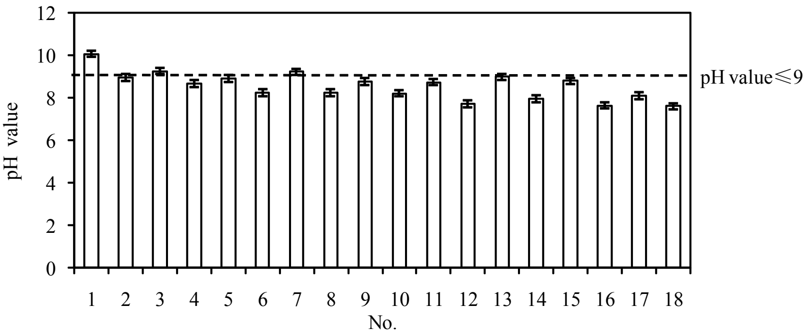

Fig. 5. The pH value of grass-planting concrete specimens.

Alkalinity

Fig. 5 shows that the pH values of concrete measured for all test specimens varied from 7.60 to 10.07, and the average pH value was 8.56. The pH value is affected by the hydration reaction of cement, and an increase in pH value is observed with the cement content increase. The pH value was as high as 9.0 when the cement content was greater than 230 kg/m^3.

Flow Velocity Difference

The 10th mix of 18 mixes was selected for the construction of the prefabricated grass-planting concrete blocks and cast-in-place concrete. Figure 6 shows that flow velocity through different blocks is decreased due to the convex and concave areas. The built-in regular hexagon member shows the greatest effect of decreased flow velocity with an increase in flow resistance. The difference between mean flow velocity measured on the convex and concave area of blocks was 0.27 m/s, whereas the water level was 0.5 m. The slope formed by the built-in cross member has the second-highest water scouring resistance, with a mean flow velocity difference of 0.23 m/s. The lowest value is for the built-in I-shaped member, with a mean flow velocity difference of 0.17 m/s. With the increase in the water level, the flow velocity difference for each member increases, and the water level is positively correlated with the flow resistance coefficient, which indicates that as the water level increases, more flow energy is consumed to overcome the resistance. The flow velocity difference between different blocks increases at different rates as the water level varies from 0.5 m to 1.0 m. The built-in regular hexagon member shows the greatest reduction in flow velocity difference, with an increase of 0.13 m/s, and the built-in cross member shows the least reduction, with a flow velocity difference increase of 0.04 m/s. Thus, the flow velocity of water decreases for different prefabricated grass-planting concrete blocks to different extents, which shows that the decrease in flow velocity and construction shape are closely related.

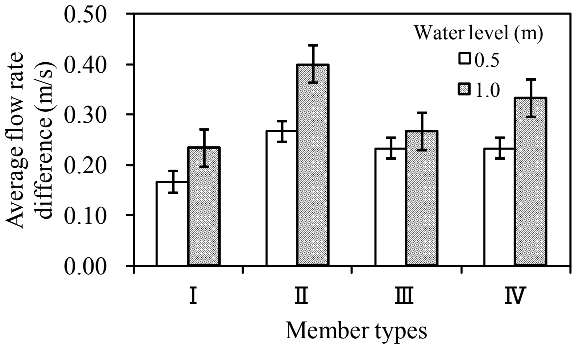

Fig. 6. Average flow rate difference between different prefabricated grass-planting concrete under different water levels.

Scouring Resistance

The rate of scouring reduction (R_s) was calculated by Eq. (3): $R_s = (b - a)/b \times 100\%$, where a is the amount of cumulative scouring with the prefabricated blocks laid on the slope, and b is the amount of cumulative scouring with the cast-in-place smoothing concrete laid on the slope.

Fig. 7 shows that the amount of erosion per 10-20 min for cast-in-place smoothing concrete changes little under the test conditions with a water level of 0.5 m, bank slope of 1:2, and flow velocity of 1.2 m/s. The erosion level of the prefabricated grass-planting concrete blocks increased rapidly at first and then slowed down. The scouring level for the five types of blocks grew rapidly while the surface soil was scoured in 10 min. After a 20 min time period, the cumulative scouring levels of the slope with cast-in-place concrete are distinct larger than the slopes with prefabricated blocks. After 40 min, under the conditions of a 0.5-m water level and a water flow rate of 1.2 m/s, the average rate of scouring reduction with the four types of prefabricated blocks was found to be 39%, which demonstrates that the prefabricated blocks played a role in water scouring resistance. However, Fig. 8 demonstrates that the rate of scouring reduction with different prefabricated blocks laid on the slope was in the range of 35%-43% after 40 min; thus, the results were similar. The slopes

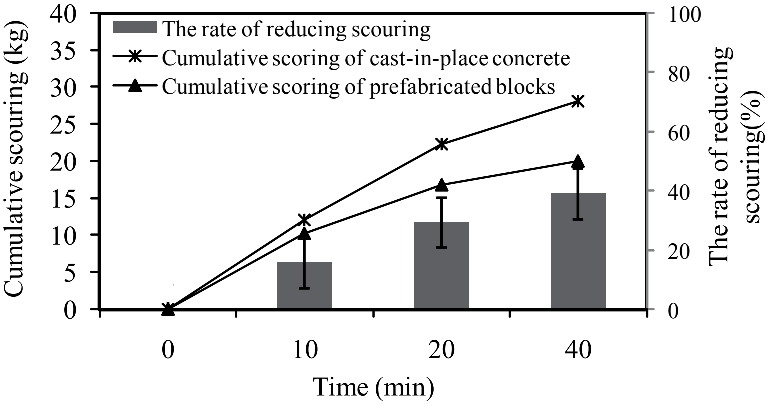

Fig. 7. Change in cumulative scouring level for different structural types over time. The cumulative scouring of the prefabricated blocks is the mean of the cumulative scouring of the four types of blocks and cast-in-place concrete.

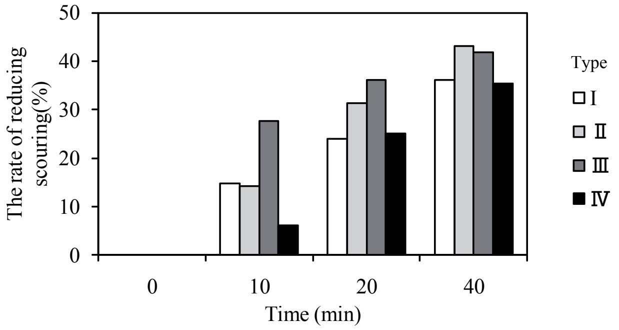

Fig. 8. The rates of reducing scouring with prefabricated blocks laid on the slope over time.

formed by the built-in regular hexagonal blocks and the built-in concrete cross blocks had slightly higher water scouring resistance. It can be concluded that the slopes of the prefabricated blocks play an important role in reducing the amount of scouring, and the different types of slopes of prefabricated blocks have different potentials for soil conservation and scouring resistance.

Because the built-in regular hexagon member showed the best results for reducing the flow rate of inshore water and improving scouring resistance and soil conservation in revetments, it was used as a typical experimental object in different scouring tests under test conditions from case 6 to case 9. Fig. 9a) shows that the scouring level of blocks of slope under the water level of 0.5 m is less over time than that under the water level of 1 m in case 2 and case 6. As the water level increases, the soil scouring amounts of blocks of slope also increases significantly. The higher the water level, the weaker the scouring resistance of the blocks. The difference between the cumulative scouring amounts of blocks at a gradient of 1:2, and that of precast blocks at a gradient of 1:3 grows larger over time in case 2 and case 9 (Fig. 9b). After 40 min, the soil scouring level at a gradient of 1:2 is 1.59 times that at a gradient of 1:3. The slope has a very obvious influence on the scouring resistance of the slope protection, that is, the greater the slope, the worse the scouring resistance of the prefabricated slope protection. Fig. 9c) shows that the initial scouring level at a higher flow rate increases significantly, and the amount of erosion increases rapidly at first and then decreases gradually in 0.7 m/s (case 7), 1.2 m/s (case 2), and 2.0 m/s (case 8). This shows that soil particles can be carried away by decreased water flow over time After 40 min, the total scouring level for the 2.0 m/s water flow is almost 3 times that of the 0.7 m/s water flow. Therefore, water flow velocity, designed gradient,

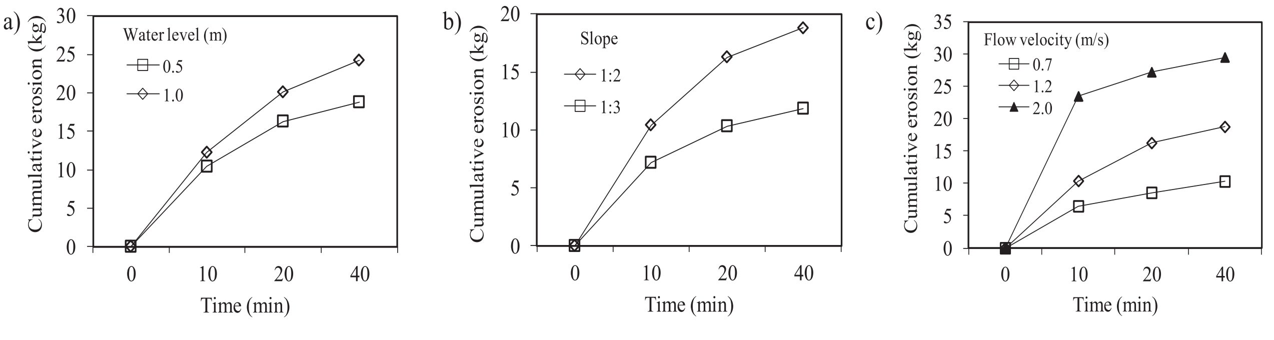

Fig. 9. Variation in cumulative scouring level over time under different flow velocities, water levels, and slopes.

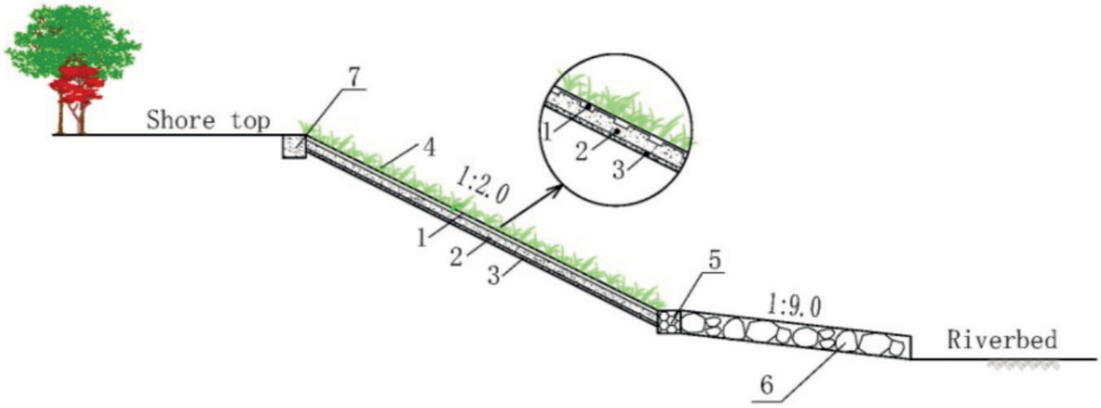

Fig. 10. Standard construction cross-section. 1.Casing soil; 2. Prefabricated grass-planting concrete; 3. Sand- gravel cushion; 4. Herbs; 5. Gabion; 6. Stone paving; 7. Cast-in-place top concrete.

Fig. 11. Process of construction (a) Set up of prefabricated grass-planting concrete; b) Covering soil; c) Covering *Bermudagrass* turf and planting *Vetiveria*.).

and water level are the main factors to be considered in designing revetments with prefabricated grass-planting concrete blocks, and flow velocity is the most sensitive of the three factors.

Field Construction and Analysis

A cross-section of the slope using prefabricated blocks is shown in Fig. 10. The application of prefabricated blocks includes the processes shown in Fig. 11. The first step was the manufacturing and curing of blocks, then the riverbank was cleaned and flattened. The gabion foundation and cast-in-place top concrete were constructed, and then blocks were installed on the slope of the riverbank after the gravel cushion was laid. Soil with seeds was then applied (5 cm thick) on top. Finally, the surface of the slope was covered with black geotextile for protection from the harsh rays of the sun and rain scouring, and it was cured and regularly watered. *Vetiveria* and *Bermudagrass*, which have developed roots, strong vitality, and cold and drought tolerance, were selected for grass planting and slope protection. The roots of these grasses grow well, and play an anchoring role after penetrating the slope, thus unifying the slope surface and shore base.

Vegetation coverage was systematically measured by the normalized difference index (NDI) method via the use of digital photographs [30]. The thickness of the soil covering on the slope when different types of prefabricated blocks were used was measured. Five measuring points of the cross-sections for each type of block were selected, and they were distributed in the upper, middle, and lower parts of the slope. Fig. 12 presents the average thickness calculated for each type of block. After a flooding period, the average surface thickness of the soil covering was 4.4 cm, and the thickness of the surface covering over 85% of the area was greater than 3 cm. The average thickness of the

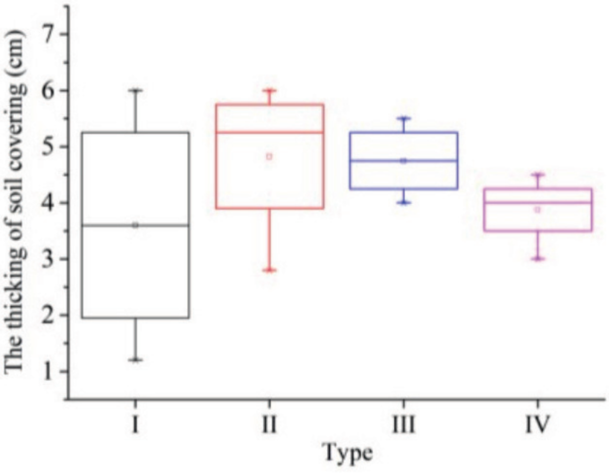

Fig. 12. The thickness of soil covering for four types of prefabricated grass-planting concrete.

Fig. 13. Effects of revetment after one year.

prefabricated concrete blocks was greater than that of flat concrete, which was only 1.2 cm. The soil covering with a smaller thickness was distributed at lower parts of the slope, because these parts were scoured for a longer amount of time and with a higher water level. The thickness of the soil covering at the middle parts of the slope varied only slightly, and even exceeded 5 cm due to the downward movement of the upper soil covering that was affected by water flow and rain erosion. According to the demonstration applications, this revetment structure had good soil conservation and scouring resistance, with vegetation coverage up to 95% on average (see Fig. 13). Compared with that of the cast-in-place grass-planting concrete, the vegetation coverage of the prefabricated concrete blocks was up to 86% higher. Therefore, prefabricated grass-planting concrete can effectively reduce the flow rate of inshore water, improve scouring resistance, and increasing the vegetation coverage in revetments. The results provide new river revetment techniques for flood control, ecosystem protection, and environment beautification.

Conclusions

In this study, the concept of prefabricated grass-planting concrete was proposed, and four types of blocks were tested. Through physical modeling and practical application, the precipitation flow velocity, scouring resistance, and soil conservation on the coastal slope of revetments were quantitatively analyzed, which provided important technical support for revetment design and ecologically friendly riverbanks. The following conclusions can be drawn:

1. The concave-convex structure of prefabricated grass-planting concrete on a three-dimensional slope can better reduce inshore flow velocity. The flow velocity-reducing capacity of prefabricated blocks with different types is different.

2. The rate of scouring reduction with different prefabricated blocks laid on the slope was in the range of 35%-43%; thus, the results were similar. The prefabricated revetment blocks were demonstrated to have superior anti-scouring effects. The slopes formed by the built-in regular hexagon blocks and the built-in concrete cross blocks had slightly higher water scouring resistance. The concave-convex structure can effectively prevent soil from sliding, and effectively maintain the planting soil and provide rich nutrition and a rich growing environment for vegetation.

3. Flow velocity, design slope, and water level are the key factors that affect the anti-scour performance of prefabricated grass-planting concrete revetments, and should be considered in the design process. In addition, the design of through-holes or grooves, and plant anchorage measures can also be considered. Self-locking and overall interlocking can improve the ability of prefabricated blocks to resist different degrees of water erosion in order to adapt to the continuous fluctuation in the slope gradient, and deformation of the slope foundation.

4. Four types of prefabricated grass-planting concrete blocks were validated for in-situ application. The average vegetation coverage ratio reached 95% after one year. This study provides theoretical data and a factual basis for promoting the innovation and application of grass-planting concrete technology.

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Conflict of Interest

The authors declare no conflict of interest.

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