



Recent advances in slope stabilization using porous vegetation concrete in landslide-prone regions: A review

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ABSTRACT

The risks of soil erosion and landslides in tropical regions are severe. They are triggered mainly by excessive rainfall, which leads to a pore water pressure spike and a lower shear strength of earth materials. In recent years, there has been a growing interest in the application of durable, economical, and sustainable slope stabilization technologies, and porous vegetation concrete (PVC) has proven to be a promising solution. The PVC technique incorporates both porous concrete and vegetation. Combining these two materials aims to achieve dual benefits: immediate slope protection from porous concrete and continued vegetation growth, which positively influence the mechanical and hydrological properties of the slope and enhance its aesthetic appeal. This review presents the latest advancements in the use of PVC for slope stabilization, focusing on material mix designs and properties (porosity, strength, pH, and durability), challenges hindering its effective implementation, such as the type and quantity of vegetation seeds compatible with porous concrete, and prospects for future studies that could improve its application. Furthermore, it highlights the advantages and disadvantages of other slope stabilization techniques. This review serves as a valuable resource for practitioners, researchers, and policymakers to implement new methods of slope protection using PVC.

1. Introduction

In the past decade, the frequency of natural disasters and extreme climatic events has increased significantly, resulting in slope failure worldwide [1]. Also, this trend has been observed in countries with rapid infrastructural development in projects such as construction of highways, railways and dams, which has contributed to slope instability [2–8].

Rainfall has been recognized as the primary triggering factor for most slope failures, particularly in tropical regions [9–12]. Rainfall infiltration and seepage reduce soil matric suction (negative pore water pressure) and shear strength, resulting in slope failure [11,13]. Scholars have suggested different methods for mitigating slope instability, such as the use of impermeable concrete or shotcrete retaining structures [14–18], vegetation [19–23], structural reinforcements (soil nails, anchor bolts, micropiles) [24–28], and geosynthetic materials (geogrids, geocells, geomats, and geonets) [27,29–33]. However, these methods are not fully sustainable in terms of cost, ecological friendliness, and durability [34]. Conventional concrete does not allow plant roots to sprout [35,36]. In addition, after prolonged exposure to sunlight, the durability of concrete structures is compromised [34]. It was also found that vegetation alone is not appropriate because, when it ages, the roots lose strength and fail to provide the required reinforcement to the soil [37].

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Moreover, Fan et al. [34] revealed that on steep slopes (greater than 45°), plant roots alone could not provide adequate shear resistance; therefore, additional stabilization methods are required to prevent sliding. To improve the service life and aesthetic appearance of the existing stabilized slopes, numerous studies on coarse aggregates are being conducted to create multifunctional porous concrete with enhanced water and air permeability, sound absorption, managing stormwater runoff, water purification, and vegetation adaptability [36,38–46]. This kind of concrete is called porous vegetation concrete (PVC). It is a modification of two conventional slope protection methods: vegetation and concrete slope stabilization techniques [47]. This process involves the use of porous concrete materials (cement, coarse aggregates, and admixtures) and vegetation, as illustrated in Fig. 1 [3,8,48–52]. Compared to other bioengineering methods, PVC has several benefits, as illustrated in Fig. 2. For example, it can effectively protect slopes from huge scouring by making soil more resistant to erosion caused by water, wind, or gravity [53,54]. Vegetation roots can also penetrate porous concrete and provide additional shear resistance to soil.

1.1. Justification and contribution of this study

Studies on slope stability using PVC have been conducted in countries such as China, Japan, Korea, India, and Australia [8,48,56,57]. These studies found that this technology has more benefits than the conventional methods. However, limited reviews concerning slope stability using PVC have been published, as this technology is still in its early stages [8]. In the few review papers published regarding the application of vegetation concrete in slopes [49,53,58], some gaps were identified. The use of calcined clay as a supplementary cementitious material, which has recently become a promising material in the concrete industry and is readily available in most parts of the world, has not been discussed. The currently popular supplementary cementitious materials (SCMs) are fly ash (FA), granulated blast furnace slag (BFS), and silica fume (SF), which have limited or decreasing supply with time [59,60]. Few researchers have used calcined clay (metakaolin) in porous concrete for pavement applications [61,62] or in conventional concrete [63,64]. Incorporating calcined clay into PVC for slope stabilization has various benefits, such as reducing the pH of concrete to a level suitable for vegetation growth, improved durability, and strength.

Previous reviews did not provide enough information on the type and amount of vegetation seeds used in PVC for different environmental conditions, which is necessary in slope design. The quantity and type of vegetation planted on a slope are believed to significantly affect the stability, erosion control, and ecological function of the slope.

Past studies have focused only on cast-in-place PVC for slope applications. This paper discusses both cast-in-place and prefabricated PVC blocks. Prefabricated PVC blocks possess more advantages such as ensuring quality control and reducing construction time. Furthermore, limited or no information regarding the comparison of PVC-stabilized slopes with other stabilization techniques is available in previous reviews. Highlighting the advantages and disadvantages allows planners and practitioners to decide which technique is most appropriate for a particular slope project.

This study provides an up-to-date comprehensive review of slope stabilization using cast-in-place and prefabricated PVC. It also focuses on the latest advancements and challenges faced in its implementation, and provides recommendations for future studies. The outcomes of this review can provide a reference for researchers and guide geotechnical engineers to achieve better design standards for slope stabilization using PVC.

2. Slope stabilization

Slope stabilization refers to the process of preventing the occurrence of failures in new slopes or strengthening and securing slopes that are at risk of failure due to natural or human-made causes. Stabilizing slopes is essential to protect people and infrastructure on or near slopes, as landslides and other types of slope failures can cause significant damage and even loss of life. Different slope stabilization techniques have been used across the world. According to Kumar and Das [65], slope stabilization techniques can involve a variety of methods, including mechanical techniques such as the use of retaining walls, geosynthetics, soil nails, rock bolts, gabion baskets, shotcrete, and concrete blocks, chemicals such as cement, lime, or polymers, drainage systems, and vegetation. Some researchers have combined two or more stabilization methods to provide a more robust, secure, and flexible system for stabilizing a slope. For example, both retaining wall and soil nails [66,67], shotcrete and vegetation [34,57,68], concrete blocks, anchor bolts and vegetation [69], micropiles, geogrid, and geocells [27], and porous concrete and vegetation [8,70–73]. Table 1 outlines the advantages and disadvantages of commonly used slope stabilization techniques.

The slope stabilization methods mentioned in Table 1 have their own advantages and disadvantages. Therefore, the choice of the slope stabilization method depends on the specific conditions of the slope, such as slope geometry, soil type, geological composition,

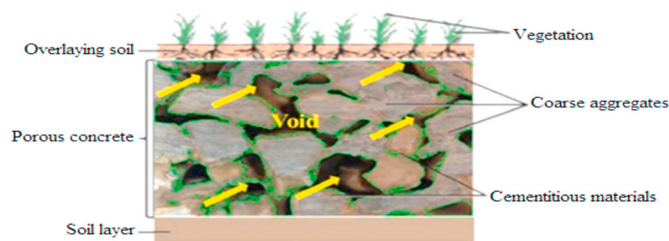


Fig. 1. Schematic structure of porous vegetation concrete [3,50,55].

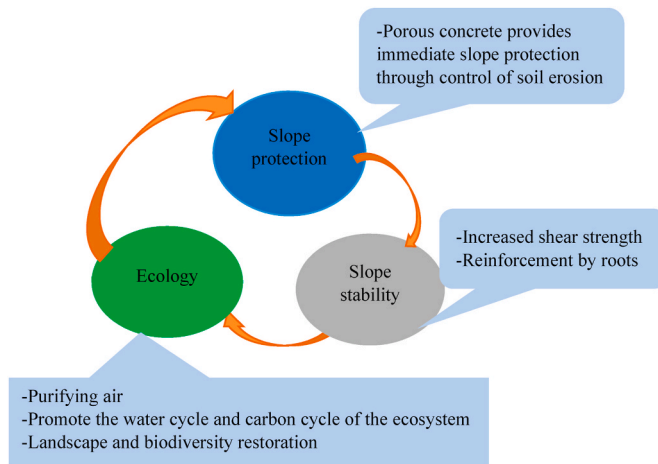


Fig. 2. Mechanism of sustainable slope protection.

Table 1
Advantages and disadvantages of commonly used slope stabilization techniques.

No.	Slope stabilization technique	Advantages	Disadvantages
1	Vegetation	<ul style="list-style-type: none"> -Surface erosion control by reducing surface water flow velocity -Removes excess water from the soil through evapotranspiration -Vegetation roots enhance mechanical properties of the soil, i.e., shear and tensile strength 	<ul style="list-style-type: none"> -Effective only on gentle slopes -Does not provide permanent reinforcement to the soil because the reinforcing capacity reduces as the plant grows. -Requires growing time and constant maintenance -Susceptible to drought, and diseases
2	Shotcrete	<ul style="list-style-type: none"> - Can be applied quickly and efficiently, thus reducing construction timelines and costs. - Requires minimal excavation - Can be applied to a wide range of soil types and slope geometries, making it a versatile stabilization technique. 	<ul style="list-style-type: none"> -Suffers from non-uniform quality, and concrete thickness coverage. -May require periodic maintenance, such as crack repair or surface sealing, which can increase long-term costs. -Requires specialized equipment and trained professionals to apply it correctly, which can increase the complexity of the project.
3	Retaining structures	<ul style="list-style-type: none"> -Effective solution to control soil erosion on steep slope -Can be used in a wide range of slope stabilization scenarios, from small residential landscapes to large-scale civil engineering projects. 	<ul style="list-style-type: none"> -High construction costs -Sometimes require special materials, equipment, and skilled labor -Conventional retaining walls have poor aesthetics
4	Geosynthetic cementitious composite mats (GCCM)	<ul style="list-style-type: none"> -Control soil erosion -Easy to install in the field -Possess high strength after setting -Possess uniform thickness 	<ul style="list-style-type: none"> -GCCM products are relatively expensive - May not be suitable for stabilizing very steep slopes, as their strength and stability may be limited. - Limited data on their long-term performance in slope stabilization applications, since it is a relatively new technology
5	Chemical stabilizers	<ul style="list-style-type: none"> -Control soil erosion and suppress dust -Cost-effective solution compared to other stabilization methods such as retaining walls or geosynthetics 	<ul style="list-style-type: none"> -Insufficient information regarding their long-term impacts on the environment -Getting the optimum percentage to fully stabilize the soil is at times tedious. -Handling, storage, and usage require specialized training
6	PVC	<ul style="list-style-type: none"> -Porous concrete provides immediate slope protection, and all advantages provided by vegetation are assured. -Reduced construction period -Minimal maintenance -Cost-effective in the long-run -Well-designed PVC could be suitable for gentle and steep slopes 	<ul style="list-style-type: none"> -High pH of concrete may interrupt vegetation growth -Inadequate data regarding its application since it is in its infancy -Balancing strength and porosity of porous concrete is tedious

and financial resources.

3. Application of vegetation concrete in slope stabilization

Vegetation concrete is a sustainable slope stabilization technique that has currently gained popularity [8,49]. The applications of vegetation concrete include stabilizing highway embankments, dams, riverbanks, and facing material for retaining walls. This technology was introduced by the Japanese Society of Concrete Engineering in 1995 [74]. Since the inception of vegetation concrete, it has been practiced in both developed and relatively developed countries [40]. However, this technology is still lacking in developing countries. Li et al. [75] defined vegetation concrete as the concrete that permits plant roots to penetrate through its voids and the plant to grow on it. It has several benefits in slope management, such as controlling soil erosion, reinforcing the soil, purifying air quality, aesthetics, and water conservation [34,41,71,75–77]. However, several researchers have cited the limitations of vegetation concrete, for example, poor vegetation growth, reduced compressive strength, poor aggregate-to-binder bond, and reduced freeze-thaw resistance [8,49,75]. Some researchers have attempted to use organic compounds and admixtures to enhance the growth of vegetation and improve the strength of vegetation concrete, respectively. For example, Lei et al. [3] used isobutylidene diurea (IBDU) as an organic compound in vegetation concrete. Their study revealed that 3.5% IBDU drastically reduced the pH of concrete without adversely affecting its compressive strength and porosity. The sample that contained 3.5% IBDU showed a 10.3% increase in compressive strength compared to the sample that did not contain IBDU. Additionally, the porosity of the sample with IBDU was greater than 34%. Liu et al. [78] utilized wood-based and coal-based carbon to explore the fertility and mechanical properties of ecological concrete. Their research concluded that the addition of activated carbon to ecological concrete resulted in a significant improvement in its properties when subjected to freeze-thaw conditions. Zhou et al. [79] utilized urea as a fertilizer in vegetation concrete with ceramsite as a coarse aggregate, and an improvement in the compressive strength and porosity was noticed. On the contrary, Huang et al. [80] cited some negative impacts of organic compounds in vegetation concrete, for example, prolonged setting time and decreased early compressive strength. However, in the later curing periods, the compressive strength increased. Zhou et al. [79] found that diammonium hydrogen phosphate (DAP) significantly reduced the compressive strength and porosity of ceramsite vegetation concrete. Therefore, their study concluded that DAP is not an appropriate fertilizer for use on vegetation concrete. Zhou et al. [79] suggested that the best water-to-binder ratio should be kept at 0.25 when using ceramsite aggregates and urea as fertilizer in vegetation concrete to come up with improved porosity and compressive strength.

Vegetation concrete could be achieved in two ways, i.e., concrete vegetation spray-based technique (CVSBT) and PVC. For the CVSBT, cement is mixed with greening additives, nutritious soil, mulching materials, and vegetation seeds [34,57,68,71,81,82]. These materials are mixed in different proportions; for example, Xiong et al. [71] mixed sandy loam, cement, green additives, and organic matter in the mass ratios of 100, 8, 4, and 7, respectively. To increase the performance of vegetation concrete, Kong et al. [83] utilized a combination of different admixtures (municipal solid waste, wheat straw, FA, SF, organic fertilizer made of kitchen waste, and fallen leaves). After mixing all these materials, a wire mesh fixed by anchor rods is placed on the slope, as seen in Fig. 3(a), and the mixed materials are sprayed to provide the required protection, as seen in Fig. 3(b). Several studies have demonstrated successful field implementation of the CVSBT [34,57]. The study by Chang et al. [57] utilized this method on carbonaceous rock slopes along the Hechi-Baise expressway link in China. They found that 180 days after the implementation, the slope was covered by vegetation, as seen in Fig. 3(c). Field implementation of the CVSBT in Taiwan by Fan et al. [34] also revealed that it could prevent scouring within the shortest period. Moreover, Fan et al. [34] recommended that the CVSBT should be used for steep slopes ranging from 45° to 75° and retaining walls. Their study in Taiwan proved that a slope protected by the CVSBT had better performance results. The slope provided a

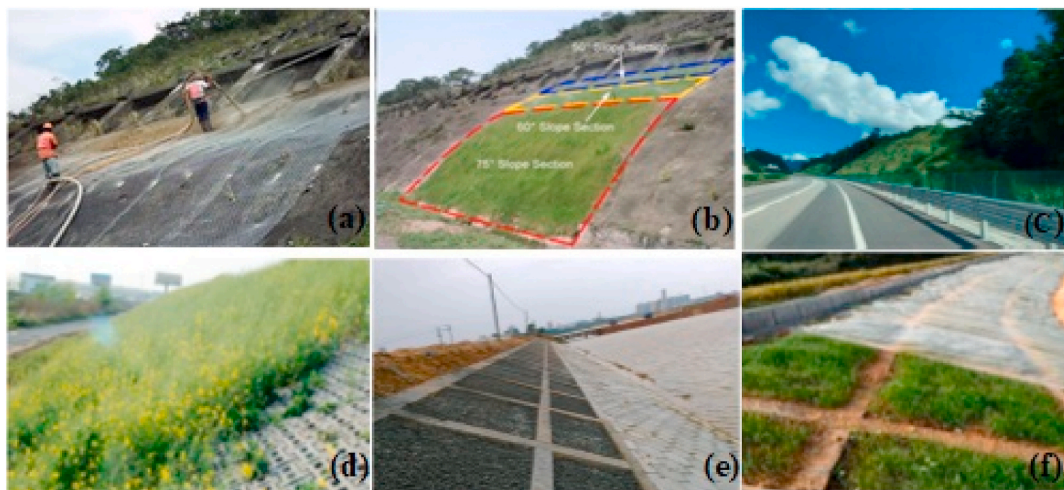


Fig. 3. Vegetation concrete on different projects (a) application of shotcrete on a slope (b) growth of vegetation after using CVSBT [34] (c) concrete vegetation along the Hechi-Baise expressway link, China [57] (d) prefabricated PVC block [69] (e) cast-in-place porous concrete and (f) vegetation growth on top of cast-in-place PVC [49].

better environment for vegetation growth and had sufficient strength to prevent soil erosion during the heavy flood that occurred in June 2005. However, they proposed that further research is needed to explore the optimal selection of soil and appropriate vegetation seeds, as well as the ability of the mulch layer to withstand erosion and hydraulic loading. In another study, Chen et al. [84] investigated the effect of concrete content on sprouting and survival of three fast-growing vegetation seed species with a well-developed root system, i.e., tall fescue (*Festuca arundinacea*), *Magnolia multiflora*, and alfalfa (*Medicago sativa*). Their study revealed that the concrete content significantly affects these two parameters. After a series of experiments, they found that a concrete content lower than 8% is suitable for use in shotcrete vegetation concrete, considering the vegetation species in their study. The drawback of using the spray-based shotcrete method could be environmental problems caused by steel wire mesh production. Its production process results in the emission of toxic gases such as carbon dioxide, sulfur dioxide, and nitrogen dioxide [76].

Another method is porous vegetation concrete (PVC), which can be either prefabricated or cast-in-place, as shown in Fig. 3(d) and (f). It is composed of concrete with numerous pores, little or no fine aggregates, and a plant-growing substrate, which enhances the growth of vegetation [8,41,48,70,73]. The production process of PVC involves mixing porous concrete materials (coarse aggregate, binder, and water), and filling the pores of porous concrete with nutritious soil and seeds, as seen in Fig. 4.

PVC is a modification of two conventional methods (concrete slope protection and vegetation slope protection methods), as seen in Fig. 5(a). It involves placing porous concrete on the erodible soil and adding vegetation on top of the porous concrete, as shown in Fig. 5(b) [49,56]. This slope protection technique offers ecological, structural, and economic benefits [70]. Porous concrete provides immediate slope protection against erosion as vegetation grows [76]. When vegetation is fully established, its roots permeate through the concrete pores and reinforce the erodible soil [50]. In addition, vegetation plays an essential role in hydrological processes and improves the aesthetic appeal of the slope. Studies that utilized prefabricated PVC blocks, e.g. Refs. [72,85], showed that the technique has more benefits than cast-in-place PVC, such as quality control, ease of installation, time and labor efficiency, and flexibility. Some studies have revealed that PVC is not suitable for steep slopes (greater than 45°) and retaining walls [34]. To make it feasible for stabilizing steep slopes, prefabricated interlocking PVC blocks have been proposed [69]. Studies that used prefabricated conventional concrete blocks to stabilize steep slopes by different researchers, e.g., Lin et al. [17] and Sujantoko et al. [18] showed success in preventing the slope from erosion. However, this method did not take ecological aspects into consideration because conventional concrete impedes the Earth's hydrological cycle due to its impermeable nature and inability to enhance plant growth [34,53,56]. For this reason, prefabricated interlocking PVC anchored blocks can provide both structural stability of the slope and ecological benefits [69]. Besides, quality is assured because it is prepared in a controlled environment. To provide more reinforcement to the soil, Bao et al. [56] applied grid beam structures joined using ground anchors.

Well-designed PVC slope stabilization offers several advantages over other stabilization techniques, including environmental

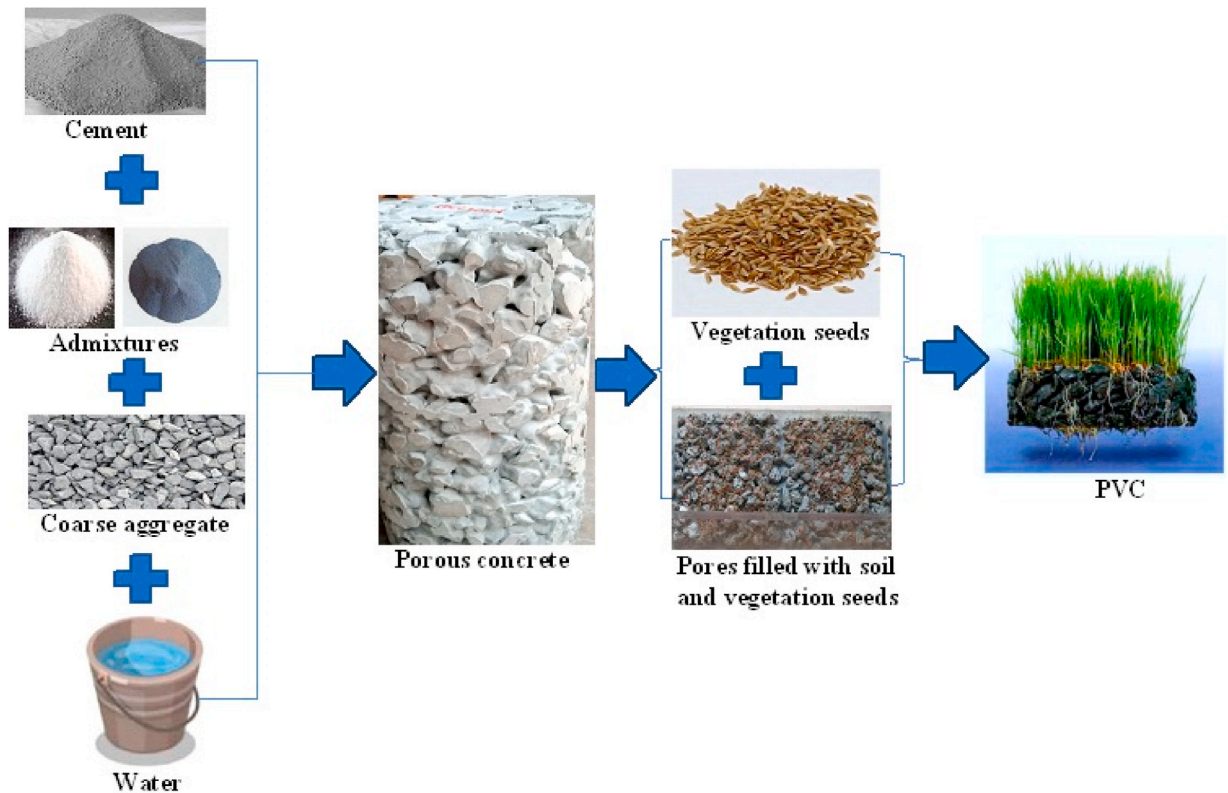


Fig. 4. Production process of PVC.

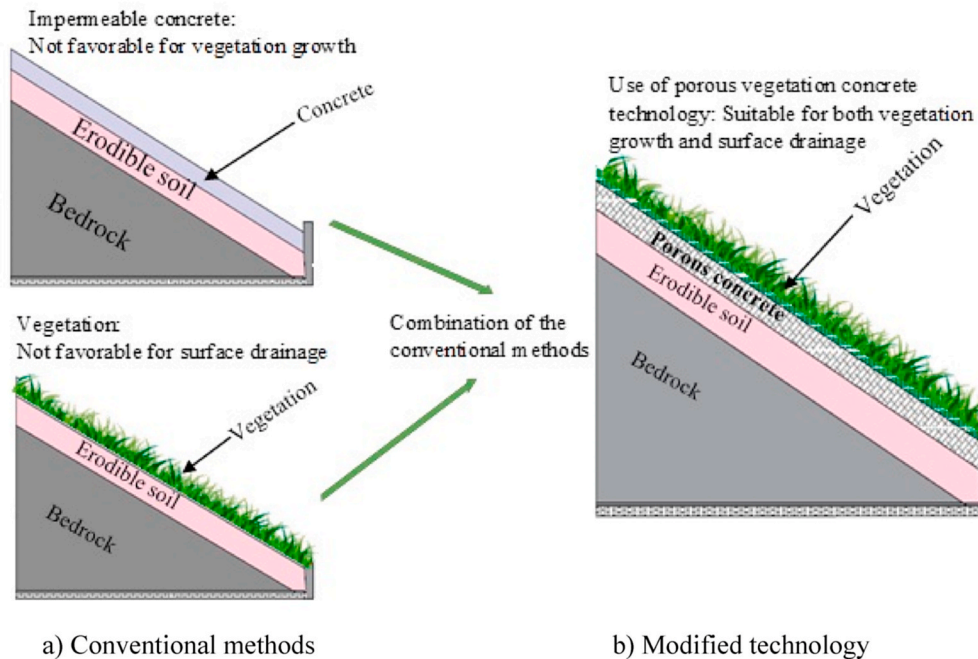


Fig. 5. Slope protection using conventional and improved methods [49,56].

sustainability, minimal maintenance, cost-effectiveness, aesthetics, increased stability, improved drainage, and reduced runoff. These advantages make it a viable option for slope stabilization projects.

4. Materials for making porous vegetation concrete

PVC involves two kinds of materials, i.e., porous concrete materials and vegetation. Porous concrete materials are almost similar to materials used in conventional concrete. Porous concrete differs from conventional concrete in that it contains larger pores ranging from 15 to 30%, with pore sizes varying from 2 to 8 mm [46,86–88]. In PVC, the target is to achieve adequate strength without jeopardizing porosity. Porous concrete is composed of a binder, typically cement, admixtures, coarse aggregates, and minimal or no fine aggregates [89]. The aggregate utilized consists of either single-sized particles or particles with a gradation ranging between 19 and 9.5 mm [90]. To make PVC more environmentally friendly, scientists have proposed replacing the conventional porous concrete materials with other unique green materials, such as steel slag powder and lime powder, as a partial substitution for cement and steel scrap residue as a partial replacement of natural aggregates [40,89]. Other studies have used coal gangue aggregates [91,92] and recycled aggregates (RA) [41,77,93]. The following sub-section describes the materials used in production of PVC.

4.1. Cementitious materials

Cementitious materials have been instrumental in engineering construction projects [94]. Portland cement is one of the most widely used cementitious materials in conventional concrete and PVC. However, its high alkalinity does not meet the requirements for PVC. Studies have shown that its pH is higher than 12, and therefore, it does not favor the growth of vegetation [3,95]. Besides, during the production of Portland cement, Portland clinker is burnt, thus resulting in the generation of greenhouse gases. These pose a danger to the environment [96,97].

In recent years, researchers have been exploring the use of SCMs, such as FA, SF, pulverized BFS, etc., to reduce carbon dioxide emissions [44]. Different scientists have used other cement with low alkalinities, such as sulphoaluminate cement (SAC) [3,36,50,70,79,98], magnesium phosphate cement [99,100], and calcium aluminate cement (CAC) [8]. The pH levels of all these categories of cement vary. Li et al. [98] asserted that the pH of pore fluid of hydrated SAC is lower than Portland cement due to the hydration products from these cement categories, e.g., those in Portland cement are C–S–H and calcium hydroxide, whereas those in SAC are ettringite (Aft) and monosulfoaluminate (AFm). Tang et al. [8] used CAC with a pH lower than that of ordinary Portland cement (OPC) and then substituted cement with 20% FA, which later reduced the pH from 9.7 to 8.7. Bao et al. [56] found that the previous studies showed success in reducing the alkalinity of Portland cement after using conventional methods; however, the physical and strength properties were strongly affected. In order to respond to this, Bao et al. [56] came up with a method of reducing cement alkaline (RCA) that reduced the alkalinity of concrete and enhanced its performance. RCA in their study consisted of SF (37.8%), ultra-fine calcium carbonate (7.6%), polycarboxylate-type superplasticizer (7.5%), sodium nitrite (2.3%), polyacrylamide (0.4%), and water (44.4%).

4.2. Coarse aggregate

The size, shape, and type of coarse aggregate affect the performance of PVC [99,101]. Typically, angular crushed stone or crushed limestone, as well as rounded gravel, are used as coarse aggregates for PVC. The aggregate is often graded between 19 and 9.5 mm or a single-sized coarse aggregate [90]. However, researchers went ahead and used large-sized coarse aggregates, e.g., Chen et al. [101] used two kinds of coarse aggregate gradations, i.e., 10–30 mm and 20–40 mm, with the same water-to-binder ratio. As expected, their study showed that the porosity of 10–30 mm and 20–40 mm aggregates was less than 32.5% and greater than 34%, respectively. This clearly shows that sizeable aggregate gradation leads to high porosity. Regarding compressive strength, it is noticed that large-size or single-size coarse aggregate reduce compressive strength. In the study by Jiang and Liu [35], different sizes of aggregates (10–20, 15–30, and 20–40 mm) were used. They found that the 15–30 mm gradation is more appropriate for PVC than other gradations because it can help achieve a compressive strength greater than 7 MPa and a porosity higher than 20%. To promote the use of waste materials, some researchers replaced natural coarse aggregates with RA to fabricate PVC, e.g. Refs. [41,77,93], among others. It is noted that replacing natural aggregates with RA could reduce greenhouse gas emissions by 24% [102]. Zhang et al. [41] utilized three gradations of recycled coarse aggregate, i.e., 5–15, 10–20, and 20–25 mm. They found that 20–25 mm is more appropriate for vegetation concrete because the germination rate for Bermudagrass in specimens with 20–25 mm coarse aggregates was only five days, while those with 5–15 and 15–20 mm took eight days to germinate. Moreover, the plant height for the specimens with 20–25 mm was 30 and 40% more than those with 5–15 and 15–20 mm, respectively. Kim et al. [93] utilized BFS aggregate in different percentages to replace natural coarse aggregate. According to their findings, substituting natural coarse aggregate with BFS aggregate entirely resulted in an increase in porosity from 15% to over 27%. However, it reduced the compressive strength from 13 to less than 12 MPa. Wang et al. [103] also noticed a reduction in compressive strength after replacing natural aggregates with RA. This reduction could be attributed to the prolonged mechanical wear, chemical degradation, and mechanical damage experienced during the crushing processes of recycled aggregate [49,101].

The choice of coarse aggregate is vital to attain the desired porosity and strength of the PVC. Additionally, the environmental impact of the coarse aggregate could be considered, and recycled materials could be used as a sustainable alternative. However, it is important to ensure that the recycled materials meet the necessary quality standards to ensure the durability and performance of the PVC.

4.3. Admixtures

Admixtures are added to PVC to enhance the concrete's performance. Besides, some are added to reduce the alkalinity of the concrete [35,53]. It is believed that the pH of porous concrete is above 12 [3]. This high pH cannot favor the growth of vegetation. Therefore, admixtures are used to reduce alkalinity. The commonly used admixtures in PVC are divided into chemical and mineral admixtures. Chemical admixtures include retarders, superplasticizers, water-reducing agents, accelerators, and air-entraining agents. On the other hand, mineral admixtures include SF, FA, BFS, and calcined clay (metakaolin). Some mineral admixtures are discussed as follows.

4.3.1. Fly ash (FA)

FA is a byproduct of coal combustion that can be used as a supplementary cementitious material in PVC. Its small particle size and spherical shape make it an ideal candidate for use in concrete as it can fill in the gaps between cement particles, resulting in denser and stronger concrete. Approximately 600–800 million tonnes of FA per annum are produced globally [104]. The use of FA can help reduce the amount of waste that would otherwise end up in landfills. By incorporating FA into PVC, it can be used as a beneficial resource instead of being discarded as waste.

When used in PVC, FA can partially replace cement while still providing the necessary strength. Additionally, FA can react with calcium hydroxide in the mixture to form hydrated calcium silicate (C–S–H) gel, which can enhance the binding properties of the concrete [53]. Two classes of FA exist, i.e., low CaO and high CaO. Khankhaje et al. [44] revealed that the strength index of low calcium FA is lower than that of high calcium FA at short-term curing. However, at long-term curing, the strength increases. Therefore, low CaO FA shows better long-term performance results than high CaO.

From the reviewed studies, it was found that FA reduces the alkalinity of concrete and hence provides a good environment for plant growth. The optimum FA content to substitute cement in porous concrete is 10–30% [8,70]. As the quantity of FA in the concrete mixture increased, the amount of Portland cement decreased. A higher percentage of FA as a substitute for cement affects the rate of hydration, thus resulting in low compressive strength. Therefore, FA is recommended for use as a partial replacement for cement in PVC because of its advantages, such as enhancing the properties of PVC and contributing to sustainable practices by reducing waste.

4.3.2. Calcined clay

Calcined clay is a material obtained from processing clayey material with sufficient mechanical strength for a particular purpose. Once the clay is calcined (burned at high temperatures >760 °C), it develops new properties allowing it to be used as SCMs. Calcined clay possesses a high percentage of silica that could react with calcium hydroxide from the hydration of concrete [105]. A few studies that investigated the performance of pervious concrete pavements incorporating calcined clay as concrete admixture found that it is more beneficial than concrete with OPC only, e.g., Bright Singh and Murugan [61] found that replacement of OPC by 15% calcined kaolinite clay and aggregate of gradation 12.5 mm increased the compressive strength by 39.25% higher than the porous concrete with OPC only. Other properties, such as tensile strength, and flexural strength of porous concrete were also improved. However, porosity and permeability were reduced by 6.74%, and 13.28%, respectively. The study by Saboo et al. [62] utilized a combination of FA (5–20%) and calcined kaolinite clay (2%), and showed higher compressive strength than specimen with OPC only. Some other

Table 2
Different mineral and chemical admixtures used in vegetation concrete.

Year	Admixture	Dosages	Significant findings	Author (s)
2023	High Cao FA SF	17–33% 4–12%	Increasing the replacement rate of FA decreases strength while increasing SF replacement rate increases strength of porous concrete. The optimum mix design was 20% FA and 12% SF.	[73]
2023	Bentonite	0.5–10%	Replacement of cement by less than 2% bentonite enhanced strength properties of porous concrete during the early stages of curing, and the alkalinity was reduced from 11.4 to 10.95 upon replacement of cement by 10% bentonite.	[47]
2022	IBDU Boric acid Polycarboxylic acid	0–5% 0.4% 1.1%	The admixtures led to an increase in compressive strength, porosity, and pH reduction that enhanced vegetation growth.	[3]
2022	SR-4 Ganister powder	3 L/m ³ 15 kg/m ³	An improvement in the strength and durability properties was observed in the prefabricated concrete blocks.	[35]
2021	Water reducer FA BFS Biochar	1.45 kg/m ³ 56 kg/m ³ 26 kg/m ³ 0–30 kg/m ³	The mix having the highest content of biochar (30 kg/m ³) showed the highest compressive strength (21.69 MPa), and the lowest pH (8.95). However, the porosity and permeability were the lowest compared to other mix designs, i.e., 18.5%, and 9.2 mm/s respectively. The study concluded that biochar in the range of 15–20 kg/m ³ could be used to balance all the properties.	[111]
2020	Water reducer Retarder Urea	2.5 kg/m ³ 0.9 kg/m ³ 0–3.5%	The admixtures enhanced the properties of ceramsite vegetation concrete, with 3.5% the mix having urea resulting in an increased 28-day compressive strength (5.69 MPa), porosity (33.1%), water permeability (>35 mm/s), and a reduced pH (<9).	[79]
2020	Low CaO FA SF Superplasticizer	0–20% 5–10% ND	The study showed improved workability of PVC concrete, and the vegetation grew well because of reduced pH from 12.3 to 9.4, brought by mineral admixtures. SF and FA significantly increased the strength properties of PVC from 8.24 to 13.22 MPa. However, the porosity of the mixture without admixture was higher compared to the mixture with admixtures.	[48]
2020	FA Iron slag SF Oxalic acid Citric acid Ferrous sulfate Polycarboxylate	380–760 kg/m ³ 380–760 kg/m ³ 95–285 kg/m ³ 0.19–0.57 kg/m ³ 0.19–0.57 kg/m ³ 0.19–0.57 kg/m ³ 19 kg/m ³	Incorporating these admixtures significantly reduced the pH of the sample at the end of 56 days of curing, and replacement of cement with 10% SF is more effective in reducing pH than other admixtures.	[20]
2019	BFS FA Poly carboxylic acid Biochar	56 kg/m ³ 26 kg/m ³ 1.45 kg/m ³ 0–20 kg/m ³	These admixtures enhanced the workability, strength, and porosity of PVC. The study suggested utilization of 5 kg/m ³ of biochar for effective growth of vegetation and structural performance of vegetation concrete.	[112]
2019	FA BFS	10–30% 10–30%	The mineral admixtures reduced the alkalinity of the PVC; however, the study recommended incorporation of other alkaline reducing technologies so as to achieve the acceptable pH favoring growth of vegetation.	[70]
2018	FA Air-entraining admixture	10–30% ND	The admixtures led to the improvement in compressive strength for the 56-day cured specimen from 2.49 to 2.75 MPa. Furthermore, 20% FA reduced the pH of PVC from 9.7 to 8.7, which was suitable for vegetation growth.	[8]
2018	Carbamide Water reducer (polycarboxylate superplasticizer) Cement retarder (boric acid)	0–3.5% 1.1% ND	The admixtures improved the workability of the PVC mixes. Carbamide increased the setting time and increased the fluidity of cement paste. The pH was significantly reduced to 8.31, favoring vegetation growth. However, a high percentage of carbamide (3.5%) led to the reduction of compressive strength.	[110]
2018	Urea Retarder (boric acid) Superplasticizer (polycarboxylate polymer)	0.44, 4.4, & 7.7 kg/m ³ 0.87 kg/m ³ 2.39 kg/m ³	The inclusion of the admixtures improved the properties of the porous concrete, e.g., polycarboxylate polymer improved the workability of PVC. Besides, 4.4 kg/m ³ urea reduced concrete's alkalinity, thereby enhancing vegetation's growth.	[50]
2017	Reducing cement alkaline (RCA)	0–3.6%	These admixtures led to enhanced workability, porosity, and strength. This study achieved a maximum porosity of about 23% and compressive strength of more than 25 MPa after substituting cement with 3.6% RCA.	[56]
2017	Natural zeolite	0–30%	Replacement of cement by 30% natural zeolite reduced the alkalinity of hardened concrete by 8.9%.	[113]
2016	Natural jute fiber Styrene butadiene latex	1.2 kg/m ³ 6.2 kg/m ³	The inclusion of styrene butadiene latex enhanced void ratio, compressive strength, and freeze–thaw resistance compared to the control sample. The maximum void ratio was >28% and compressive strength >13 MPa.	[109]
2014	Palm fiber Silicon powder JY-AR20*	0.25–1% 1–5% 0.05–0.8%	Incorporation of 1% palm fiber, 3% silicon powder, and 0.05% JY-AR20 improved the frost resistance of vegetation concrete better than other mix designs.	[114]

Note: SR-4 - Mixture of CaCO₃, SiO₂ & other inorganic materials, JY-AR20*. This is a special anionic surface-active agent, ND-Not Detected.

experimental studies conducted on conventional concrete made of calcined clay revealed that the properties of the concrete were greatly enhanced upon inclusion of calcined clay [63,64,106]. Kijjanon et al. [63] used a binary and ternary binder system composed of OPC, FA and Kaolite calcined clay. Their study showed that a ternary binder (55% OPC, 30% calcined clay and 15% FA) gave the best performance results in all the tests they conducted.

Calcined clay has a low percentage of CaO ranging from 0.39 to 5.69% [61–63], which results in a lower amount of calcium hydroxide produced during hydration. This, in turn, reduces the alkalinity of concrete. When calcined clay is incorporated into PVC, vegetation growth is enhanced. Additionally, it can increase the strength and durability of PVC.

4.3.3. Silica fume (SF)

SF is a byproduct of the production of silicon metal and ferrosilicon alloys. It is a very fine and reactive material that consists mainly of silicon dioxide (85%–95%). Its main component is silica, accounting for 85%–95%. In PVC, SF can be used as supplementary cementitious material to improve material's strength, and durability [58].

SF particles are very small, with an average diameter of 0.1 μm, and have a large surface area-to-volume ratio. This makes them highly reactive with the calcium hydroxide present in the cement paste, producing additional calcium silicate hydrate gel, thus lowering alkalinity, and filling the pores of the cement paste [20,56]. Different studies showed that 5–7% SF improves the compressive strength of porous concrete [42,107,108].

In PVC, the target is to improve compressive strength without interfering with the porosity. The impacts of admixtures in PVC are illustrated in Table 2. Bao et al. [56] asserted that producing effective PVC requires combining mineral and chemical admixtures. Their assertion agrees with what Ng and Østnor [106] found in conventional concrete. They found that calcined clay improves durability and strength properties of normal concrete but decreases its workability [106]. Therefore, it is advisable to combine both chemical and mineral admixtures to balance both properties. In this response, some researchers attempted to combine them and achieved promising results [48,56,109,110]. Studies revealed that the combination enabled them to improve the mechanical properties and reduce the pH of concrete; for example, Bao et al. [56] found that SF enhanced strength when combined with polycarboxylates. Cheng et al. [48] obtained outstanding results after combining FA, SF, and a superplasticizer. The compressive strength, porosity, and pH were better than their target performance results, i.e., compressive strength greater than 10 MPa, porosity greater than 20%, and pH less than 9.5.

Based on the articles reviewed, it has been found that the most common chemical and mineral admixtures used in PVC are boric acid and polycarboxylates, and FA, SF, and BFS powder. The physical appearance of these admixtures is seen in Fig. 6. It was found that the combination of mineral and chemical admixtures enhances both strength and durability of PVC. Calcined clay has not been widely used in PVC. However, based on the results of the few studies that utilized it in porous concrete and conventional concrete, its incorporation in PVC provides additional benefits.

4.4. Vegetation

Vegetation plays a vital role in stabilizing artificial and natural slopes. Plant roots absorb water from the soil, hence increasing the soil suction and improving the shear strength of the soil through soil-root reinforcement [115]. Slope stability is normally associated with superior fine root content and high root length density [23]. In Southeast Asia, vetiver has been widely used as a sole slope stabilization mechanism because of its well-developed deep roots and superior tensile strength. However, in PVC, it is hard to use vetiver because of the unavailability of its seeds. Normally, the method used in planting vetiver is the slip method [116]. In PVC, vegetation seeds are preferred to be used. The common herbaceous seeds used by different researchers in vegetation concrete include bahiagrass (*Paspalum notatum*) [56,57], Bermudagrass (*Cynodon dactylon*) [20,34,75,117,118], ryegrass [20,109,112], tall fescue [20,34,38,48,71,79,101,119], and zoysiagrass (*Zoysia japonica*) [20,103], and Kentucky bluegrass (*Poa pratensis*) [86]. The physical appearance of the common vegetation species is shown in Fig. 7.

Vegetation used in PVC for slope stabilization should satisfy the requirements of well-developed roots, strength, ability to grow fast, and drought tolerance [53]. Table 3 presents the major advantages and advantages for different herbaceous perennial vegetation species used in PVC. PVC should have adequate pores to allow vegetation roots to penetrate and reinforce the underlying soil. On this note, Li et al. [50] suggested that the porosity of porous concrete to favor vegetation growth should be at least 25%. However, it is believed that as the plant ages, the root diameter increases, which subsequently reduces its reinforcing capacity. Therefore, designing PVC with additional reinforcements, for example, anchors or nails could be vital. To provide room for germination of plants, the alkalinity of concrete should be kept low, thus concrete with low pH is highly recommended. Admixtures and other organic compounds

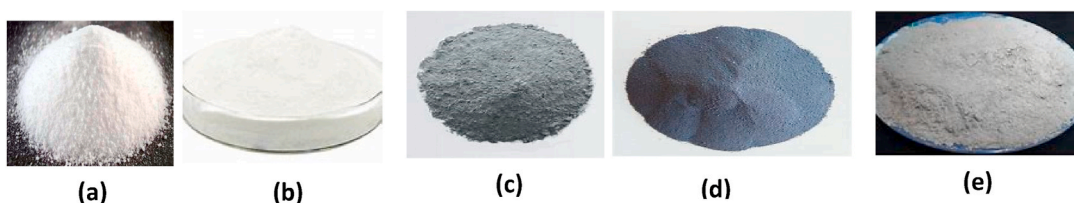


Fig. 6. Commonly used admixtures (a) boric acid (b) polycarboxylates (c) FA (d) SF (e) BFS powder.

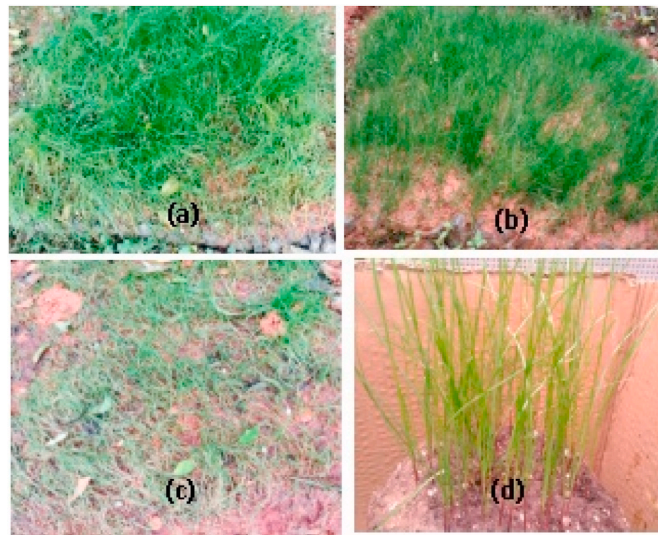


Fig. 7. Vegetation species commonly used in PVC (a) tall fescue (b) Bermudagrass (c) Zoysia [20] (d) ryegrass [112].

Table 3
Vegetation species commonly used in vegetation concrete.

Vegetation species	Advantages	Disadvantages	Culm height (m)	Author (s)
Bermudagrass	Deep root system, trampling resistance, good resistance to alkali, strong adaptability, high durability	Low cold and drought tolerance, requires consistent edging	0.10–0.35	[20]
Tall fescue	Good resistance to alkali and extreme environments, developed deep roots for anchoring the soil, germinates fast, trampling resistance	Intolerant to prolonged wet and cold seasons	0.70–1.10	[20,38]
Ryegrass	Fast germinating rate, drought tolerant	Susceptible to diseases, requires high maintenance	0.30–0.90	[20, 103]
Bahiagrass	Deep and fine structured root system	Slow germination, turns brown during winter	0.20–0.75	[20]
Zoysiagrass	High drought tolerance, thick growth pattern, adaptable to most soil types	Takes a long time to establish fully	0.12–0.13	[20, 103]

are often used to reduce the pH of concrete.

Different authors came up with quantities of vegetation seeds to be planted in PVC; Chang et al. [57] suggested 20 g/m² of bahiagrass, 10 g/m² of molasses grass, 20 g/m² of ryegrass, 15 g/m² of *Leucaena leucocephala*, and 15 g/m² *Cajanus cajan*. For Bermudagrass, 10–12 g/m² seeds are planted [34,57,75]. Chen et al. [101] planted 30–40 g/m² of tall fescue in their study. These plant species sprouted after planting during the monitoring period. However, some studies show that they sprout and die after a few weeks, e.g., Bao et al. [56] revealed that bahiagrass sprouted one week after planting, and then started dying in the fifth week. Ryegrass started withering and dying 30 days after its plantation in the study by Wang et al. [103]. This could be due to environmental conditions that didn't favor the growth of these species. Shen et al. [38] planted tall fescue on top of the cured porous concrete specimen and monitored the growth of vegetation for 28 days. They found that the vegetation grew steadily, as shown in Fig. 8, and concluded

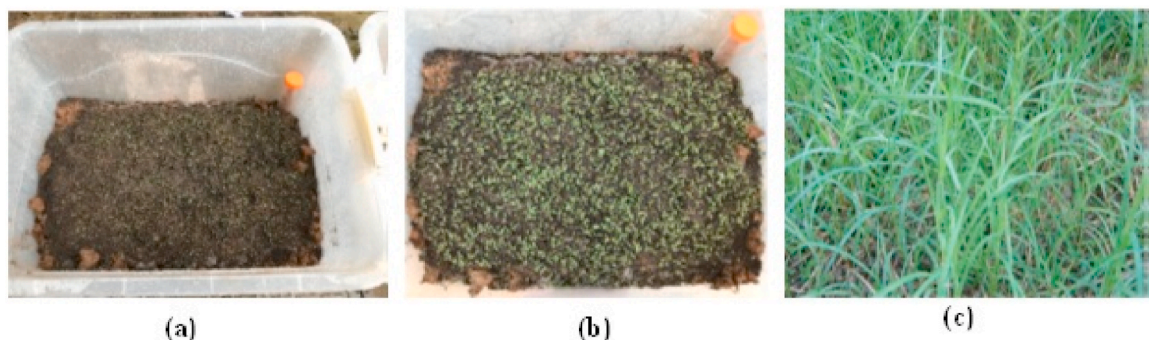


Fig. 8. Growth of tall fescue (a) at seven days, (b) at 14 days (c) at 28 days [38].

that tall fescue is resistant to alkali and extreme environments. Tang et al. [8] investigated the root development of three Australian herbs (*Themeda triandra*, *Chloris truncata*, and *Elymus scaber*). They found that these species have superior roots that are well-compatible with porous concrete, as seen in Fig. 9. Vegetation species like *Cynodon dactylon* flourished in PVC even under high pH (>11) [120]. The study by Chen et al. [84] showed the success of *Cynodon dactylon* in CVSBT, where they noticed a high germination rate (>77%) after 11 days and a high survival rate (>78%) after 56 days when 8% concrete was used. Wang et al. [103] investigated the compatibility of different plant species (tall fescue, white clover, ryegrass, and dwarf fescue) with porous concrete. All these grasses showed good growth after 30 days on the plantation. It was found that tall fescue had the fastest germination rate (seeds started sprouting three days after planting), and its roots could penetrate the PVC of 6 cm thickness after 60 days of planting. The studies by Chen et al. [101] and Li et al. [20] was in agreement with Wang et al. [103]. Tall fescue utilized in the study by Chen et al. [101] also started to sprout three days after sowing. Li et al. [20] found that the roots of tall fescue had penetrated porous concrete within 60 days, with a height of 8 cm. On the contrary, the study by Zhao et al. [112] utilizing Bermudagrass, ryegrass, and tall fescue found that ryegrass showed better growth in the biochar-modified vegetation concrete than other species. These contradictions lead to the conclusion that the adaptability of a certain vegetation species in porous concrete depends on environmental conditions, such as weather conditions, pH, etc. The study on four different species, i.e., Bermudagrass, ryegrass, tall fescue, and Zoysia, revealed how pH affects the growth of the vegetation Li et al. [20]. The sprouting rate of ryegrass (89.7%) was higher than that of tall fescue (84.3%) on day-16 when the soil pH was 7. These two species showed better germination rates than Bermudagrass and Zoysia at a pH of 7. When pH was increased to 8, tall fescue flourished with the highest germination rate (80.1%), followed by Zoysia (74.5%). Zoysia and Bermudagrass took over when the pH was increased to 9, with the germination rate of 73.9% and 69.2%, respectively. Furthermore, Bermudagrass emerged the best when the pH was increased to 10 and 11, with a germination rate of 57.6%. Bermudagrass can thrive under high pH conditions [20,75,120]. Li et al. [75] investigated the compatibility of *Cynodon dactylon* (L.) Pers, *Agrostis stolonifera* and *Sasa argenteostriatus*. Their study found that *Cynodon dactylon* (L.) Pers had the fastest germination rate among these three species.

Designing a suitable PVC requires consideration of the appropriate quantity and type of vegetation to be planted on a slope. The quantity of seeds planted depends on different factors such as the type of vegetation, soil conditions, slope gradient, and climate. Planting too many vegetation seeds may lead to competition among plants for nutrients and water, which can hinder their growth and ability to stabilize slopes. In addition, they can exert pressure on the porous concrete, which can lead to erosion over time. Overcrowding can also limit the amount of sunlight received by each vegetation type, which can further inhibit growth and contribute to slope instability. However, planting insufficient seeds on a slope may also lead to lower vegetation growth. Therefore, planting a sufficient number of vegetation seeds on a slope is recommended to ensure good coverage and optimal growth conditions. Regarding vegetation type, it was found that the most suitable vegetation type in PVC was Bermudagrass, tall fescue, and Zoysia. These species possess good qualities in terms of root development and rapid growth rates in alkaline and extreme environments.

5. Mix proportions

Designing the mixtures for porous vegetation is complex because there is a need to balance workability, porosity, strength, and pH [90]. While discussing the mix designs for PVC, it is better first to discuss the mix design of porous concrete because vegetation seeds are added after coming up with a good mix design. Studies have suggested different mix proportioning for porous concrete.

- 1) Absolute volume method (AVM) suggested by [90,121,122].
- 2) Excess paste theory suggested by [123].
- 3) Paste volume (PV) to inter-particle voids (IPV) ratio suggested by Ref. [124]. The optimum PV/IPV ratio range to provide better performance results of porous concrete was found to be 30% and 60%.

Generally, the two parameters that affect the properties of porous concrete are aggregate-to-binder ratio (a/b) and water-to-binder ratio (w/b) [49,120,125,126]. Studies have revealed that a low w/b ratio leads to unsatisfactory cohesion and stability, and a high w/b ratio results in segregation during the placement of porous concrete, thus blocking some pores and causing non-uniformity [79,90,124,125,127]. Different scholars noted that the optimum w/b should range from 0.26 to 0.45 [126], 0.37 to 0.42 [128], 0.27 to 0.34 [129],



Fig. 9. Root development in porous vegetation concrete [8].

0.20 and 0.35 [49], and 0.26 to 0.45 [90]. However, ACI 522 Committee [90] recommended a trial-and-error method of determining the optimum w/b. On the other hand, the a/b ratio also affects the properties of the porous concrete in the way that a high a/b ratio results in low strength because of the inadequate bond between particles. On the contrary, a low a/b ratio leads to a strong bond between the particles, thus higher strength. However, this significantly reduces porosity because the cement paste occupies the void spaces. Debnath and Sarkar [125] recommends a/b in the ratios ranging from 4:1 to 6:1. Tang et al. [8] used an a/b ratio of 5:1, and the vegetation flourished; however, the 28-day compressive strength was low (ranging from 1.67 to 2.28 MPa). Based on the aforementioned, there should be a clear balance between strength and porosity in PVC that could enhance slope stability whilst favoring vegetation growth. The mix designs from different studies are recapitulated in Table 4.

The appropriate mix proportions of PVC are critical to achieving its desired characteristics, such as porosity, strength, and durability. From the studies reviewed, the minimum and the maximum w/b ratio to provide adequate porosity and compressive strength to PVC are 0.20, and 0.40, respectively. Also, many studies have used a/b ratio of 4–7:1 to minimize the reduction in PVC compressive strength. Optimization of PVC mix designs remains an important area of research, as the demand for sustainable construction practices grows. Therefore, future studies could try w/b and a/b ratios within the forementioned ranges and change other parameters such as aggregate size, and amount of cement paste or explore alternative materials and additives to achieve more enhanced PVC characteristics.

6. Properties of porous vegetation concrete

The properties of PVC that have been discussed include workability, porosity, permeability, compressive strength, and durability. Experimental studies revealed different results for these properties depending on the materials and mixing techniques used. Some of the results from different studies are shown in Table 5.

Based on the mix designs and properties for PVC shown in Tables 4 and 5, a water-to-binder (w/b) ratio of 0.3 and an aggregate-to-binder (a/b) ratio of 5 are suggested to maintain the desired porosity (>25%) and compressive strength (>10 MPa). In terms of admixtures, FA and SF are more suitable for enhancing strength and providing low-pH concrete for vegetation growth.

6.1. Workability

The workability for porous concrete is determined by forming a ball with the hand, as shown in Fig. 10, to establish the mouldability of the porous concrete [61]. This method is recommended by ACI 522 Committee [90] and Tennis et al. [129] because it is impossible to use the slump test as in the case of conventional concrete.

The presence of numerous voids in porous concrete makes it less workable than conventional concrete. The workability could be improved by increasing the w/b ratio; however, this affects the strength and porosity. Several researchers have used different admixtures to improve the workability whilst attaining sufficient strength and porosity [56,103,110,112]. Bao et al. [56] used self-made admixtures, identified as RCA, which consisted of a combination of SF, ultra-fine calcium carbonate, polycarboxylate-type superplasticizer, sodium nitrite, polyacrylamide, and water in different proportions. All these admixtures had different roles; however, the ultimate goal was to develop enhanced workability, porosity, and strength. Their study achieved all those objectives (porosity of about 23% and compressive strength greater than 25 MPa). Li et al. [50] used a retarder (boric acid) and a superplasticizer (polycarboxylate

Table 4
Mix proportions from different studies on porous vegetation concrete.

Year	Binder (kg/m ³)	Aggregates (kg/m ³)	Water (kg/m ³)	Aggregate size (mm)	w/b ratio	a/b ratio	Author(s)
2022	320.2	1601	70.4	26.5–31.5	0.22	5	[3]
2022	215.0	1575	75.0	5.0–10.0	0.35	7.33	[131]
	250.0	1555	100	15.0–20.0	0.40	6.22	
2022	NS	NS	NS	10.0–30.0	0.25–0.31	4.90	[101]
				20.0–40.0			
2021	294.7	1600	85.6–94.4	10.0–25.0	0.29–0.32	5.42	[111]
2021	NS	NS	NS	20.0–40.0	0.28–0.30	4–7	[55]
2020	231.3	411	53.2–54.9	16.0–19.0	0.23–0.27	1.7	[79]
2020	323.8	1432	103.6	10.0–19.0	0.32	4.42	[48]
2019	294.7	1600	85.6–93.3	NS	0.29–0.32	5.4	[112]
2019	260.0	1500	75.4	9.5–16.0	0.29	5.8	[52]
	270.0	1500	78.3	16.0–19.0		5.6	
	280.0	1500	84.1	19.0–26.5		5.4	
2018	220.0	1320	55.0	20.0–25.0	0.25	6	[50]
2018	266.4	1465	52.3	NS	0.20	5.5	[110]
2018	311.2	1539	62.2	19.0–26.5	0.20	4.9	[130]
2018	350.0	1750	140.0	20.0	0.40	5	[8]
2017	300.0	1600	105.0	19.0	0.35	5.33	[56]
2016	320.0	1200	84.0	25.0	0.26	3.75	[93]
2016	306.0	1412	79.0	25.0	0.26	4.6	[109]
	306.0	1412	75.0				
2013	282.0	1528	56.0	10.0–20.0	0.20	5.4	[36]

Note: NS-Not shown.

Table 5
Properties of porous vegetation concrete from different studies.

Year	Porous concrete materials	Compressive strength (MPa)	Porosity (%)	Permeability (mm/s)	pH	Author (s)
2023	High alumina cement, FA, SF, and fine aggregate, and coarse aggregates (10–20 mm)	5–21.27	16.51–21.9	0.5–6.1	10.50–11.31	[73]
2022	SAC, IBDU, boric acid, and coarse aggregates (26.5–31.5 mm)	4.6–8.4	33.0–35.2	34.2–36.5	8.19–8.23	[3]
2022	OPC, ganister powder and coarse aggregates (10–20, 15–30, & 20–40 mm)	6.0–7.1	23.2–24.8	ND	7.60–10.07	[35]
2022	OPC, hydroxypropyl methylcellulose, and RA	6.01–7.2 ^a 6.2–7.6 ^b 6.5–7.9 ^c	20.9–27.0 ^a 8.3–14.0 ^b 12.8–18.21 ^c	ND	ND	[41]
2022	OPC, Nano-CaCO ₃ , and coarse aggregate (5–10 & 15–20 mm)	11.3–13.7	30.5–31.9	ND	8.50–8.80	[131]
2022	OPC, and coarse aggregate (10–30 & 20–40 mm)	6.9–7.1* 7.8–8.1**	30.8–31.0* 29.8–30.5**	ND	ND	[101]
2021	OPC, FA, BFS, water reducer, biochar, and coarse aggregates (10–25 mm)	15.5–21.7	18.5–27.7	9.2–16.3	8.95–9.18	[111]
2020	SAC, urea, DAP, and ceramsite coarse aggregate (16–19 mm)	5.0–5.7	33.0–33.2	37.5–42.5	9.43	[79]
2020	OPC, FA, SF, superplasticizer, and coarse aggregates (10–19 mm)	8.2–13.2	21–25.8	ND	9.40–12.30	[48]
2020	OPC, FA, SF, slag, alkali-modified materials, fine aggregate, and coarse aggregate (19–26.5 mm)	5.0–12.1	20.9–30.7	ND	11.25–12.55	[20]
2018	SAC, urea, DAP, and natural coarse aggregate and RA (20–25 mm)	3.7–6.5	40.9–47.1	26.8–33.6	8.24–9.38	[50]
2018	CAC, FA, air-entraining admixture, and coarse aggregate (20 mm)	1.7–2.3	31.9–37.4	ND	8.70–9.90	[8]
2017	OPC, RCA, and coarse aggregates (19 mm)	15.7–25.2	22.1–23.4	17.9–18.7	ND	[56]
2016	BFS cement, styrene butadiene latex, BFS aggregate (25–28 mm), and natural aggregate (<25 mm),	13.6	27.2	ND	ND	[85]
2016	BFS cement, natural jute fiber and styrene butadiene latex, natural aggregate (<25 mm), and BFS aggregate (8–25 mm)	9.4–13.5	15.0–28.2	ND	ND	[109]

Note: ^aFor 10–30 mm aggregate (w/b ratio 0.31–0.33), ^{**}For 20–40 mm aggregate (w/b ratio 0.31–0.33), ^a20–25 mm coarse aggregates, ^b15–20 mm coarse aggregate, ^c5–15 mm coarse aggregate, ND-Not Determined.

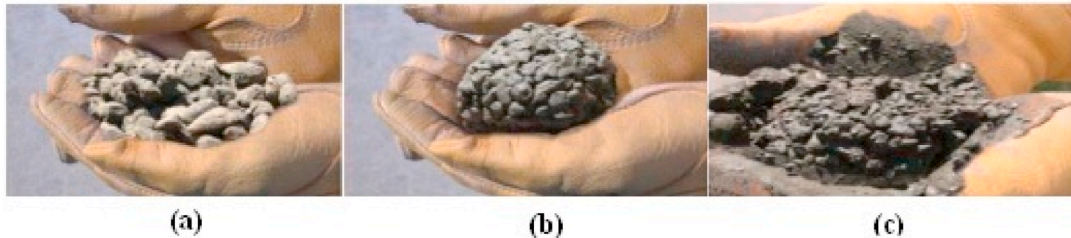


Fig. 10. Workability test of porous concrete (a) inadequate water dosage (b) suitable water dosage (c) excess water dosage [129].

polymer) to improve the workability of porous concrete fabricated from both natural and RA. These admixtures significantly improved the workability of the porous concrete. In the study conducted by Gong et al. [110], they also found that boric acid and polycarboxylate significantly improved the overall performance of porous concrete (improved workability, setting time, and compressive strength).

Admixtures play a significant role in enhancing the workability of porous concrete by improving its consistency, reducing its w/b ratio, and increasing its ability to flow. However, careful selection and dosage of admixtures are critical for achieving the desired properties of porous concrete while maintaining desirable porosity and permeability.

6.2. Porosity and permeability

Porosity is one of the essential properties in estimating the performance of PVC [79,132]. Higher porosity presents large voids that are beneficial for the roots of the plants to penetrate but have adverse effects on the compressive strength [101]. Porosity is understood as connected (effective) porosity and total porosity. Zhong et al. [46] defined effective porosity as the ratio of the volume of connected pores to the material's overall volume. This is the desirable aspect of PVC because sufficient connected voids allow the vegetation roots to penetrate and reinforce the soil [79,101]. There are no standard methods for determining the porosity of porous concrete. However, different researchers suggest drainage method [50,56,79,103], where the mass of the specimen is determined while it is submerged in the wire basket. The formula for determining effective porosity is seen in Eq. (1). On the other hand, total porosity is the total pore volume divided by the material's total volume (see Eq. (2)).

$$\text{Connected Porosity} = \left[1 - \left(\frac{Md - Ms}{\rho_w \text{Vol}} \right) \right] \times 100\% \quad (1)$$

$$Total\ Porosity = \left[1 - \left(\frac{M_{ssd} - M_s}{\rho_w Vol} \right) \right] \times 100\% \tag{2}$$

where Md is the mass of the oven-dried sample at $60 \pm 2 \text{ }^\circ\text{C}$ for 24 h, M_s is the mass of the sample submerged in water, M_{ssd} is the mass of the saturated surface dried specimen after curing, Vol is the specimen volume, and ρ_w is the density of water.

Permeability, on the other hand, is the ability of water to percolate through the pores of the concrete. Currently, the permeability coefficient K_t for porous concrete is determined using the method proposed by Japan Concrete Institute [79,91,133]. A permeability coefficient between 1 and 20 mm/s could be attained in porous concrete depending on aggregate gradation, water-to-cement ratio, and compaction effort [134]. Xie et al. [111] obtained a permeability coefficient between 9.2 and 16 mm/s with an aggregate gradation of 10–25 mm, while Bao et al. [56] achieved a permeability coefficient of 17.9–18.7 mm/s with an aggregate size of 19 mm. As seen in Fig. 11, permeability coefficient is related to porosity. The higher the porosity, the higher the permeability coefficient, and the lower the porosity, the lower the permeability coefficient.

As shown in Table 5, the porosity of most studies on PVC ranges from 15 to 35%, which agrees with the ACI 522 Committee [90]. The observed permeability coefficient was between 9.2 and 42.5 mm/s. This permeability allows adequate rainwater to penetrate PVC and provides a suitable environment for vegetation growth.

6.3. Strength properties of PVC

Compressive strength, flexural and tensile strength affect the performance of PVC. Compared to conventional concrete, the strength properties of porous concrete are low. The strength is influenced by many factors, such as the aggregates-to-binder ratio, water-to-binder ratio, aggregates size, mixing procedures, adding admixtures, type of binder used, etc. Scientists revealed that compressive strength mainly depends on the void ratio and the bond between the aggregate and the binder [101,135]. There is a strong correlation between compressive strength and porosity, as illustrated in Fig. 12. The higher the porosity, the lower the compressive strength. This phenomenon has been noticed by several researchers, e.g. Refs. [3,8,48,56,85,100,103,109,111]. As seen in Table 5, the study by Bao et al. [56] showed the highest compressive strength (25.2 MPa). They incorporated different materials in their porous concrete, such as SF, polyacrylamide, sodium nitrite, ultra-fine calcium carbonate, and polycarboxylate-type superplasticizer. The combination of all these admixtures led to an increase in compressive strength. Tang et al. [8] found that 10% FA as partial replacement of cement increased the 28-day compressive strength of PVC from 1.7 to 2 MPa, reduced splitting tensile strength from 1.19 to 1.01 MPa. Furthermore, when 30% FA was used, the compressive strength increased to 2.3 MPa, and the splitting tensile strength decreased to 0.67 MPa. The increase is a little; this could be due to the type of cement and aggregates used. Cheng et al. [48] incorporated SF and FA in their mixtures and found a significant increase in compressive strength. The highest compressive strength attained was 13.2 MPa after replacing cement with 10% SF and 20% FA. The study by Wang et al. [103] incorporated ultrafine slag as partial replacement of cement, and two kinds of coarse aggregates (recycled and natural aggregates). Their study found that ultrafine slag increased compressive strength. This happens because of the reaction between slag and calcium hydroxide resulting in hydrated calcium silicate that is vital for strength. However, beyond 20% ultrafine slag, compressive strength starts decreasing. This could be due to high quantities of slag resulting in a decrease of cement clinker present in the cement, which in turns decreases the hydration rate of cement. The tensile strength obtained by Wang et al. [101] was high for aggregate gradation between 5 and 25 mm and low for 5–16 mm aggregates.

The compressive strength was significantly affected by the numerous pores in the PVC. As shown in Fig. 12, an inverse exponential relationship between the compressive strength and porosity of the PVC was observed. As shown in Table 5, the values of compressive strength obtained by different researchers for PVC range from 2.3 to 25.2 MPa. Most of these compressive strength results are within the results reported by the ACI 522 Committee [90], which is 3–20 MPa. However, PVC with a higher compressive strength could still be obtained using a ternary binder system (OPC, FA, and calcined clay). Additionally, the incorporation of fibers, such as synthetic or natural fibers, results in a high compressive strength while maintaining desirable porosity. The fibers help distribute loads more evenly

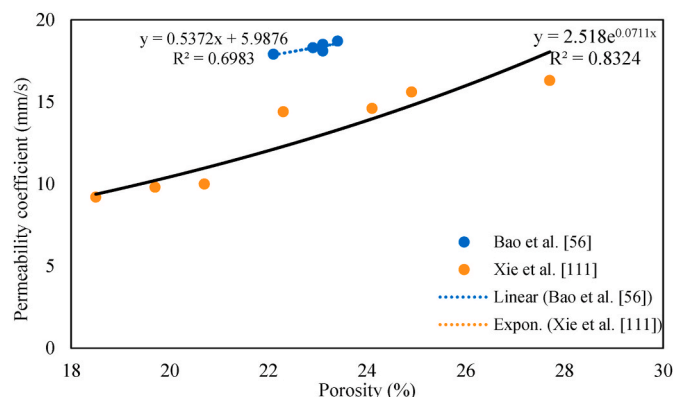


Fig. 11. The relationship between permeability coefficient and porosity of PVC.

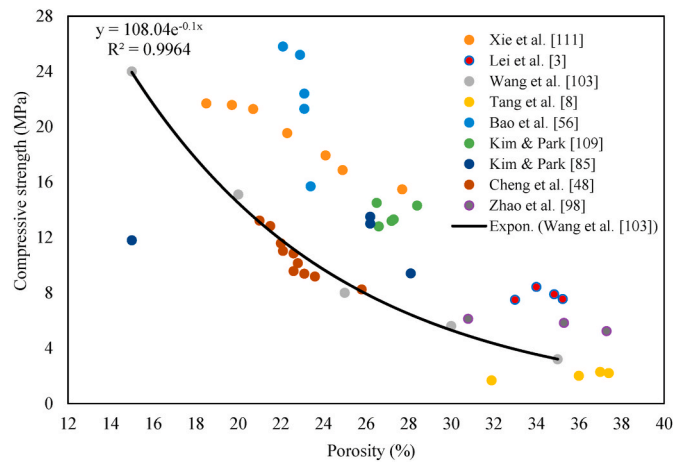


Fig. 12. The relationship between porosity and compressive strength.

throughout the material, reducing the risk of cracking and improving its overall strength. In addition, the proper curing of PVC could enable it to achieve its maximum strength and porosity. The curing conditions, such as humidity and temperature, can be adjusted to optimize the properties of the material. A slower curing process can increase the porosity of PVC while still allowing it to achieve sufficient compressive strength.

6.4. Durability properties of porous vegetation concrete

The durability of PVC is affected by the quality of materials in the porous concrete mix, the species and quality of vegetation used, and the maintenance procedures. Proper installation and regular vegetation maintenance are essential to ensure the long-term stability of the slope. Vegetation growth within the material can help to reinforce the slope and prevent erosion. However, if the vegetation is not adequately maintained, it may die off and leave gaps that could result in degradation of materials and improper functioning of PVC in the long-term. To stabilize slopes effectively, it is necessary to use PVC with excellent resistance to dry-wet cycles and abrasion. The durability is greatly affected by the numerous pores of the porous concrete. A few studies have explored freeze-thaw resistance [68, 103] and abrasion resistance [136]. Wang et al. [101] noted that porous concrete made of RA had lower freeze-thaw resistance than

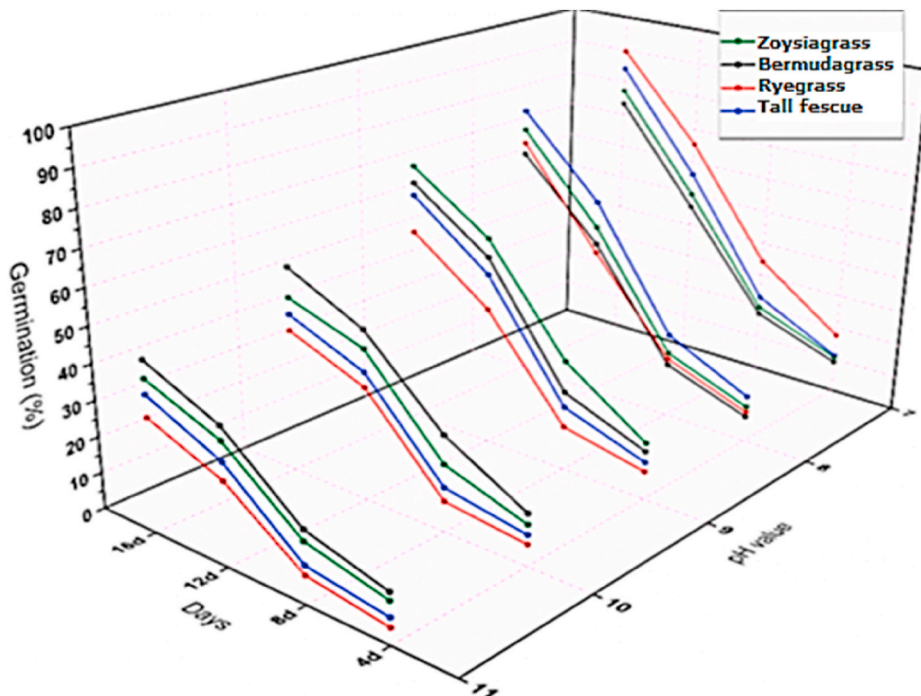


Fig. 13. Influence of pH on the growth of vegetation [20].

conventional concrete. However, different studies have found that the solution to mitigate low durability characteristics could be the incorporation of admixtures, such as latex and SF, into porous concrete [42,93].

7. Influence of pH on the properties of PVC and the vegetation germination rate

pH has a significant influence on the growth of vegetation in porous concrete. Since concrete has high pH, it becomes hard for most vegetation species to germinate. As illustrated by Fig. 13, different vegetation species react different under different pH conditions [20]. It can be seen that ryegrass has the best sprouting rate (90%) when the pH was 7, while Bermudagrass (37%) and Zoysiagrass (31%) has the best sprouting rate when the pH is 11. It is evidenced that most vegetation species prefer neutral to low-alkaline conditions [53].

Various methods that can be utilized to decrease the alkalinity of concrete, thereby promoting the growth of vegetation are discussed below. The advantages and disadvantages of these methods are presented in Table 6.

- i) Using mineral admixtures. Mineral admixtures play a significant role in reducing the alkalinity of concrete. They are capable of consuming calcium hydroxide, thus lowering the pH. However, Li et al. [70] revealed that with mineral admixtures, it becomes hard to achieve the required pH for the growth of many plant species. Their study suggested combining mineral admixtures with other alkali-reducing agents. The study by Tang et al. [8] showed that the pH of CAC concrete was reduced from 9.7 to 8.7 by replacing CAC with 20% FA. Replacement of cement by 10% SF reduced pH to 11 [20].
- ii) Carbonation curing method. This technique involves capturing CO₂ emitted from industries and using it for curing concrete structures. It is believed that it has the potential of reducing the pH of concrete from 12.8 to less than 9.5 [137–139]. This is due to the fact that CO₂ gas penetrates the pores of porous concrete reacting with calcium hydroxide there to produce carbonate and water, altering the chemical composition and microstructure of porous concrete and lowering its pH. Carbonation curing increases strength and durability properties of porous concrete [102,138,139]. Besides, it contributes to the sustainable development agenda towards reducing carbon footprint; however, Higuchi et al. [137] asserted that the method is not favorable for reinforced concrete because it may cause steel bars to corrode. The method could be suitable for porous concrete, as there are no steel reinforcements. Chen and Gao [102] used carbonation and standard curing in porous concrete and found that samples cured by carbonation for 6 h possessed higher compressive than those than the standard cured samples; nevertheless, 24 h carbonation cured samples possessed lower compressive strength than standard cured samples. Thus, appropriate carbonation curing is necessary to yield the best performance results.
- iii) Using cement with low alkalinity. Some cement produced have low pH, e.g., CAC, SAC, magnesium phosphate cement, etc. Tang et al. [8] used CAC and found that it has lower pH than OPC. Kim and Park [109] used BFS cement alongside BFS aggregates. Their study showed that vegetation had a better environment for growth. Zhao et al. [100] used magnesium phosphate cement, whose pH ranged between 6.8 and 8.5 in PVC, and seeds started sprouting after one week.
- iv) Soaking the sample in acid solution or pure water. This method leaches calcium hydroxide from porous concrete into the soaking solution through its voids [53]. Wang et al. [103] soaked the samples in clear water, ferrous sulfate, and oxalic acid. Their study revealed that the pore pH could be reduced to less than 8 by soaking the sample in ferrous sulfate solution, oxalic acid, and clear water for 6, 10, and 26 days, respectively. However, Yang et al. [140] found that pH was reduced to 10.8 using oxalic acid soaking.
- v) Protective film painting. This method involves brushing the surface of the porous concrete specimen using alkali-blocking agents like epoxy resin, styrene butadiene latex, paraffin, silane, etc. [53]. These agents block the release of alkaline substances into the surroundings. Kim and Park [109] utilized styrene butadiene latex in PVC, and the vegetation could grow well.

From the reviewed studies, the pH of concrete affects the growth behavior of different plants. Bermuda grass, Zoysia grass, and tall fescue can withstand high pH, and their growth rates are high. Species such as ryegrass thrive in porous concrete with a low pH, but are significantly affected when the pH increases.

8. Limitations associated with the use of PVC

Previous studies have shown the success of PVC in stabilizing slopes. However, some limitations that hinder its implementation were noted. These include:

- i) Standardization issue. Since PVC is a new technology, the test standards are not yet developed. ASTM, ACI, and other conventional concrete standards are adopted while testing the material's properties. These could lead to unsatisfactory results. Therefore, this calls for collaboration among experts from industry, researchers, and policymakers to formulate standards based on available results that have been conducted and field experience.
- ii) Optimization issue: Several studies concerning PVC have been conducted in the laboratory. Researchers always target obtaining cost-effective and efficient PVC for stabilizing slopes. In this regard, they combine different materials and use the trial-and-error method to maximize the benefits of each. This is tedious, time-consuming, and costly. Therefore, future studies are needed to optimize the mix design suitable for integrating environmental and safety goals, porosity, and strength requirements of a slope.
- iii) Alkalinity issue. PVC has a high pH, and most vegetation species grow under neutral to low alkaline conditions. This still remains a challenge towards implementation of PVC.
- iv) Low compressive strength. The high porosity and permeability lead to low compressive strength. The compressive strength of PVC is often lower than the compressive strength of conventional concrete because of the numerous pores in PVC.

Table 6
Advantages and disadvantages of different methods of reducing pH of PVC.

Method	Advantages	Disadvantages
Using mineral admixtures	Long-term strength development, improved durability, eco-friendly	Decreased porosity and permeability, pH reduction is not significant for some admixtures e.g., FA, high dosages of some admixtures lead to increase in pH
Carbonation curing method	pH reduction is significant, improved mechanical and durability properties, reduction of CO ₂ emission	Decreased porosity and permeability
Using cement with low alkalinity	It is cost-effective, reduction of CO ₂ emission	Decreased strength properties, reduced workability
Soaking the sample in acid solution or pure water	It is relatively simple and cost-effective	Improper dosage of the acid solution may cause damages to concrete and adversely affect the mechanical properties
Protective film painting	Increased strength, enhanced durability	It is time consuming since it requires surface preparation, coating application, and curing time, pH reduction is not significant

- v) Insufficient water and fertilizers for plant growth in CVSBT and a high self-weight of concrete may significantly lead to slope instability. Zhou et al. [79] noted that some fertilizers are not desirable for CVSBT, e.g., DAP, as they significantly reduce the strength of concrete.

9. Prospects for future research on PVC

The use of PVC in slope stabilization is still in its infancy. Future studies are recommended for the effective implementation of PVC in stabilizing slopes. The recommendations are as follows.

- i) Most studies have focused on testing the material properties in the laboratory. It is widely accepted that different parameters affect slope stability. Admixtures and other unique materials may be used to produce PVC with superior properties; nevertheless, when integrated with the slope, they may fail to bring an acceptable factor of safety. Therefore, it is suggested to perform physical slope models to mimic field conditions and numerical models to investigate the effect of geometrical parameters of the slopes stabilized by PVC on the factor of safety. This could show how PVC will work in the field.
- ii) Different plant species showed success in germination; however, slope stability depends on other parameters not discussed in the studies reviewed, such as root diameter, root depth, and root geometry. Further studies could investigate the effect of these parameters on the stability of PVC-stabilized slopes. Furthermore, studies related to the effects of root pressure on PVC have not yet been conducted. It is believed that vegetation roots exert pressure on porous concrete, and this pressure could have an impact on the slope. Further studies are required to examine this aspect.
- iii) Few studies have been conducted on the durability of PVC. Exposure to environmental conditions such as temperature and rainfall could have an adverse effect on the durability of PVC. Studies related to the resistance of PVC to sulfate attack have not been conducted. This can be particularly problematic for PVC, designed to be permeable to allow water and nutrients to pass through for vegetation growth. PVC may be more susceptible to cracking or other forms of damage if it is weakened by sulfate attacks. Therefore, future studies should focus on the long-term performance of PVC under different weather conditions.
- iv) Several experimental studies on cast-in-place PVC have been conducted. However, a few on prefabricated PVC have been conducted. Prefabricated PVC could be a better option considering the need for quality control and reduced construction time. The installation technique of prefabricated interlocking PVC blocks using anchors could also bring additional benefits to the slope stability. The quality is believed to be better controlled with prefabricated PVC blocks than with cast-in-place PVC. The prefabricated blocks could be subjected to carbonation curing, as it could significantly reduce pH and improve porous concrete's physical and durability properties [138]. Moreover, it is one way to reduce the carbon footprint, thus conserving the environment. Therefore, future studies should focus on this method.
- v) Few or no experimental studies have been conducted on PVC made of calcined clay. Studies conducted using calcined clay in porous concrete for pavement application showed enhanced strength [61,62], and since calcined clay possesses low calcium oxide, it is believed that it can significantly reduce the alkalinity of concrete to favor the growth of vegetation in porous concrete.
- vi) Future studies should focus on economic analysis. We suggest performing a cost-benefit analysis for slopes stabilized by PVC and comparing it with other slope stabilization techniques such as geogrids, geocells, and geosynthetic cementitious composite mats.

10. Conclusions

This paper reviewed recent trends in the use of PVC to stabilize slopes, focusing on material mix designs and properties, limitations to its effective implementation, and recommendations for future research. The review shows that PVC is a promising slope stabilization technique that can protect the slope from scouring while ensuring ecosystem, air quality, and landscape restoration, and is thus suitable for tropical regions with excessive rainfall. Experiments conducted in the laboratory can guide engineers in developing standards for PVC material testing and mix design. Furthermore, numerical simulations can provide better insights into the impact of various parameters, such as slope geometry, on slope stability. Based on the literature, the following conclusions were drawn.

1. The materials used to produce PVC include binders, coarse aggregates, and vegetation. The trial-and-error method is used to determine the optimum w/b and a/b ratios. Single-size coarse aggregates with diameters of 10–20 mm or 20–25 mm diameters could produce PVC with compressive strength and porosity above 10 MPa and 25%, respectively, allowing vegetation roots to penetrate the porous concrete. In most studies reviewed, the observed minimum and maximum w/b ratios were 0.20 and 0.40, respectively, while the a/b ratio was 4–7:1.
2. The incorporation of mineral and chemical admixtures enhanced the properties of PVC, making it durable and resistant to degradation. However, the specific effects of these admixtures on PVC depend on the type and proportions of the admixtures, properties of the aggregates and cement, and environmental conditions.
3. The reviewed studies showed that Bermudagrass, tall fescue, and Zoysia possess good qualities in terms of root development and faster growth rates in alkaline and extreme environments for PVC application.
4. Most vegetation grows under low alkaline conditions. The use of low-alkaline cement and mineral admixtures such as calcined clay, FA, and SF is beneficial to vegetation growth. Additionally, carbonation curing can significantly reduce the pH and increase the durability of porous concrete.
5. The major hindrance to PVC implementation is the failure to obtain a proper balance between the strength, porosity, and alkalinity of the porous concrete. The incorporation of synthetic or natural fibers, chemical admixtures, and proper curing can increase the porosity of PVC while maintaining sufficient compressive strength and providing a suitable environment for vegetation growth.
6. Based on the gaps identified in the reviewed papers on PVC-stabilized slopes, future studies could focus on prefabricated PVC, performing numerical and physical modeling, long-term performance evaluation of PVC materials, and conducting cost-benefit analyses in comparison with other techniques and their field implementation.

CRedit authorship contribution statement

John Bosco Niyomukiza: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft. Amin Eisazadeh: Conceptualization, Supervision, Formal analysis, Visualization, Writing – review & editing. Somnuk Tangtermsirikul: Supervision, Formal analysis.

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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

Data will be made available on request.

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