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Application of miscanthus to enhance plant growth adaptability of bio-based vegetal concrete

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A R T I C L E I N F O

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A B S T R A C T

Poor water retention capacity and the interior porous structure of vegetal concrete are the main factors for the limited lifespan of plants. In this study, bio-based miscanthus is applied to enhance water absorption-release behaviour and plant growth adaptability by filling the pore structures of porous vegetal concrete. The effects of varying miscanthus powder content (0%, 5% and 10% by volume) on the physical properties (including density, porosity and water absorption-release behaviour), mechanical strengths (compressive and flexural strengths) and plant growth performance indicators (plant height, number of leaves, rooting behaviours and plant cover) of concrete are investigated. Furthermore, the influences of different cement-to-miscanthus ratios (1:0.25, 1:0.5, 1:0.75, 1:1) and planting methods (mixing seeds with mortar matrix vs sowing seeds on mortar surface) on the performance of miscanthus mortar are analysed. The addition of miscanthus not only strongly improves the water absorption-release behaviour of porous vegetal concrete but also helps lower its density and high alkalinity, both of which enhance plant growth. The miscanthus increases the 24-hour water absorption of bio-based vegetal concretes by 119–246%, compared to the reference concrete, rapidly reaching a saturation status when soaked in water. Moreover, adding miscanthus at a 10% volume enhances the plant cover percentage by 36.5% and slows down early plant degradation. It also shows that sowing seeds on the mortar surface is better than mixing them with mortar matrix because it makes plants much taller and covers more ground. It can be concluded that the cement-to-miscanthus ratio of 0.5–0.75 is recommended for bio-based vegetal mortar to foster lush plant growth considering the mechanical strengths and plant growth adaptability.

1. Introduction

Recently, the progressive rise in global temperatures has been caused by the retention of heat in the atmosphere due to the presence of greenhouse gases [1]. To work towards mitigating the global warming phenomenon, one approach is to encourage low-carbon urban development, which involves promoting practices like urban greening [2]. Traditional concrete is a mixture of sand, coarse aggregates, cement and water that widespread used in building structures [3]. However, with the requirements of sustainable building materials development, the environmental impact of traditional concrete has received considerable attention, including high carbon emissions and the depletion of natural resources [4]. Various concretes with special functions have been applied, such as pervious concrete, lightweight aggregate concrete, sound and heat-insulating concrete, and adsorptive concrete. These concretes are typically made of sustainable building materials as a response to the environmental challenges posed by traditional concrete [5]. The increasing demand for eco-friendly alternatives for potential application in urban greening can reduce carbon footprint and promote resource efficiency [6–8].

Vegetal concrete or ecological concrete is a type of concrete that incorporates plant-based materials [9], such as fibres or aggregates or utilizes the properties of plants, such as their root systems, to enhance the environmental sustainability and performance characteristics of concrete [10]. To foster lush plant growth on concrete surfaces, porous structures are usually used in vegetal concrete [11], thus, vegetal concrete combines the porous structures of pervious concrete with the ecological benefits of plants [12]. Plants are integrated into the concrete matrix, either by embedding them within concrete or by providing a suitable vegetative substrate for plant growth on concrete surfaces.

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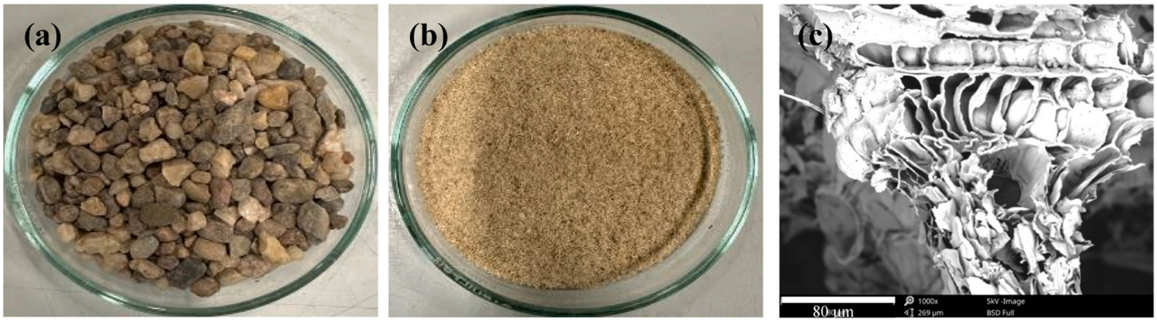

Fig. 1. (a) Coarse aggregate, (b) Miscanthus powder and (c) its microscopic image.

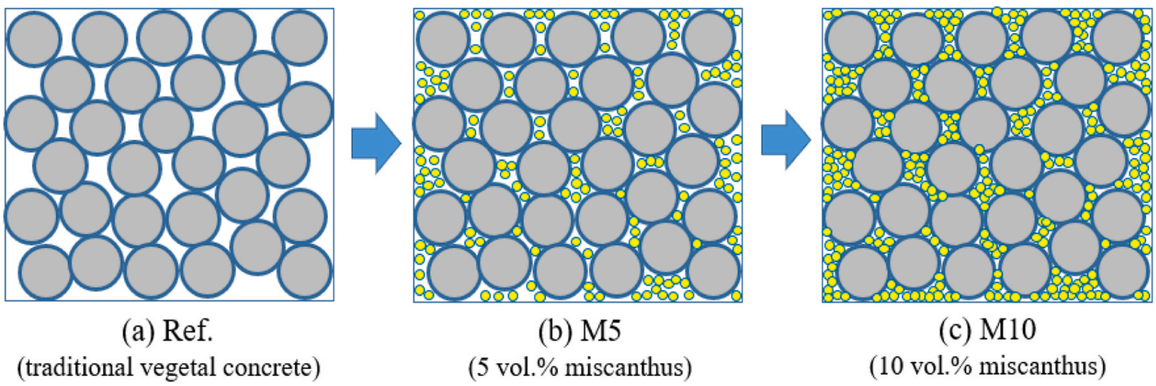

Fig. 2. Three kinds of porous vegetal concretes for plant growth.

Table 1
Mix proportions of porous vegetal concrete.

Mix no.	Cement (kg/m^3)	Aggregate (kg/m^3)	W/C	Miscanthus (kg/m^3)	Extra water for miscanthus (kg/m^3)	Total water (kg/m^3)
Ref.	301	1574	0.37	-	-	111.4
M5	301	1574	0.37	78.5	206.1	317.5
M10	301	1574	0.37	157	412.1	523.5

Vegetal concrete typically consists of a mixture of cement, aggregates, water and a suitable vegetative component [13,14]. Vegetal concrete has many potential advantages by promoting the integration of vegetation into urban environments, such as environmental sustainability, excellent stormwater management, and improved thermal and acoustic insulation [15]. Moreover, it also contributes to landscape effects and aesthetic appeal, and other good impacts on the environment [16], for instance, improved air quality, urban cooling effect, soil protection and water quality purification, etc [17–19]. Therefore, applying vegetal concrete as part of low-carbon urban development presents an effective solution for mitigating both global warming and urban heat islands [1], which can be widely used in green roofs, living walls, vertical gardens, and waterside areas, as well as in geological restoration [20–22]. However, the main disadvantage of traditional vegetal concrete is poor water and fertilizer retention capacity, leading to a rather limited lifespan of plants [23,24]. Moreover, the plant withering phenomenon is found in vegetal concrete after 1–2 weeks of germination [10]. Porous concrete is typically only covered with soil on its upper surface, and the interior is still porous without any fillings. Furthermore, the exterior soil layer often faces the risk of soil loss owing to water-driven erosion [25]. As a result, traditional vegetal concrete penetrates rainwater quickly in the rainy season, and cannot replenish water for plant growth in the dry season. Therefore, the water retention capacity of traditional vegetal concrete should be improved to extend the lifespan of plants. In addition, the relationship between plant-growing performance and the porous structures of concrete should be further investigated.

Recently, sustainable building materials have attained more attention considering their positive environmental impacts [26]. The plant-based materials have been explored by using as aggregates, fibre and other mixtures in the concrete matrix, including miscanthus [27], bamboo [28], wood chips [29], oil plam shell [30] and other agricultural wastes [31]. The addition of plant-based materials can reduce the density of concrete and improve its thermal and acoustic insulation properties thanks to the porous structure of plant-based materials [8]. However, high water absorption and polysaccharide components of plant-based materials usually have negative effects on the mechanical properties and drying shrinkage of concrete. These negative effects on durability can be reduced by alkali treatment, heat treatment and other physical treatment methods [32,33]. The advantages of using plant-based materials for sustainable cementitious composites are that it is a renewable feature, widespread availability and rapid growth.

Table 2
Mix proportions of bio-based miscanthus vegetal mortar.

Mix no.	Cement (g)	Miscanthus (g)	W/C	Extra water for miscanthus (g)	Total water (g)	Ratio of cement to miscanthus
MC0.25	1200	300	0.37	787.5	1231.5	1:0.25
MC0.5	600	300	0.37	787.5	1009.5	1:0.5
MC0.75	400	300	0.37	787.5	935.5	1:0.75
MC1	300	300	0.37	787.5	898.5	1:1

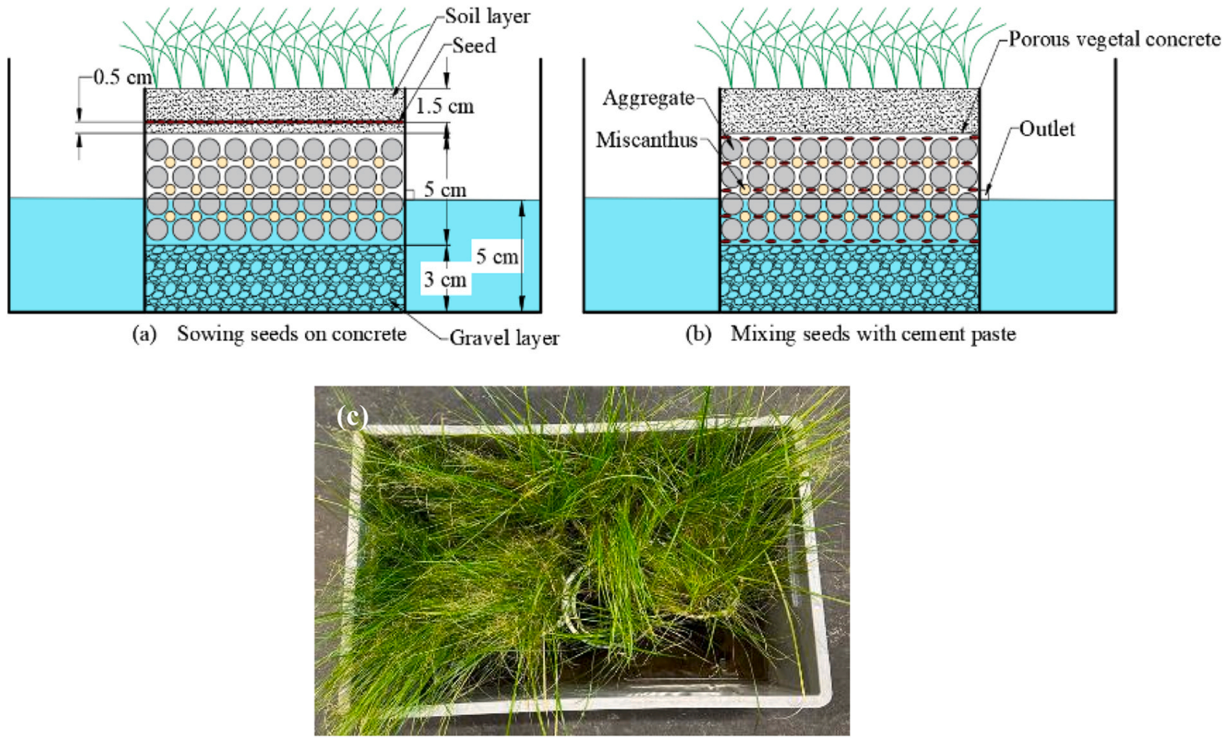

Fig. 3. Laboratory setup for plant growth test.

Therefore, rather limited research investigates the application of plant-based materials in vegetal concrete for promoting the growth of plants on vegetal concrete surfaces.

There are several necessary conditions for plant growth, including sunlight, temperature, water, air, and nutrients, which are the lifeline of plants. There is no doubt that natural conditions such as sunlight, temperature, air, etc. cannot be altered by concrete components. However, the water-release behaviour of vegetal concrete can be improved through the adjustment of concrete composition. Previous studies have reported that plant-based materials have a high water absorption capacity, for example, miscanthus powder can absorb approximately 5 times water weight. Assuming that the pores of traditional vegetal concrete can be filled with plant-based materials, it will significantly improve the water retention capacity of traditional vegetal concrete by utilizing the porous properties of miscanthus to store rainwater in the rainy season, and then slowly release it to the plants in the dry season. In this way, the lifespan of plants can be extended and their resistance to environmental changes can be improved. However, the application of bio-based materials to enhance plant growth adaptability of porous vegetal concrete requires further investigation.

This work investigates the addition of miscanthus, a type of natural fibre, into porous vegetal concrete to address its inherent poor water retention capacity and porous structure which adversely affect plant longevity. This work consists of two parts. In the first part, the effects of miscanthus content on the physical properties, mechanical strengths and plant growth of porous vegetal concrete are investigated, and 5% and 10% of miscanthus powder are added to the mixture by volume, and conventional porous concrete is used for comparison. The results show that the incorporation of bio-based materials significantly improves the water absorption-release behaviour and plant cover percentage of vegetal concrete. Therefore, to further investigate the suitability of fully bio-based materials for fostering lush plant growth, in the second part, the influences of the cement-to-miscanthus ratio and the planting methods on miscanthus vegetal mortar are analysed. Based on the results, an optimized cement-to-miscanthus ratio and planting method are obtained for sustainable bio-based vegetal concrete.

2. Materials and methods

2.1. Materials

The crushed rock with a particle size of 2–5 mm is used as coarse aggregates (Fig. 1a). The powdery miscanthus with a size of 100–500 μm is used as bio-based materials to fill the skeleton structure of porous vegetal concrete (Fig. 1b). The density and 24-hour water absorption of the miscanthus powder are 1.57 g/cm^3 and 525%, respectively. The microscopic results show the miscanthus has a well-developed microstructure (Fig. 1c). To reduce the negative impact of high-pH cementitious composites on plant growth, commercial sulfoaluminate cement is used as a binder in this work, supplied by VICAT. The density and fineness Blaine of the cement are 2.98 g/cm^3 and 4590 cm^2/g, respectively.

2.2. Mix proportion and specimen preparation

2.2.1. Effects of miscanthus content on the performance of porous vegetal concrete

In the first part of this work, the effects of the bio-based miscanthus and its filled porosity on the physical properties, mechanical strengths and plant growth performance of porous vegetal concrete are investigated. Vegetal concrete refers to the mix proportions of conventional porous concrete, a mixture containing 301 kg/m^3 cement, 1574 kg/m^3 aggregate and 111.4 kg/m^3 water is used as the reference concrete in this study. Then, 5% and 10% miscanthus powder by volume are added to the mixture to fill the pore structures of the reference concrete and labelled as M5 and M10, respectively, as shown in Fig. 2. Due to the high water absorption of miscanthus powder, an additional 50% water of its 24-hour water absorption amount is added to the mixture. The concrete samples are cast referring to the preparation process of conventional porous concrete (CJJT135–2009). All samples are demolded after 48 h and then cured under laboratory conditions at a temperature of 20±2 °C until testing. The detailed mix proportions are shown in Table 1.

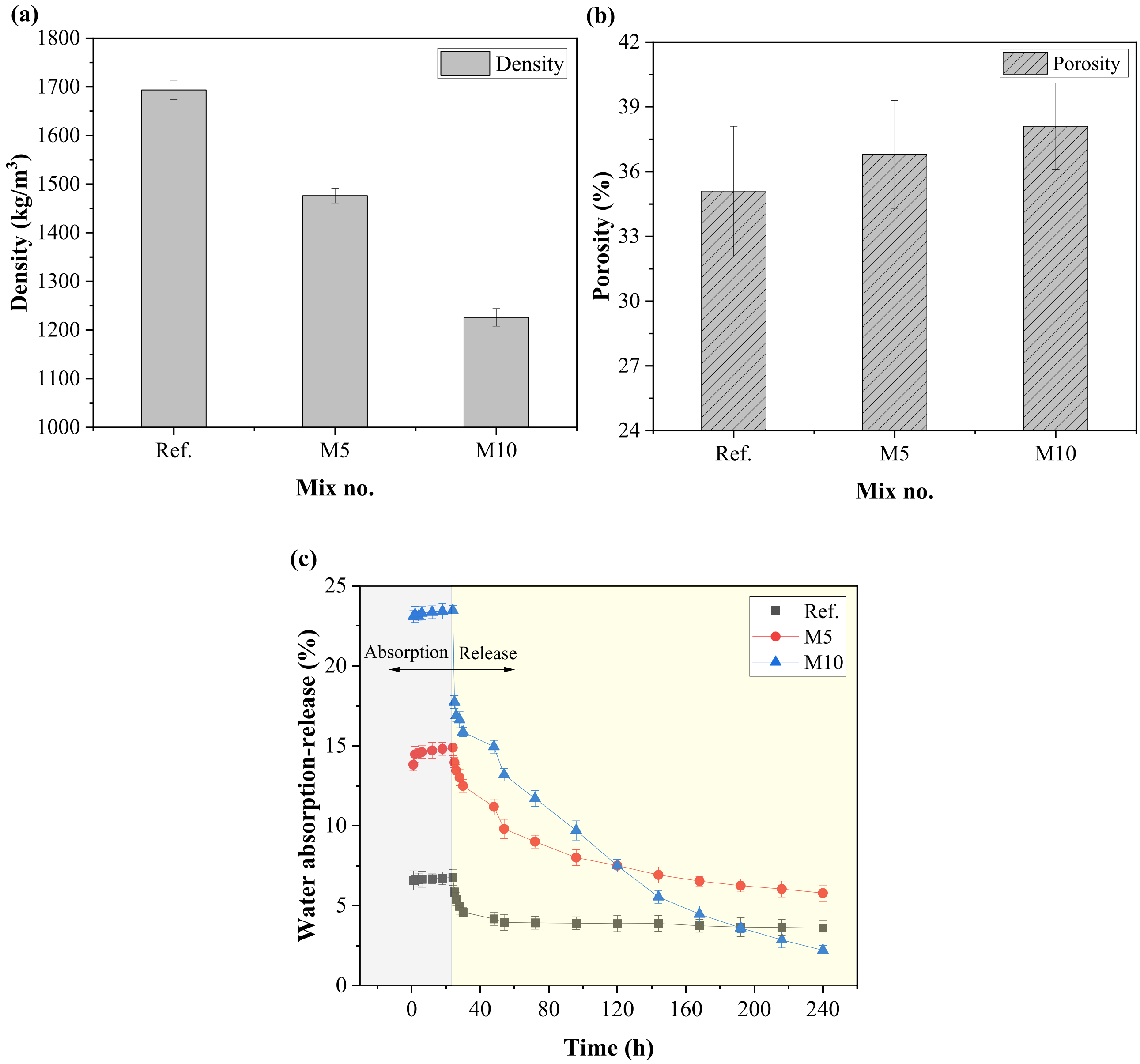

Fig. 4. Density, porosity and water absorption-release behaviour of porous vegetal concrete.

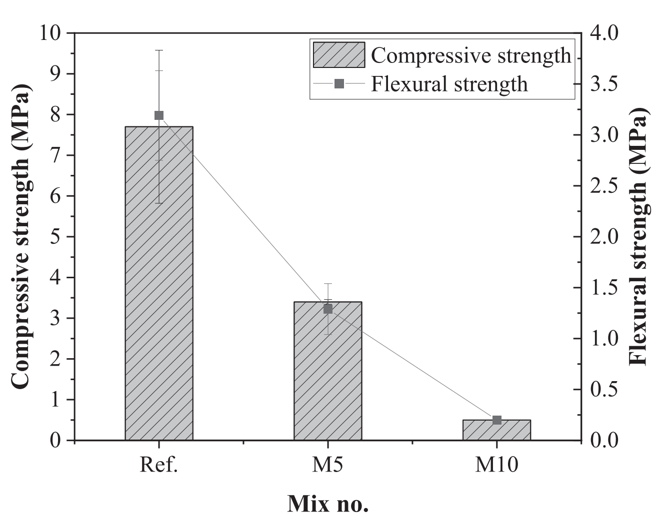

Fig. 5. Mechanical strengths of porous vegetal concrete.

2.2.2. *Mix proportion of bio-based miscanthus vegetal mortar*

Based on the preliminary experimental results, cement content has a significant impact on seed germination of plants. In the second part of this work, to explore the possibility of bio-based miscanthus vegetal mortar for plant growth, the influences of various cement-to-miscanthus ratios (1:0.25, 1:0.5, 1:0.75 and 1:1) by mass on physical properties and mechanical strengths, and plant growth performance of miscanthus vegetal mortar are investigated. The mix proportions of bio-based miscanthus vegetal mortar are shown in Table 2.

2.3. *Plant cultivation*

Two planting methods, i.e., sowing seeds on the concrete surface and directly mixing seeds with cement paste are adopted in this study, as shown in Fig. 3. Because coarse aggregates are added to the porous vegetal concrete, coarse aggregates might destroy the seeds during the mixing process when the mixing seeds into the concrete matrix method is applied, and thus, only the sowing seeds method is used in the first part of this study. Two plant cultivation methods are used in plant growth experiments of bio-based miscanthus vegetal mortar to

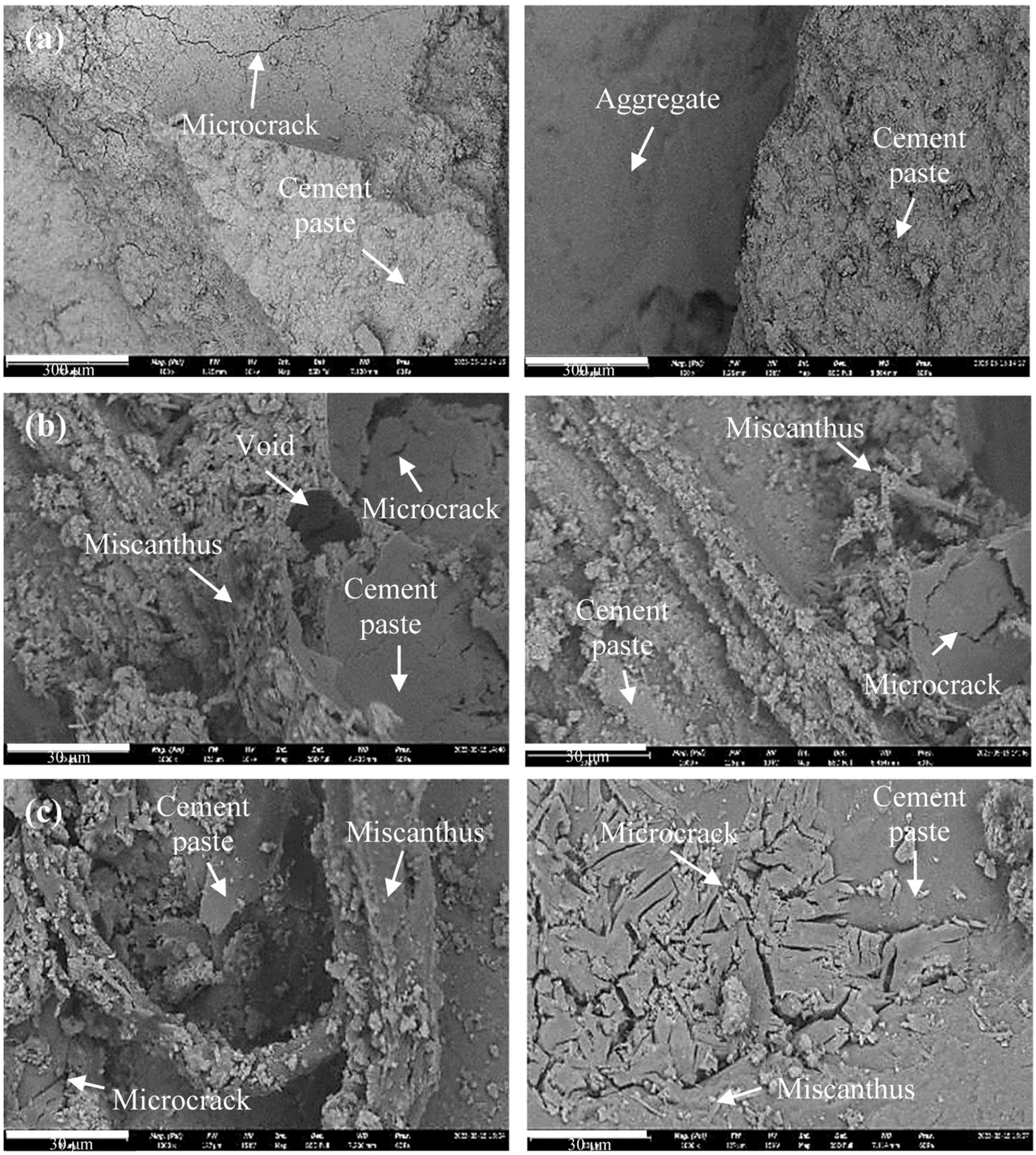

Fig. 6. Microscope images of concretes (a) Ref., (b) M5 and (c) M10.

Table 3
Ions released from concretes (mg/kg).

Mix no.	N	P	K	Ca	Na	Mg
Ref.	3.4	-	114	2345	30.9	-
M5	3.3	-	122	3429	45.4	-
M10	5.5	-	93.3	5158	32.3	-
Soil	72	1353	1500	603	140	254

investigate the influences of the cement-to-miscanthus ratios on seed germination directly in the concrete composites in the second part of this study.

For the direct sowing seed method, a layer of 2–5 cm gravel is placed at the bottom of the planting box, with a thickness of 3 cm, increasing the air permeability of the concrete to promote plant growth, and then, a concrete sample with a thickness of 5 cm is placed on top of the gravel layer, and then, a ruler is inserted into the planting box, followed by the concrete surface is covered with 0.5 cm thickness of ordinary horticultural soil, which is purchased from a nearby gardening market. After that, 1 g of grass seeds are evenly sprayed on the soil layer, and then, 1.5 cm thick soil is used to cover the grass seeds. Finally, the soil layer is moistened and its surface is covered with a plastic film, which is removed once the grass seeds germinate from the soil layer. All planting boxes are placed in a plastic box with a constant water level of 5 cm. In addition, a hole is opened at a height of 5 cm of the planting box to connect the inside concrete to the outside water. The plastic boxes are placed in a laboratory condition near a window with a constant temperature of 23 °C. Plants are watered regularly from the top of the planting box to maintain a constant water level of 5 cm to ensure consistent and sufficient water for the plants throughour the experiment. The growth situation of the plants is observed weekly.

For the method of mixing seeds into concrete, 10 g of dry grass seeds are mixed with the fresh mortar matrix (miscanthus, cement and water) during the sample preparation process, and then directly put into the planting box, and the surface is covered with 2 cm of soil layer. The other processes are the same as the direct sowing seed planting method mentioned above.

2.4. Test methods

2.4.1. Physical properties

The density and porosity of $100\times100\times100$ mm^3 samples with a curing age of 28 days are determined in accordance with ASTM C1754/C1754M-12. The water absorption of $100\times100\times100$ mm^3 samples with a curing age of 28 days is determined according to GB/T 50081–2019. The water release of the samples is evaluated by placing the saturated sample in laboratory conditions with a constant temperature of 23 °C and periodically measuring the mass loss of water.

The porosity can be calculated according to:

$$\boldsymbol{P} = \left[\mathbf{1} - \left(\frac{\mathbf{M}_{dry} - \mathbf{M}_{sub}}{\boldsymbol{\rho}_{water} \times \boldsymbol{V}_s}\right)\right] \times \mathbf{100\%} \quad (1)$$

where P is the total porosity (%); M_{dry} is the dry mass (kg); M_{sub} is the submerged mass in water (kg); V_s is the volume (m^3); ρ_{water} is the density of water (kg/m^3).

The water absorption can be calculated according to:

$$\boldsymbol{W}_a = \frac{\mathbf{M}_s - \mathbf{M}_d}{\boldsymbol{M}_d} \times \mathbf{100\%} \quad (2)$$

where W_a is the water absorption (%); M_s is the mass of the saturated sample with a dry surface (g); M_d is the oven-dry mass (g).

2.4.2. Mechanical strengths

$40\times40\times40$ mm^3 samples and $40\times40\times160$ mm^3 samples with a curing age of 28 days are used for compressive and flexural strengths test according to EN 196–1, respectively. The loading rates for compressive and flexural strength tests are 2000 N/s and 50 N/s, respectively. The test result is determined by calculating the average of a minimum of three samples.

2.4.3. Plant growth observation

(1) Plant height, number of leaves and rooting behaviours

Plant height, number of leaves, number of roots and root length are regularly measured and recorded. For the planting method of mixing seeds into the mortar, the number of germinated seeds is recorded to evaluate the germination performance of the seeds in the concrete matrix. When grass seeds are used, it is rather difficult to quantitatively evaluate the growth performance of grass, and thus, an image processing method is adopted to evaluate the percentage of the plant cover. The specific process is as follows: Firstly, the growth condition of the grass is captured using a high-definition camera; then, the grass surface image is

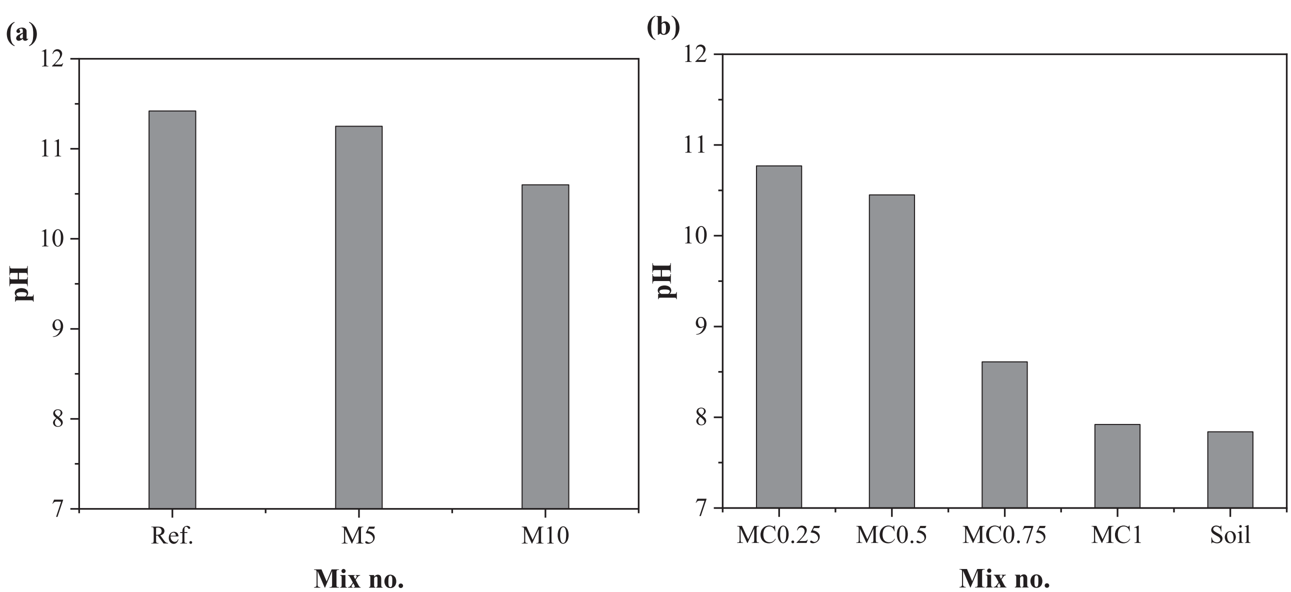

Fig. 7. pH values of the leaching solution of concretes.

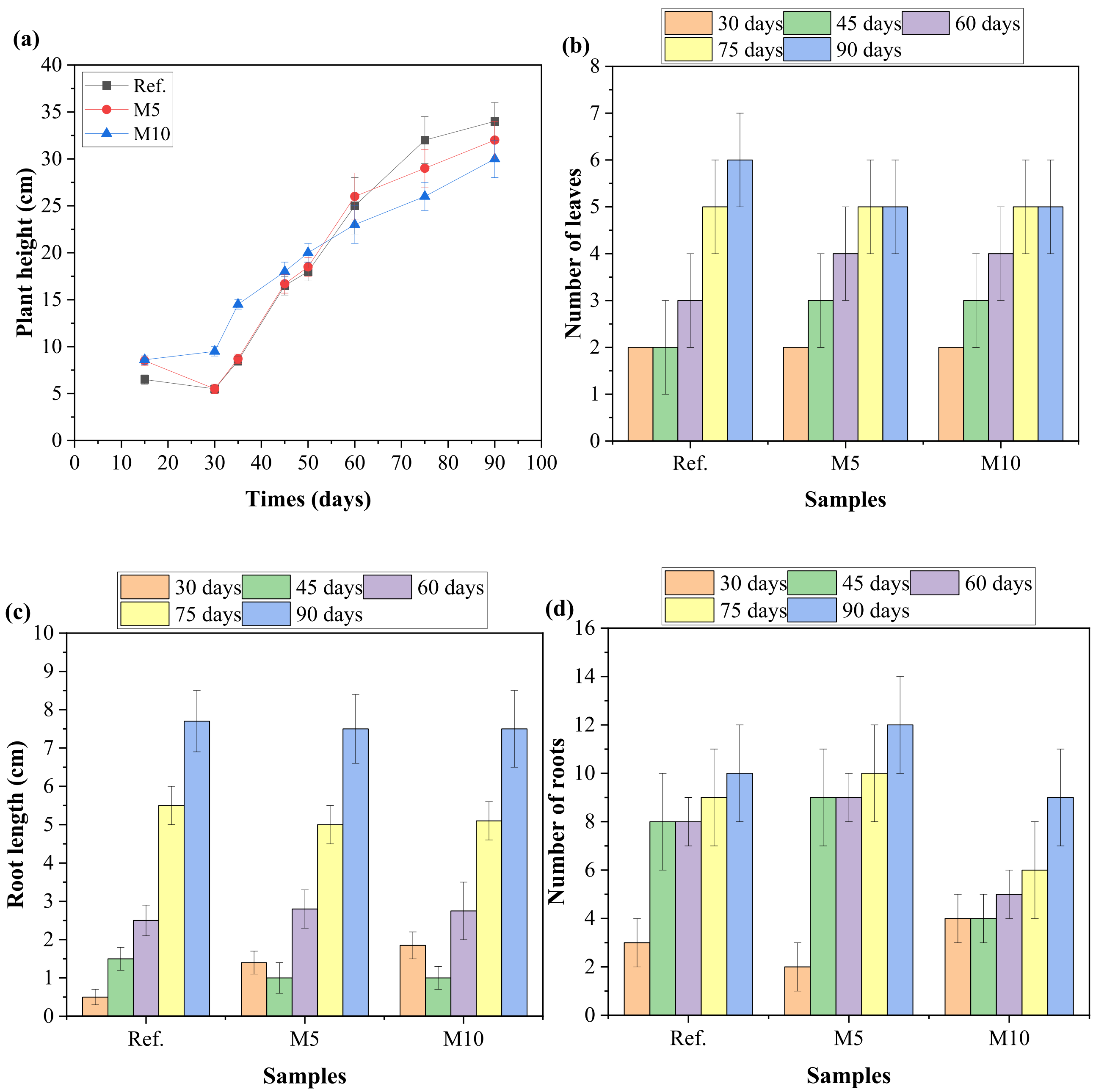

Fig. 8. (a) Plant height, (b) Number of leaves, (c) Root length and (d) Number of roots.

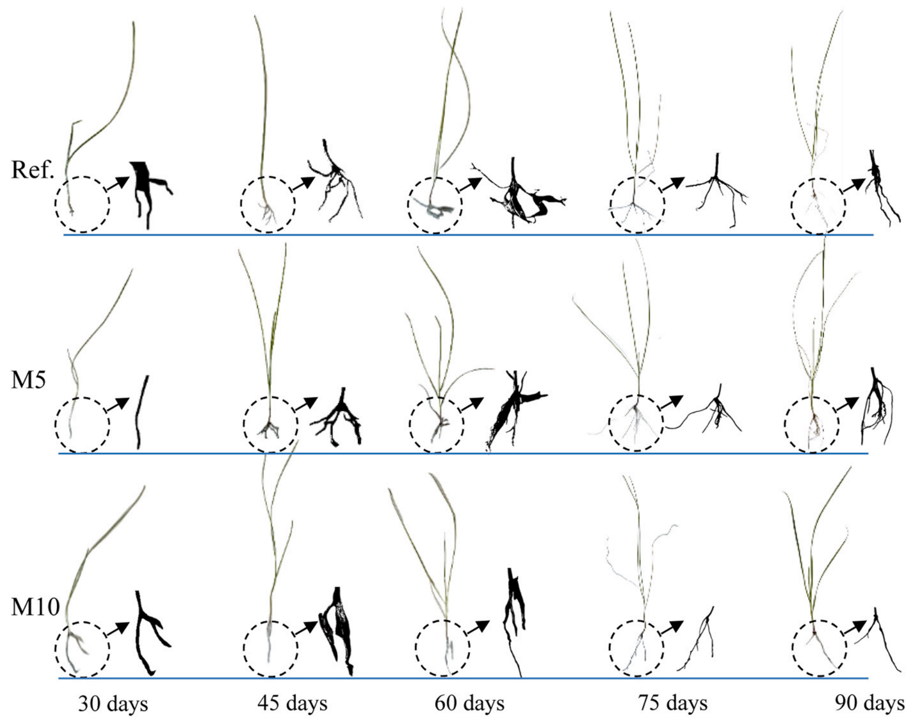

Fig. 9. Changes in root morphology of plants over time.

processed into a grayscale image; finally, the area covered by the grass is extracted and calculated as the plant cover using Image J software. Furthermore, the growth process and shape of plant roots are acquired regularly using a high-definition camera and then the images are processed into grayscale images to clearly show the shape of plant roots. Finally, after the planting experiment is completed, the surface soil is removed and cleaned to observe the growth of the plant root system between the concrete interface. The microstructure of the plant root is analyzed using a scanning electron microscope (SEM).

(2) Macronutrient leaching behaviours of concrete

The supplementation and supply of nutrients is the key to the healthy growth of plants. To evaluate the leaching behaviour of macronutrients in porous vegetal concrete, 10 g samples are first immersed in 100 ml of deionized water. The mixture is stirred at 225 rpm for 24 h and then allowed to settle in the laboratory. After 60 days, the supernatant is extracted and filtered for ion concentration measurement using an IC instrument. The ions examined included nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg), and these elements in the soil are measured for comparison. Furthermore, the pH of the solution is determined to complete the assessment of the leaching results using a pH meter.

3. Results and discussion

3.1. Effects of miscanthus content on porous vegetal concrete

3.1.1. Density, porosity and absorption-release behaviour

Miscanthus is a lightweight material that has been widely used in bio-based lightweight concrete, acoustic isolation and heat-insulating concrete, due to its porous characteristics. As shown in Figs. 4a and 4b, the addition of miscanthus in porous concrete reduces the density of concrete and increases its porosity, owing to the lightweight properties of miscanthus and weak bonding with the concrete matrix. The densities of concretes Ref., M5 and M10 are 1694 kg/m^3, 1476 kg/m^3 and 1226 kg/m^3, respectively. The densities of concretes M5 and M10 are reduced by 13% and 28%, respectively, compared to the reference concrete.

For the water absorption behaviour, all the concretes reach a saturation status rapidly after being soaked in water, and the addition of miscanthus significantly increases the water absorption of the concrete (Fig. 4c). This is attributed to the miscanthus powder can absorb quickly approximately five times its own weight once it is submerged in water. The 24-hour water absorption of concretes M5 and M10 are 15% and 24%, respectively, which increases by 119% and 246%, compared to the reference concrete. The improvement in water absorption is crucial for sustaining plant life in a vegetal concrete environment. In terms of water release behaviour, the saturated reference concrete has almost no more moisture being released at room temperature (23$\pm$1 °C) after placing it in the laboratory for 24 h, however, moisture can be continued released from concretes M5 and M10. Even after water release for approximately 120 h, the water percentage values of concretes M5 and M10 are close to that of the saturated reference concrete, indicating that the addition of miscanthus significantly improves the water absorption-release behaviour of porous vegetal concrete. The superior water absorption-release behaviour of porous vegetal concrete can promote the resistance to natural climatic environments of plants, i.e., the vegetal concrete can quickly absorb water from rainwater during the rainy season, and then slowly release the absorbed water to plant roots during the dry season, which is beneficial for plant growth. The water release rate of M10 is higher than that of M5, which may be due to the higher miscanthus content leading to more micropores inside the concrete and being prone to moisture loss, meanwhile, contributing to higher water absorption.

3.1.2. Compressive strength and flexural strength

Conventional porous concrete usually has a low compressive strength ranging from 2.8 MPa to 27.6 MPa and a high porosity varying from 15% to 30% because of the application of single-size aggregates and no addition of fine aggregates. Similarly, bio-based vegetal concrete usually has a low strength due to its porous structure, such as hemp and rapeseed concrete (0.5–2.5 MPa) [7], corn stalk concrete (1.13–5.72 MPa) [34], and diatomite-zeolite vegetal concrete (3.7 MPa) [35]. As shown in Fig. 5, the addition of miscanthus decreases the

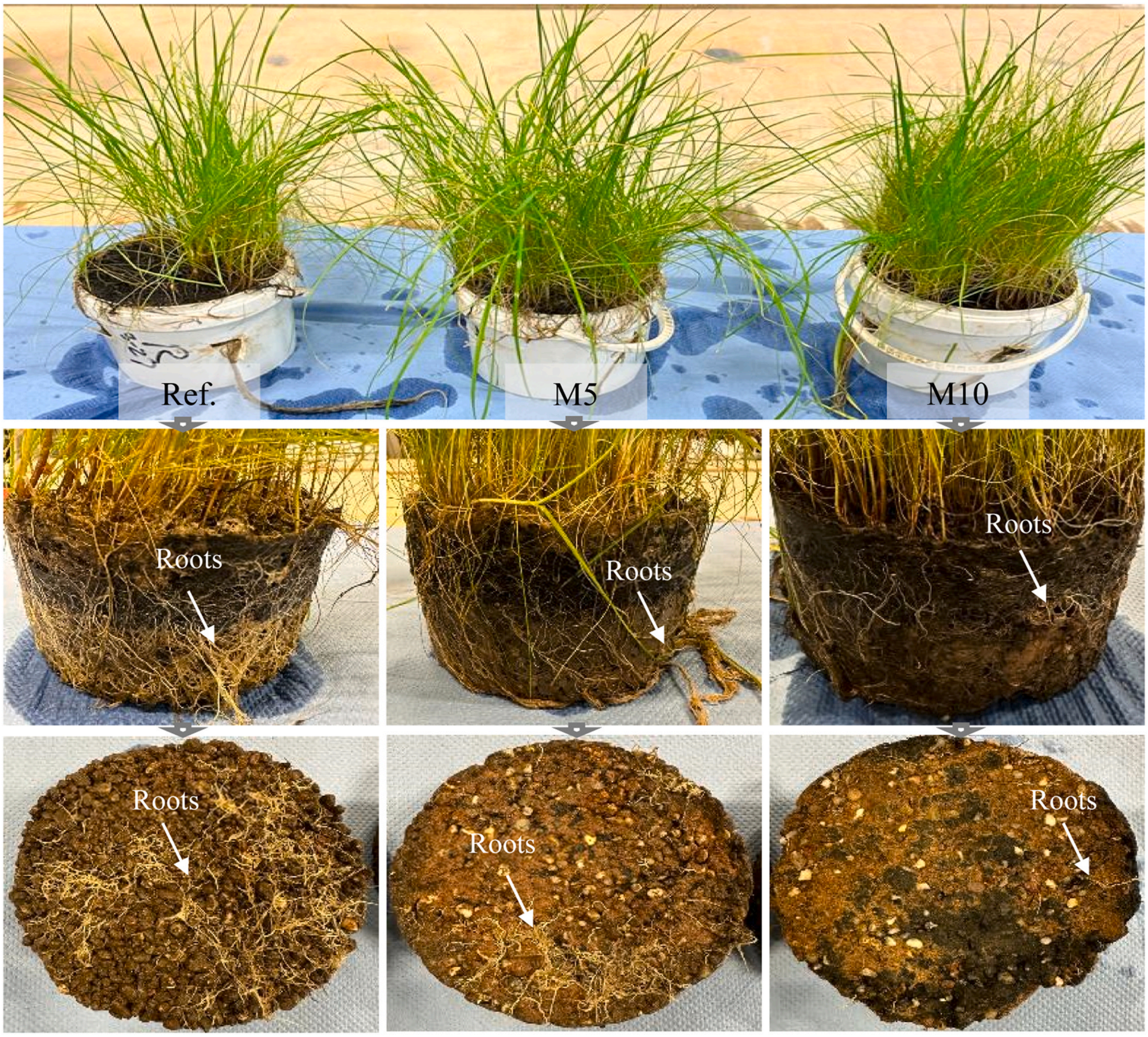

Fig. 10. Distribution characteristics of plant roots on concrete surface.

compressive and flexural strengths of porous vegetal concrete due to the increase in porosity. The compressive strengths of M5 and M10 are 3.4 MPa and 0.5 MPa, respectively, and corresponding flexural strengths are 1.29 MPa and 0.2 MPa. This is due to the fact that bio-based miscanthus can slow down the cement hydration process and increase the setting time owing to the presence of polysaccharides. Moreover, the organic acids have a strong calcium chelating group that can decrease the concentration of calcium ions and prevent the formation of portlandite and calcium-silicate-hydrate (C-S-H) [36], reducing the mechanical strength of concrete. The addition of bio-based materials in cement matrix reduces the mechanical strength of concrete and has been reported in other bio-based concretes, such as corn stalk concrete [34], oil palm shell concrete [37], coconut shell concrete [38], etc. However, porous vegetal concrete is not applied as structural concrete or even pavements like pervious concrete, it is mainly used in green roofs, vertical gardens, river banks or waterside areas, etc., to improve the landscape benefits of ecological cities, reduce rainwater runoff and heat island effect, as well as improve air quality, etc. Therefore, low-strength porous vegetal concrete is acceptable for the non-load-bearing element of ecological cities. In addition, due to the high content of miscanthus (up to 10%) used in this study, the mechanical strength of porous vegetal concrete can be improved by reducing the bio-material content, adding fibres or using fine aggregate, etc. Considering the strength deficiency of M10, M5 is recommended for porous vegetal concrete.

The interfacial transition zone is generally the weakest position of conventional normal-weight concrete, which governs the mechanical performance of concrete [39]. The microscope images of porous vegetal concrete are presented in Fig. 6. The results show that the incorporation of miscanthus increases the porosity of the mortar matrix, and it has a weak bond between the miscanthus-mortar interface. As a result, with the increase of porous miscanthus content, more micropores exist in the mortar matrix, contributing to better water absorption-release behaviour and lower mechanical strength of porous vegetal concrete.

3.1.3. Ions released from porous vegetal concrete

The main ions released from concrete are determined through the leaching test, and the results are presented in Table 3. Compared to the leaching solution of soil, the porous vegetal concrete can also release N, K, Ca and Na ions, with the exception of P and Mg. Among these elements, N, P, K, Ca and Mg are macronutrients required for plant growth. The addition of 5–10% miscanthus significantly enhances the releasing amount of Ca ion, but has little effect on N, K and Na ions. Previous studies have found that incorporating miscanthus can increase the Ca-releasing capacity, improving the P-removal capacity of cement-based materials [40]. Ecological concrete has shown potential for excess N and P removal from rainwater [12]. In the case of bio-based vegetal

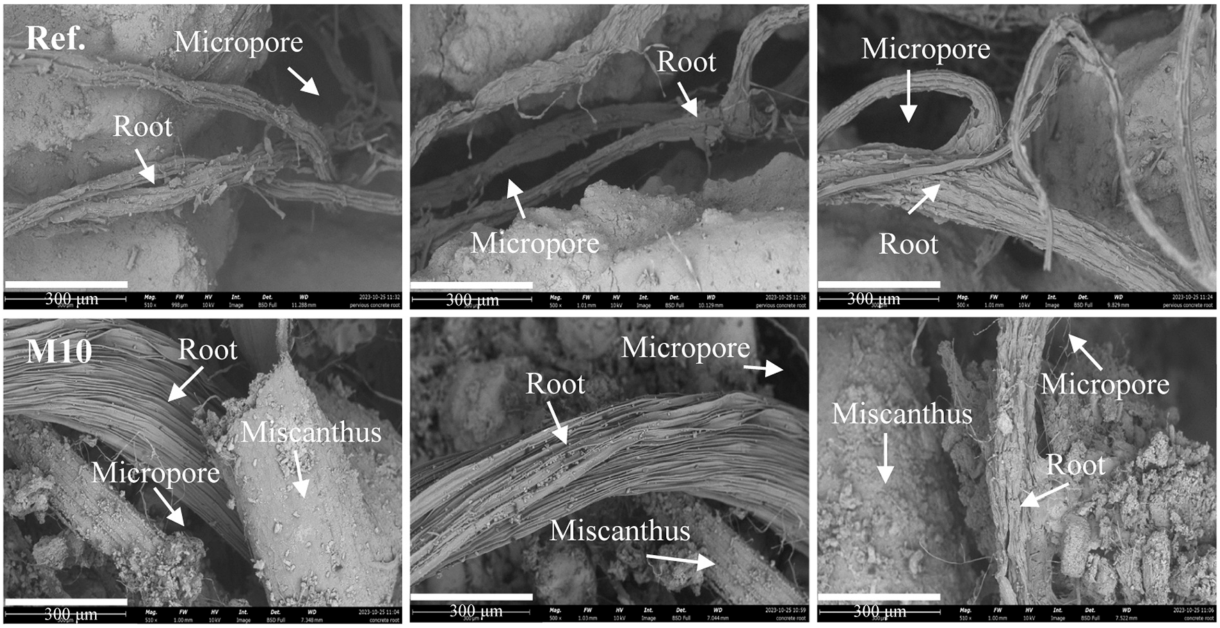

Fig. 11. Microscope images of plant roots.

concrete, the phosphate precipitating on the concrete surface is beneficial for plant growth. However, essential elements like N, P and K for plant growth require supplementation through fertilization [41]. The addition of miscanthus can improve the storage capacity of these nutrients for plant growth by utilizing its high water absorption capacity. The high alkalinity of concrete has a negative impact on plant growth [10]. As shown in Fig. 7, the incorporation of miscanthus and the reduced cement content in mortar matrix can lower the pH value of concrete, mitigating its high alkalinity and creating a more favourable environment for plant growth, especially when the ratio of cement-to-miscanthus is 1:1, the pH of miscanthus mortar is close to that of soil.

3.1.4. Plant growth observation

(1) Plant height and number of leaves

The effects of porous vegetal concrete on plant growth performance such as plant height, number of leaves, root length and number of roots are evaluated, as shown in Fig. 8. The results show that plant height and the number of leaves increase over time for grass on all kinds of concrete surfaces. In the first 50 days, the grasses on the M10 concrete surface have a higher plant height, and then its height starts to lower than that of grasses on the Ref. and M5 surfaces. At 90 days, the heights of grasses on the Ref., M5 and M10 concrete surfaces are 34 cm, 32 cm and 30 cm, respectively. This is because for the same planting area, the denser the plant grows, the more nutrients are required for plant growth. The competition for growth space and nutrients in high plant coverage conditions will result in a reduction in plant height, compared to the plants growing in sparse conditions. In this study, grasses on M10 concrete surfaces have a higher plant cover than other concretes (Fig. 12), which means that they require more nutrient supplementation for their healthy growth. It should be noted that no fertilizer is used for all plants during this experiment. Therefore, the lack of nutrients and higher coverage percentage of plants on the M10 surface will impact the plant growth in later stages. Plant cover percentage and plant growth situation will be discussed in detail in subsequent sections.

The grasses on the M5 and M10 concrete surfaces have slightly more leaves than the Ref. concrete during the first 75 days. The differences in the number of leaves are insignificant for all porous vegetal concretes. At 90 days, grasses on all concrete surfaces have 5–6 leaves. Moreover, the grasses begin to appear 1–2 yellow leaves from 60 days, which could be due to the lack of nutrients such as N, P, K, etc. Therefore, nutrient supplementation for plant healthy growth should be considered when applying porous vegetal concrete in actual engineering construction.

(2) Length and number of roots

The length and number of roots and their morphology are also used to assess plant growth status. As shown in Figs. 8c and 8d, grasses on all concrete surfaces have a root length of approximately 7.5 cm and a number of roots of 9–12 on 90 days. The root length of grasses on the M10 concrete surfaces is slightly longer than that of Ref. and M5 during the first 30 days. This may be due to the degeneration occurrence of grasses on Ref. and M5 concrete surfaces on 30 days, some of the grasses died leading to the lower plant cover percentage on Ref. and M5 concrete surfaces. Their root lengths are 0.5–1.5 cm on 30 days, which just penetrates through the soil layer (0.5 cm) and touches the concrete surface, resulting in a degeneration occurrence of plants due to high alkalinity and the existence of pore structures. However, after 30 days, the number of roots of grasses on Ref. and M5 concrete surfaces is more than that of M10. This is attributed to the higher plant cover percentage of M10, as a result, the individual root development of grasses is lower than that of Ref. and M5.

The taproot of plants is usually surrounded by smaller roots and branch roots, thus, it is rather difficult to quantitatively assessment of the root system of plants. In this study, the root morphology of plants is used to visually evaluate the growth situation of the root system of plants, as presented in Fig. 9. The root of plants gradually grows well over time, the tap root becomes more and longer, and more branch roots are wrapped around the tap root. The root morphology is evaluated based on the root morphology of a single grass, plants on Ref. and M5 concrete surfaces have more root branches than those of M10. Therefore, individual plants grow better and have more developed root systems of plants on Ref. and M5 concrete surfaces due to less competition for growth space, compared to those plants on the M10 concrete surface.

The distribution characteristics of plant roots on the concrete surfaces are shown in Fig. 10. The results show that the concrete surface is entangled with numerous randomly distributed plant roots, and the roots growing out of the planting box from the water outlet hole are

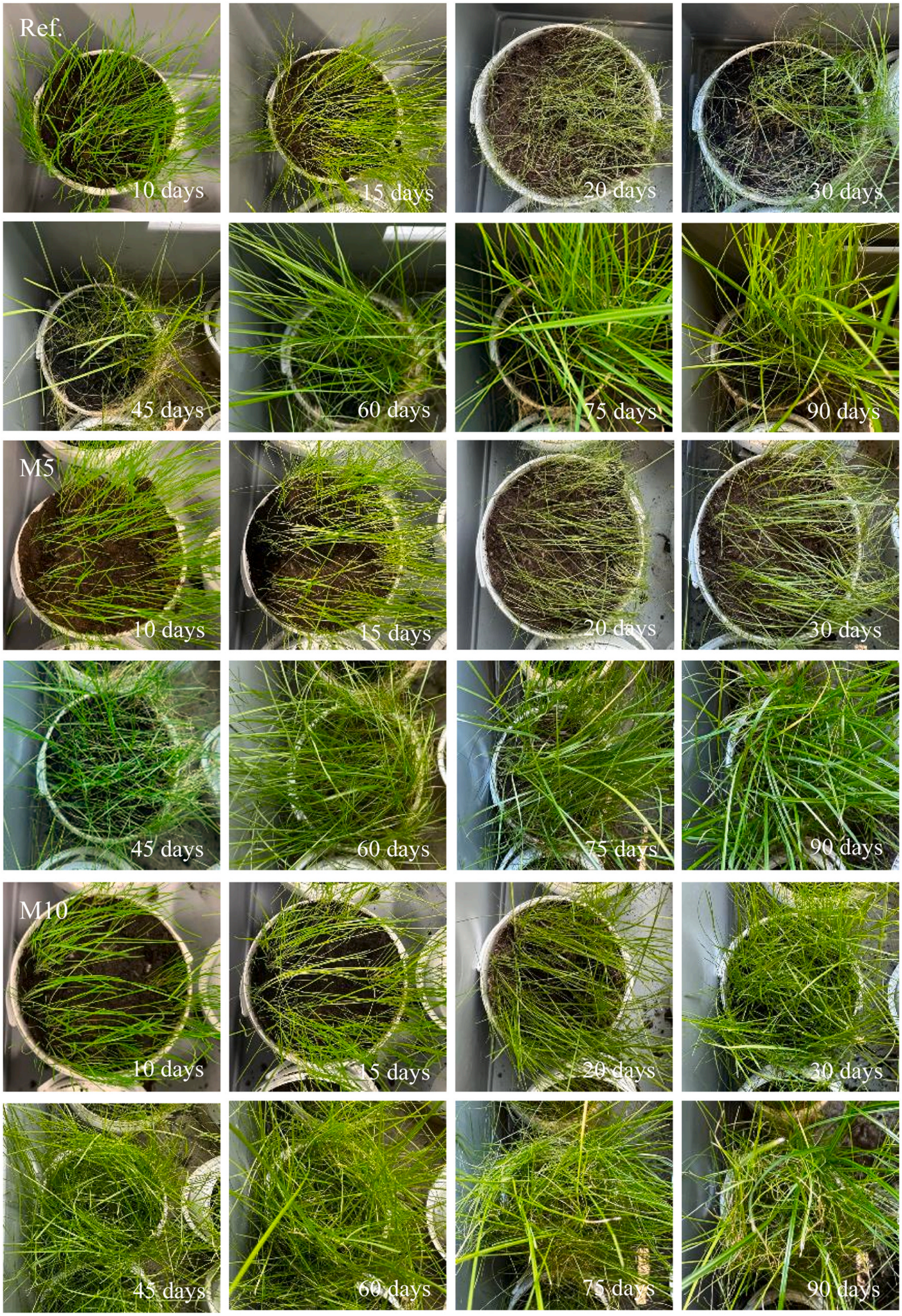

Fig. 12. Plant growth process over time.

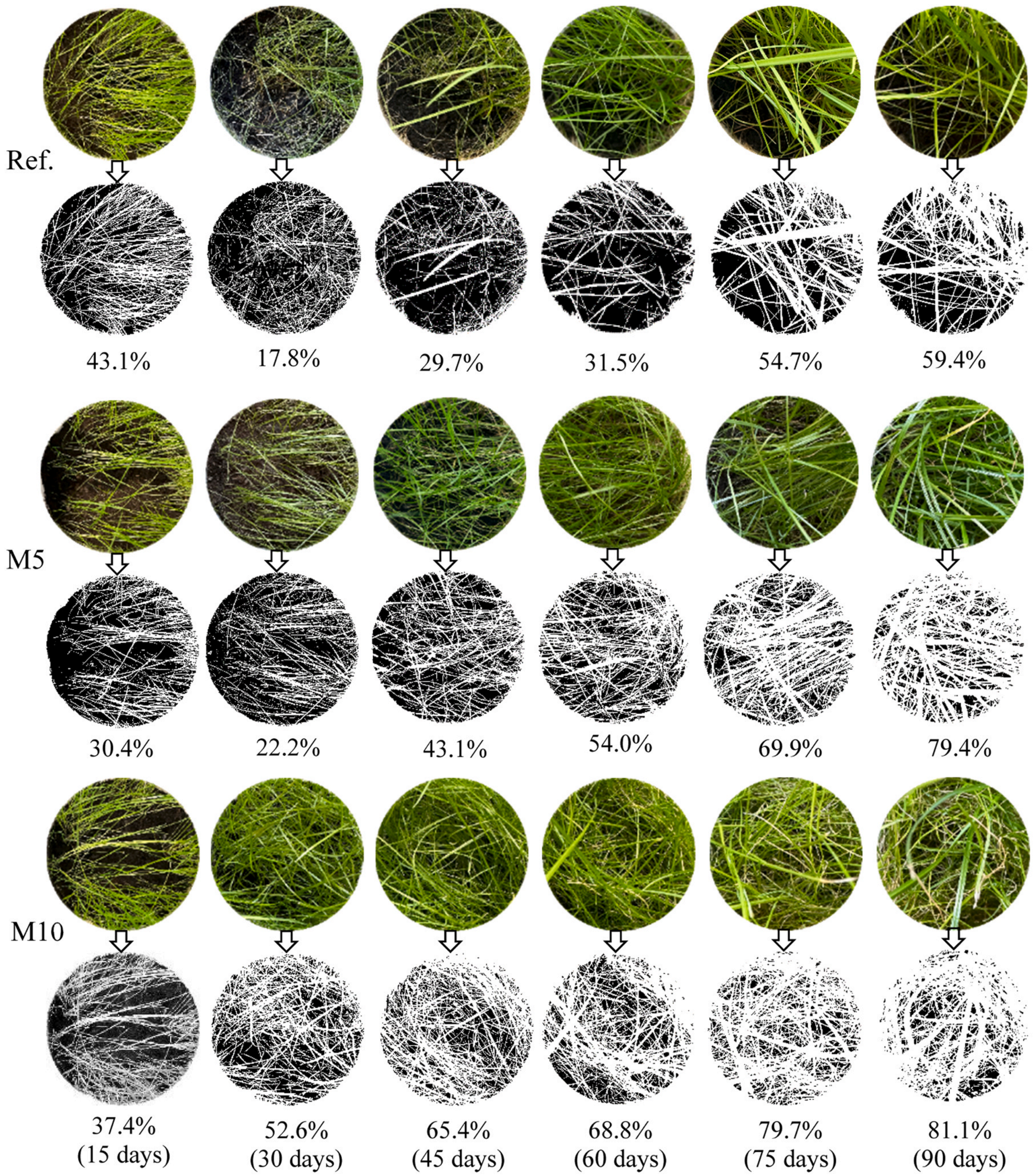

Fig. 13. Plant cover percentage results.

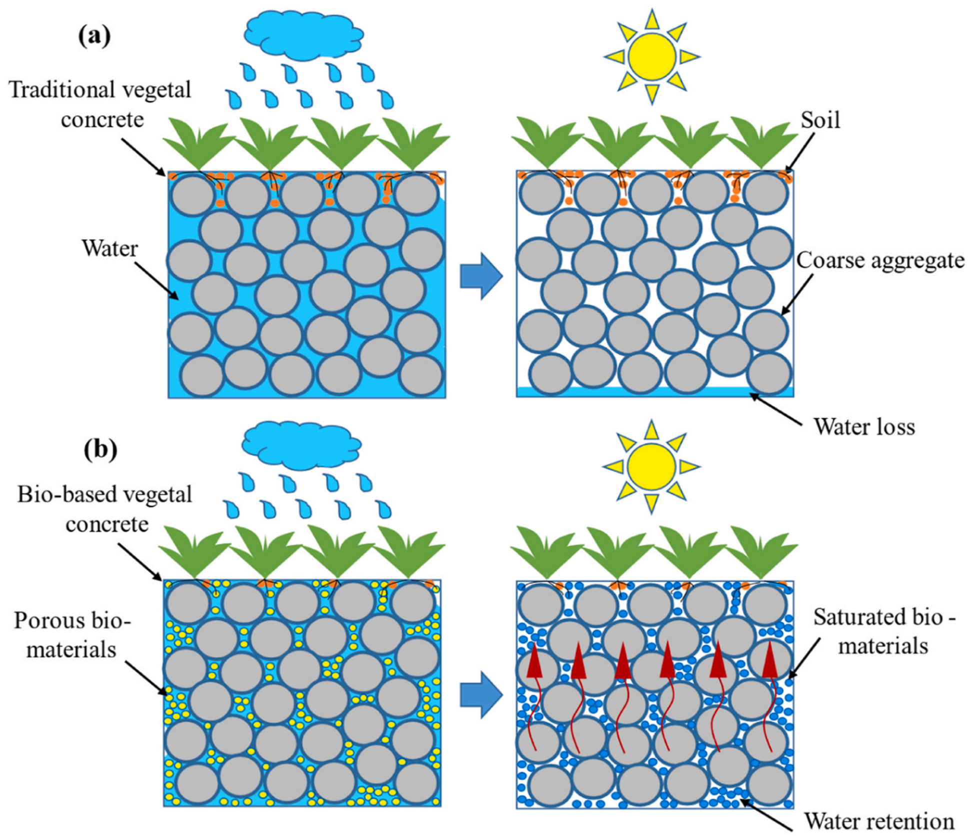

Fig. 14. Water retention behaviour of (a) traditional vegetal concrete and (b) bio-based vegetal concrete for vegetation restoration.

observed. The application of miscanthus leads to the blocking of concrete pores due to its filling effect, resulting in fewer pores available for root extension than the control concrete, which has more macropores allowing more root penetration. The constant water level method is adopted in this study for plant growth experiments, there is continuous water replenishment when the root system of plants extends into the concrete pores, thus, the plant growth situation has not been influenced during the later stages (after 30 days), only plants degenerate in early stages (before 30 days). However, conventional porous concrete has poor water retention capacity in actual engineering applications without continuous water replenishment, when the root system of plants extends into these pores of the concrete and the water is not replenished timely, the plants will face the risk of degeneration due to inadequate water supply.

As shown in Fig. 11, microscopic images of plant roots confirm that for conventional porous concrete, plant roots primarily extend into their pore structures, consequently, when these pores are not filled with soil or during dry seasons, plants will face water scarcity in the root systems, leading to their demise phenomenon. This explains why plants on conventional porous concrete surfaces are susceptible to degradation. However, when miscanthus is incorporated into concrete, plant roots not only grow within the pores of the concrete but also along the interface between miscanthus and concrete. The excellent water absorption and water retention capacity of porous vegetal concrete improves the resistance of plants to drought conditions.

(3) Plant growth and cover percentage

As shown in Fig. 12, all grasses on different concrete surfaces are indistinguishable in the early growth period (before 15 days). However, grasses on the Ref. and M5 concrete surfaces show significant vegetative degradation phenomena from 20 to 30 days, while M10 does not have significant vegetative degradation during the whole growth period. This may be because as the roots gradually grow, they come into contact with the concrete surface at this moment, resulting in the death of some grasses due to the existence of voids in porous structures. However, the surviving grasses on the Ref. and M5 concrete surfaces continue to grow well from 45 days onwards, the individual grass grows better than those planted on the M10 concrete surface due to less competition for growth space and nutrients.

As shown in Fig. 13, grasses on the M10 concrete surface have a significantly higher plant cover percentage than other concretes (Ref. and M5), with an increase of 36.5%, compared to the concrete Ref. The plant cover percentage of grasses on the Ref., M5 and M10 concrete surfaces on 90 days is 59.4%, 79.4% and 81.1%, respectively. Therefore, the addition of miscanthus can enhance the plant cover percentage of porous vegetal concrete and show down early plant degradation, showing that miscanthus helps make the environment better for plants to live and grow. A higher plant cover percentage means severe competition for growth space and nutrients, therefore, the provision of nutrients for plant healthy growth should be replenished in a timely when using porous vegetal concrete for vegetation restoration.

The water retention behaviour of traditional vegetal concrete and bio-based vegetal concrete for vegetation restoration is illuminated in Fig. 14. The improvement of plant growth performance using bio-based materials is attributed to its enhanced water retention behaviour. The planting process of plants on vegetal concrete is generally to cover the surface with a thin layer of soil after casting the fresh mixture, and then sow the seeds on the thin soil layer. In most cases, only some voids on the concrete surface can be filled with soil, and consequently, not including the voids inside the concrete. Although rainwater can easily penetrate porous concrete structures, it can store the rainwater, as a result, resulting in low resistance of plants to the dry season (Fig. 14a). When miscanthus is added to the concrete matrix, the pore structure is filled with miscanthus, excess rainwater can be effectively stored in micropores of miscanthus during the rainy season. The porous miscanthus is

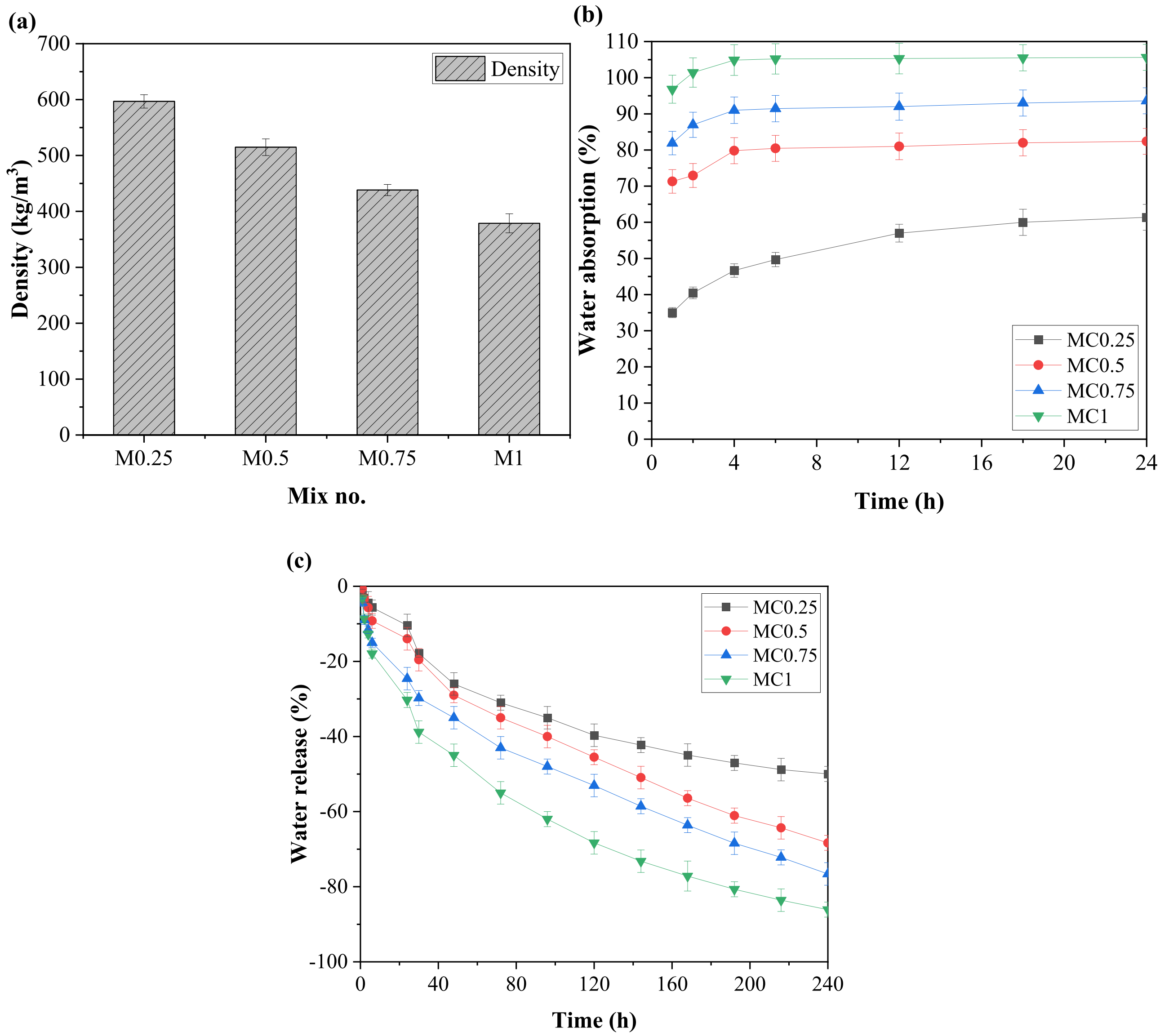

Fig. 15. (a) Density, (b) Water absorption and (c) Water release behaviour of miscanthus vegetal mortar.

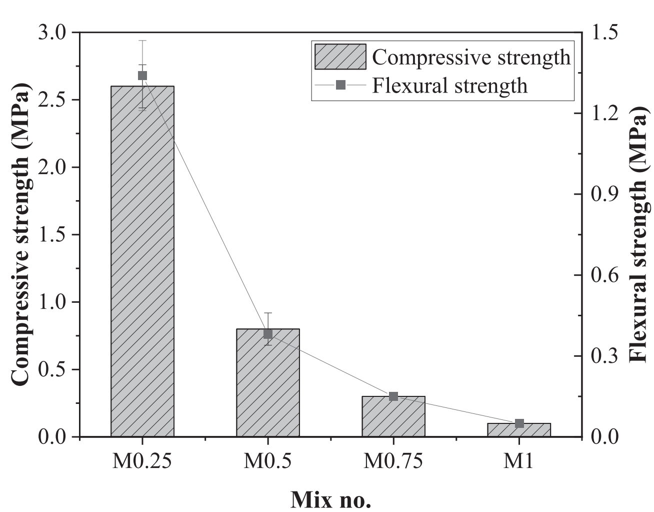

Fig. 16. Compressive and flexural strengths of miscanthus vegetal mortar.

like a reservoir or sponge, which can store rainwater and nutrients and then slowly release them for plant growth. Moreover, bio-based vegetal concrete can act as a water pump by absorbing water from the underlying soil layer using capillary action and supplying plant roots through evaporation action (Fig. 14b). Bio-based materials are abundant in micropores and have a potential for nutrient removal from rainwater and then serve as a valuable source of nutrients like N, P, and K, meanwhile, effectively mitigating the high alkalinity of cement-based materials for plant growth. Therefore, the application of bio-based materials not only solves the problem of poor water retention capacity of porous vegetal concrete but also helps the building industry achieve sustainable development goals.

3.2. Effects of cement-to-miscanthus ratio on bio-based miscanthus vegetal mortar

The findings in the first section show that the addition of miscanthus can significantly improve the plant cover percentage of vegetal concrete and reduce the negative influence of the internal pore structures on plant roots because of excellent water absorption and release behaviours. In

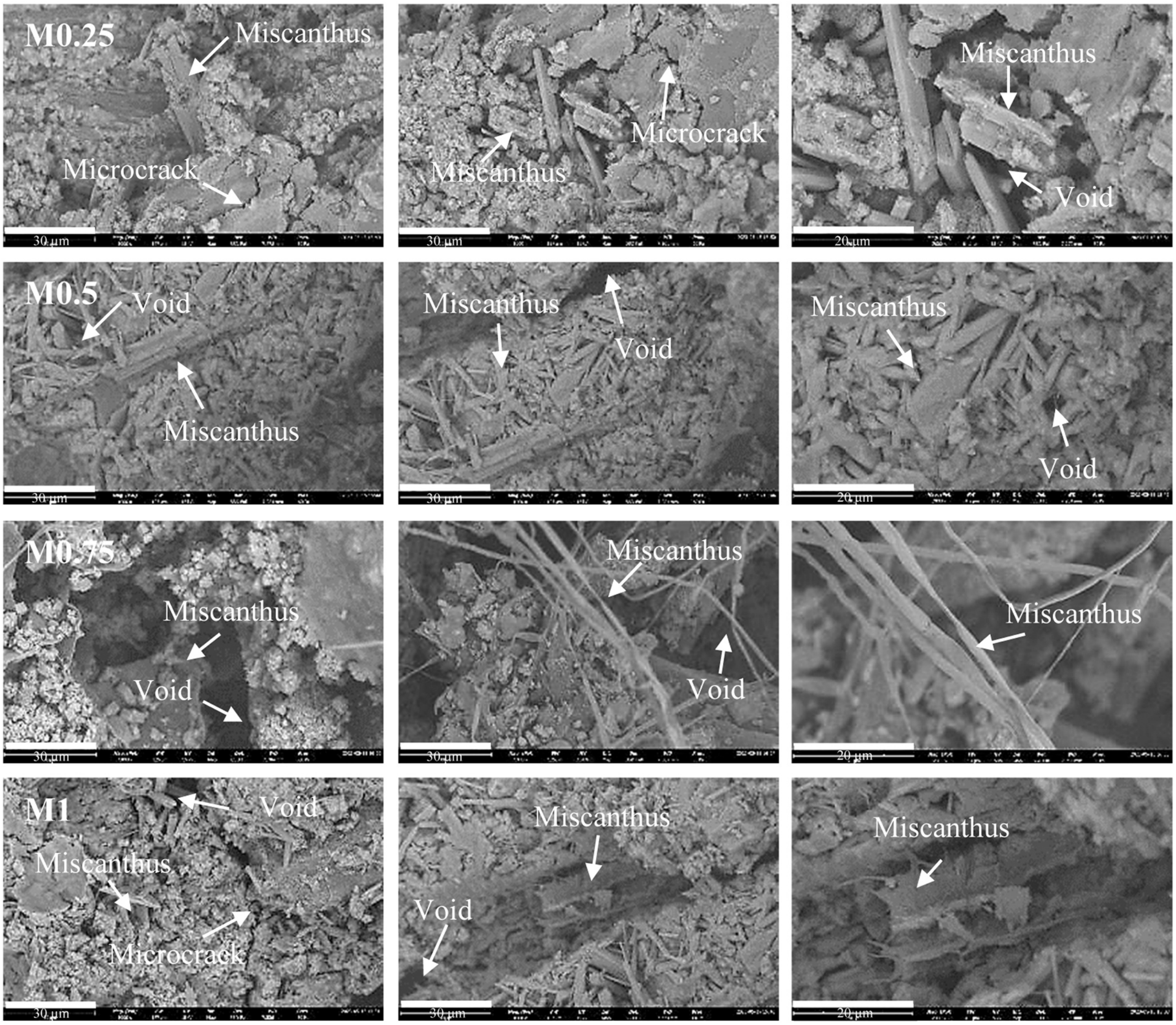

Fig. 17. Microstructures of miscanthus vegetal mortar.

the second section, the possibility of using miscanthus as bio-based vegetal mortar is investigated based on various cement-to-miscanthus ratios.

3.2.1. *Physical properties*

As shown in Fig. 15, the cement-to-miscanthus ratio has significant effects on the density and water absorption-release behaviour of vegetal mortar. The higher the miscanthus content in the mixture, the lower the density of the mortar and the higher the water absorption due to the porous structure and lightweight properties of miscanthus [27]. The density of miscanthus mortar ranges from 379 kg/m^3 to 597 kg/m^3, and they are all within the range of lightweight mortar. When the cement-to-miscanthus ratio increases from 1:0.25–1:1, the density of the miscanthus mortar decreases by 37%. Vegetal concrete is usually applied to green roofs, living walls, vertical gardens waterside areas, etc, thus, a lower density can reduce the self-weight of vegetal concrete and reduce the adverse effects of dead load on building structures.

The main disadvantage of traditional vegetal concrete is poor water absorption and retention capacities, which leads to serious plant degradation over time and shortens the lifespan of plants. As expected, the increase in miscanthus content significantly improves the water absorption of the miscanthus mortar, and more water can be released after saturation. The 24-hour water absorption of the miscanthus mortar M0.25, M0.5, M0.75 and M1 are 61%, 82%, 94% and 106%, respectively. Moreover, the 1-hour water absorption of the miscanthus mortars M0.25, M0.5, M0.75 and M1.0 accounts for 57%, 87%, 88% and 92% of its 24-hour water absorption, respectively. This phenomenon indicates that the miscanthus vegetal mortar has a quick water absorption capacity, which can store rainwater quickly during the rainy season, even if a short-time rainfall. At 240 h, M0.25, M0.5, M0.75 and M1 can release 50%, 68%, 77% and 86% of the absorbed water, respectively. Therefore, bio-based materials are very effective ways to enhance the water-retaining properties of vegetal concrete.

3.2.2. *Mechanical strengths*

The addition of bio-based materials generally leads to a decrease in mechanical strengths owing to the porous nature of bio-based materials and their weakly bonding interface with the mortar. In addition, bio-based materials can reduce the formation of cement hydration products and delay setting time due to the presence of polysaccharide components [40]. As shown in Fig. 16, the compressive strengths of miscanthus mortars M0.25, M0.5, M0.75 and M1 are 2.6 MPa, 0.8 MPa, 0.3 MPa and 0.1 MPa, respectively, and the corresponding flexural strengths are 1.34 MPa, 0.38 MPa, 0.15 MPa and 0.05 MPa. The increase in miscanthus content significantly reduces the mechanical strengths of the miscanthus mortar.

The microstructures of miscanthus vegetal mortar are presented in Fig. 17. The results show that the due to porous structure of miscanthus, the addition of miscanthus significantly increases the porosity of the mortar matrix. The more miscanthus in the mixture, the more voids can

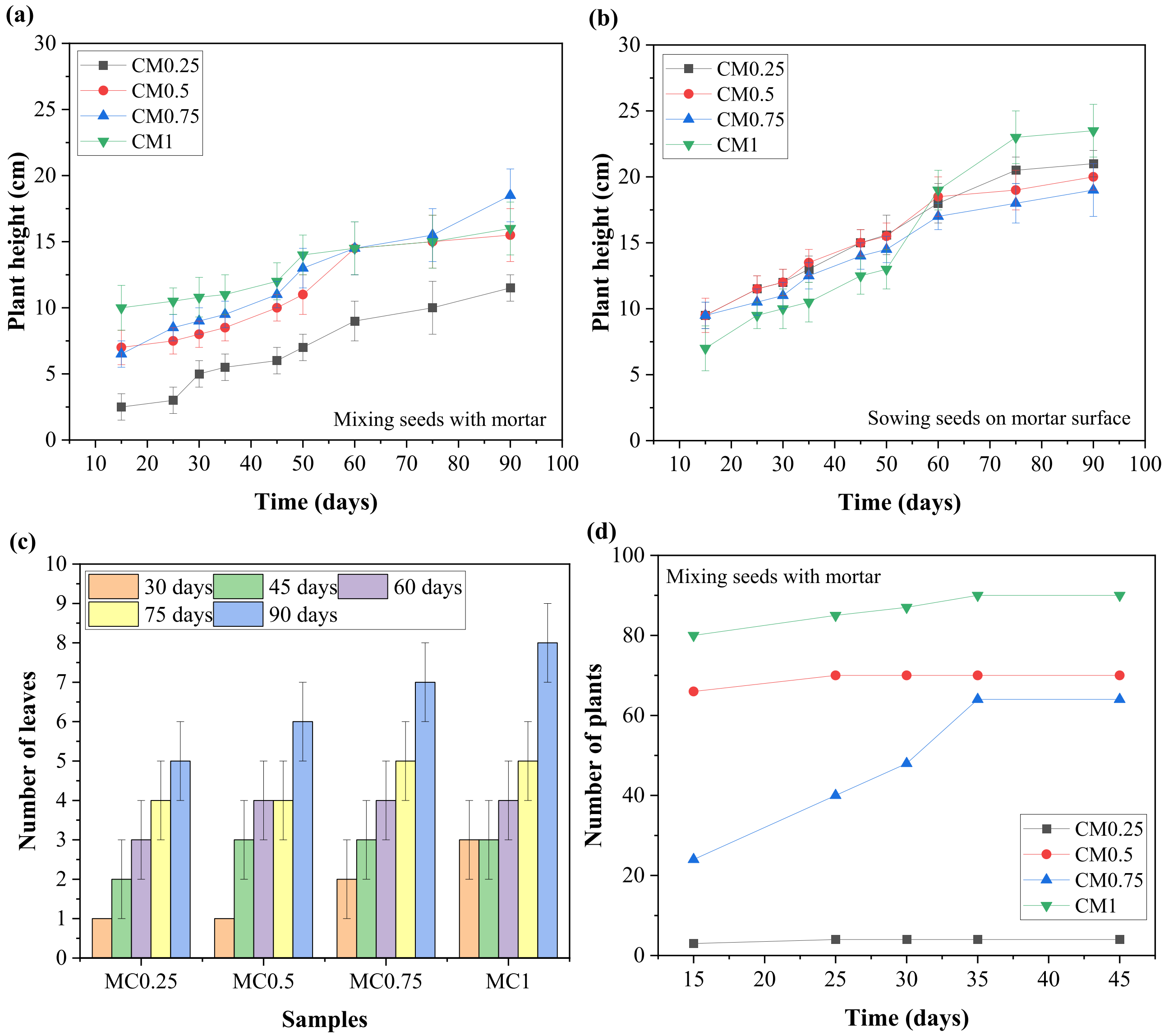

Fig. 18. Effects of (a) mixing seeds with mortar and (b) sowing seeds on mortar surface on plant height, (c) Number of leaves and (d) Number of plants when mixing seeds with mortar.

be observed in the microstructure of the mortar matrix. These microporous structures contribute to the better water absorption and release behaviour of the mortar, however, they are also responsible for the reduced mechanical strengths. Miscanthus is tightly embedded in the cement paste when the cement paste content is high, while with the increase of the miscanthus content, only less cement paste encloses miscanthus, which is the reason for the low mechanical strength of the mortar M1.

3.2.3. *Plant growth performance*

(1) Effects of planting methods on plant growth

As shown in Fig. 18, the miscanthus-to-cementratio has a significant effect on plant height, number of leaves and seed germination, particularly when mixing the seeds with the mortar matrix. When the miscanthus content in the mixture is increased, more seeds can germinate from the mortar matrix, and the height and leaves of the plants increase significantly. When mixing seeds with mortar, only 4 seeds germinate from the M0.25 surface, and 64–90 seeds germinate from other mortar surfaces (M0.5, M0.75 and M1). This is attributed to the higher strength of the mortar M0.25, and most of the seeds can not germinate normally after being embedded in the mortar matrix. Furthermore, the high alkalinity of the mortar adversely affects plant growth. The pH value of MC0.25 is 10.8, whereas MC1 has a pH value of 7.9, which is nearly identical to the pH value of soil of 7.8 (Fig. 7a). Therefore, low alkalinity of the mortar is conducive to the germination and growth of plants. However, when sowing seeds on a mortar surface, there is no discernible difference in plant height. Moreover, the plants on the M1 surface grow better than other plants after 60 days due to less competition for growth space.

The results also show that the planting methods have significant effects on plant growth, as shown in Fig. 19. The planting method by sowing seeds on the mortar surface will significantly increase plant height, compared to the method of mixing seeds with mortar. However, as the miscanthus content of the mixture increases, the negative effects of mixing seeds with mortar on the plant height gradually decrease. This may be due to miscanthus increasing the porosity of the mortar, making it a more suitable vegetative substrate for plant growth. Furthermore, the low mechanical strengths are beneficial to the root system development of plants when mixing seeds with the mortar matrix. As shown in Fig. 20, the increased mechanical strength significantly reduces the

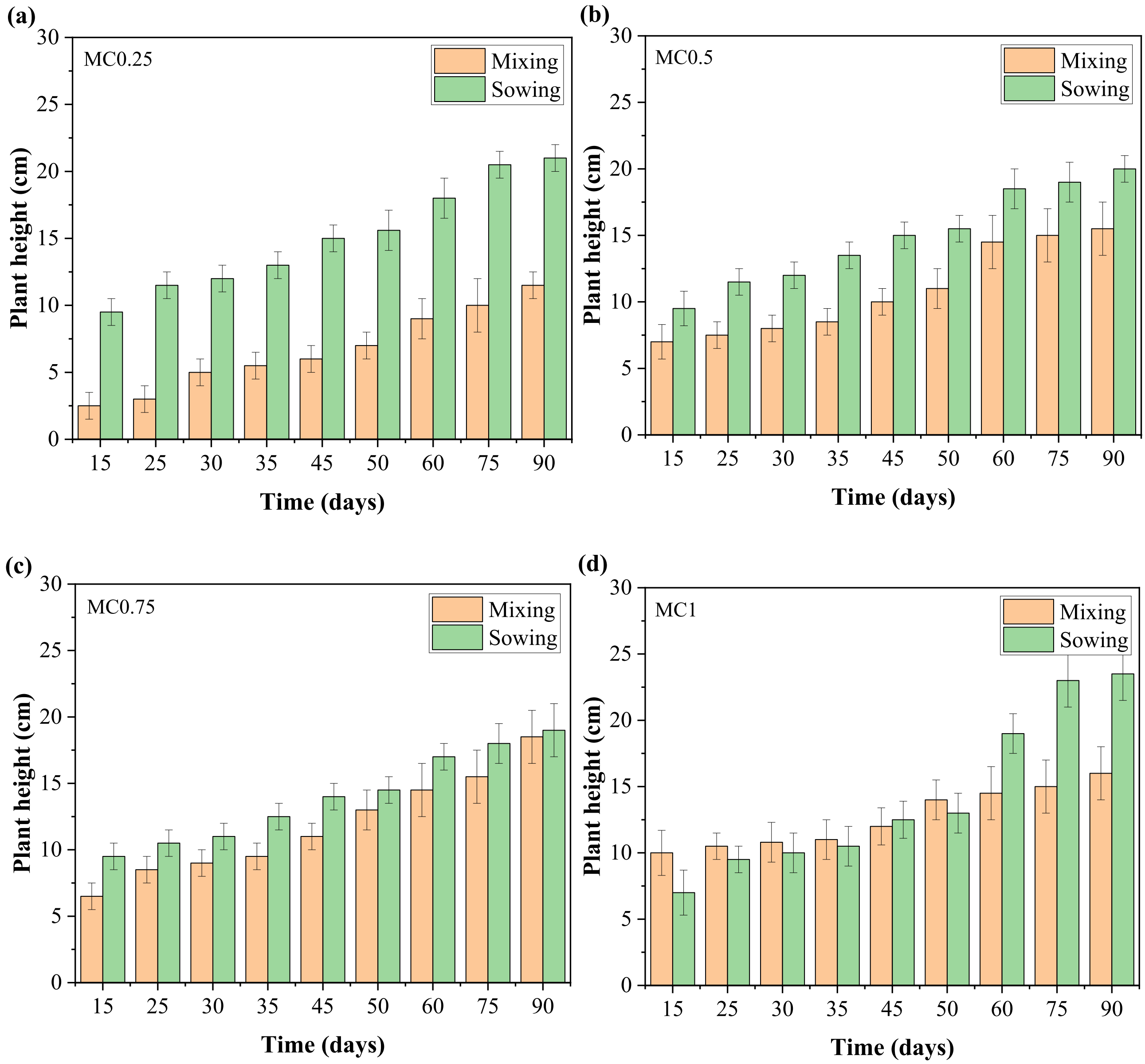

Fig. 19. Effects of planting methods on plant height.

number of plants when mixing seeds with mortar. When applying vegetal concrete for vegetation restoration of slopes, the mechanical strengths of vegetal mortar should be considered. Therefore, the miscanthus-to-cement ratio of 0.5–0.75 is recommended for bio-based vegetal mortar considering the mechanical strengths and plant growth adaptability.

(2) Root length and the number of roots

When sowing seeds on the mortar surface, the corresponding root length and the number of roots are shown in Fig. 21. The results show that the cement-to-miscanthus ratio has a significant effect on the number of roots. This may be due to the fact that although the mechanical strengths of M0.25 are higher than other miscanthus mortars, the root system can still grow laterally along the mortar surface when sowing seeds on the mortar surface. In addition, M1 has the most number of roots, which may be because the M1 matrix has more pore structure suitable for root growth. In addition, the individual grass growing well on the M1 surface due to the low plant cover percentage. The morphological results of the root system show that more taproots grow out with the increase of miscanthus content in the mixture, as shown in Fig. 22.

The distribution characteristics of plant roots on mortar surfaces are shown in Fig. 23. The results demonstrate that miscanthus-to-cement ratios have varying effects on the root system's interaction with the mortar matrix. When the ratio of miscanthus-to-cement is 0.25, the root system of plants can not penetrate into the mortar matrix due to the high strength of the mortar, while a miscanthus-to-cement ratio of 1 leads to easy root penetration and destruction of the mortar matrix. However, with miscanthus-to-cement ratios of 0.5 and 0.75, the root system of plants could successfully penetrate the mortar without compromising its integrity. Therefore, for the incorporation of miscanthus in bio-based vegetal concrete, it is recommended to use a miscanthus-to-cement ratio between 0.5 and 0.75. This range allows for a balance between root system penetration of plants and the performance fo concrete, ensuring a sustainable and robust vegetal concrete material.

(3) Plant growth and cover percentage

The plant growth observation results are shown in Fig. 24. The

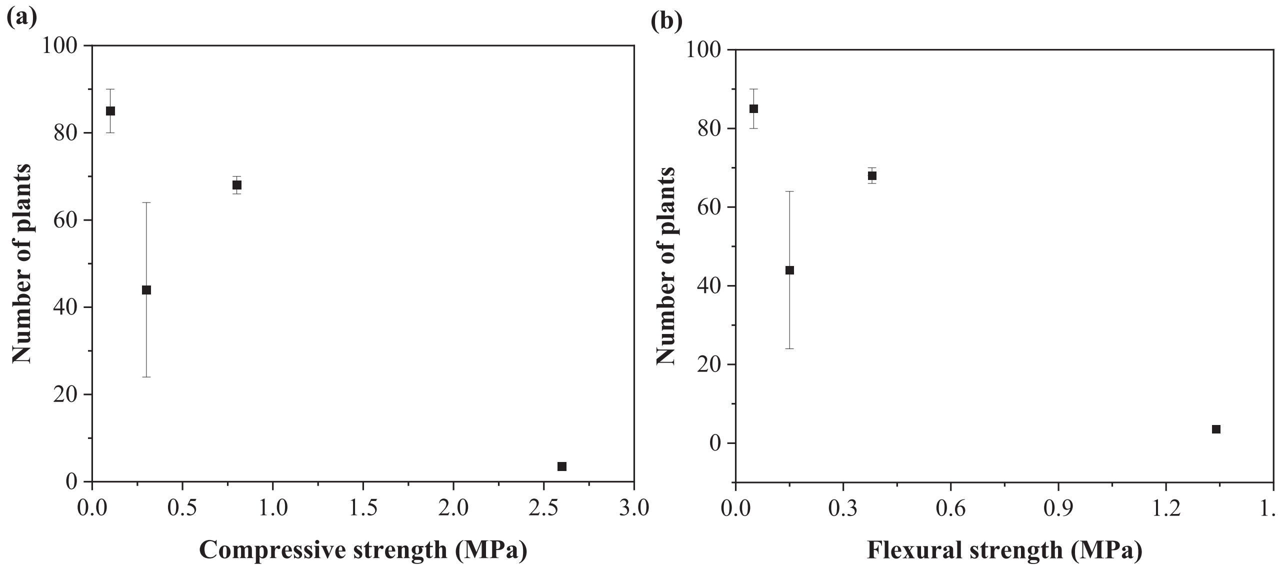

Fig. 20. Relationship between mechanical strengths and number of plants when mixing seeds with mortar.

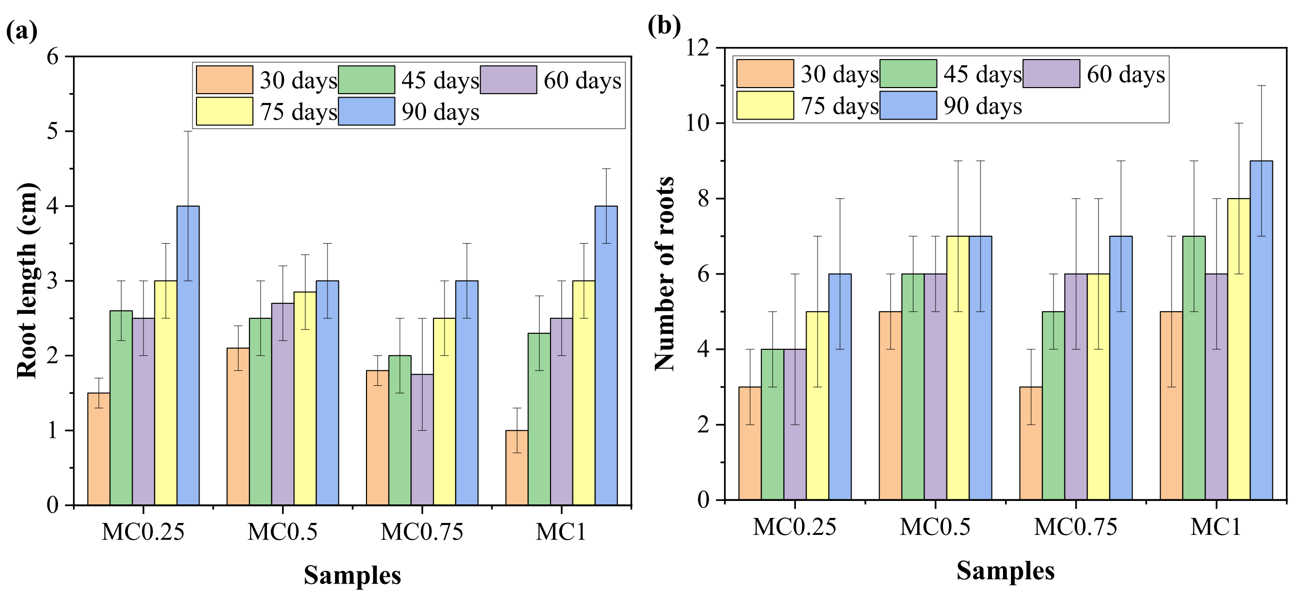

Fig. 21. Root length and its number when sowing seeds on mortar surface.

results show that the planting methods have a significant effect on plant growth and its cover percentage. When sowing seeds with mortar is used, as the miscanthus content increases, the plant grows well with a higher plant cover. The plant cover percentages of M0.25, M0.5, M0.75 and M1 are 7.3%, 33.4%, 34.5% and 52.1% on 90 days, respectively, as shown in Fig. 25. This may be attributed to the high cement-to-miscanthus ratio affecting seed germination due to the rapid setting time of cement. However, the increase of miscanthus content in the mixtures delays the hydration of the cement, allowing more seeds to germinate in the mortar matrix. The differences in plant growth on mortar M0.25, M0.5 and M0.75 surfaces are not obvious when sowing seeds on the mortar surface, and they have a plant cover percentage of 70.3–82.1%. However, M1 has a low plant cover percentage (56.3%), which may be due to the relatively high water content of M1 affecting the germination of seeds at the early growth stage. Moreover, the individual grass grows on the M1 surface is better than that of the other mortar surfaces (M0.25, M0.5 and M0.75). When applying bio-based vegetal concrete in actual engineering construction, nutrient supplementation for plant healthy growth should be considered because of the increased plant cover percentage.

4. Conclusions

To improve the water retention capacity and plant growth adaptability of porous vegetal concrete by filling the pore structure using miscanthus, the effects of varying miscanthus content (0%, 5% and 10% by volume) on the physical properties, mechanical strengths and plant growth performance indicators of porous vegetal concrete are investigated in this study. Moreover, the influences of different cement-to-miscanthus ratios (1:0.25, 1:0.5, 1:0.75, 1:1) and planting methods (mixing seeds with mortar matrix vs sowing seeds on mortar surface) on the performance of miscanthus mortar are analysed. An optimized cement-to-miscanthus ratio and planting method are obtained for sustainable bio-based vegetal concrete to foster lush plant growth. The main conclusions obtained from the present study are as follows:

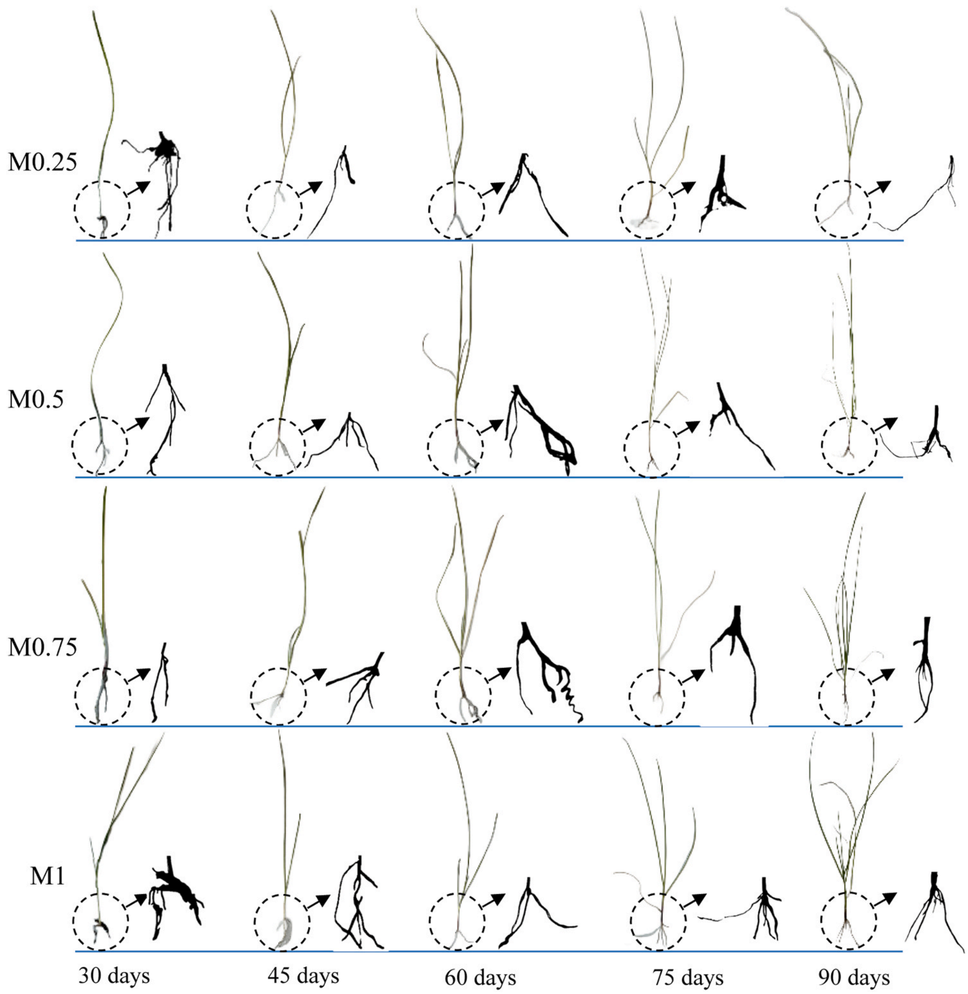

Fig. 22. Changes in plant root morphology over time when sowing seeds on mortar surface.

(1) The addition of miscanthus significantly improves the water absorption-release behaviour and reduces the density and alkalinity of porous vegetal concrete, owing to its high water absorption. The 24-hour water absorption of vegetal concretes M5 and M10 are 15% and 24%, respectively, which increases by 119% and 246%, compared to the conventional porous concrete, thereby rapidly reaching a saturation status when soaked in water. However, the negative impacts of miscanthus on the mechanical strengths of bio-based vegetal concrete need to be considered in actual ecological recovery practices, and M5 is recommended for porous vegetal concrete.

(2) The addition of miscanthus at a 10% volume increases the plant cover percentage of vegetal concrete by 36.5% and slows down early plant degradation. A significant vegetative degradation is observed from 20 to 30 days for concretes Ref., however, concrete M10 does not exhibit a significant vegetative degradation phenomenon thanks to the enhanced water retention behaviour and pore-filling effects of miscanthus. However, the addition of miscanthus has little effect on the plant height, the number of leaves and root length because of more competition for growth space and nutrients caused by high plant coverage.

(3) Cement-to-miscanthus ratio has significant influences on the density and water absorption-release behaviour of miscanthus mortar, i.e. the high cement-to-miscanthus ratio in the mixture leads to a decrease in density and an increase in water absorption. The density of miscanthus mortar ranges from 379 kg/m^3 to 597 kg/m^3, and they are all within the range of lightweight mortar, and corresponding 24-hour water absorption varies from 106% to 61%. More moisture can be released from miscanthus mortar after saturation, and the addition of miscanthus can mitigate the high alkalinity of concrete, both of which enhance plant growth. The miscanthus mortar can release 50–86% absorbed water after saturation at 240 h.

(4) Planting methods have significant effects on plant growth performance and plant cover percentage. Sowing seeds on the mortar surface is better than mixing seeds with mortar matrix because it makes plants much taller and covers more ground. The cement-to-miscanthus ratio of 0.5–0.75 is recommended for bio-based vegetal mortar to foster lush plant growth considering the mechanical strengths and plant growth adaptability.

CRediT authorship contribution statement

H.J.H. Brouwers: Writing – review & editing, Resources, Conceptualization, Supervision. **Xiaoqing Chen:** Supervision, Project administration, Funding acquisition. **Fan Wu:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

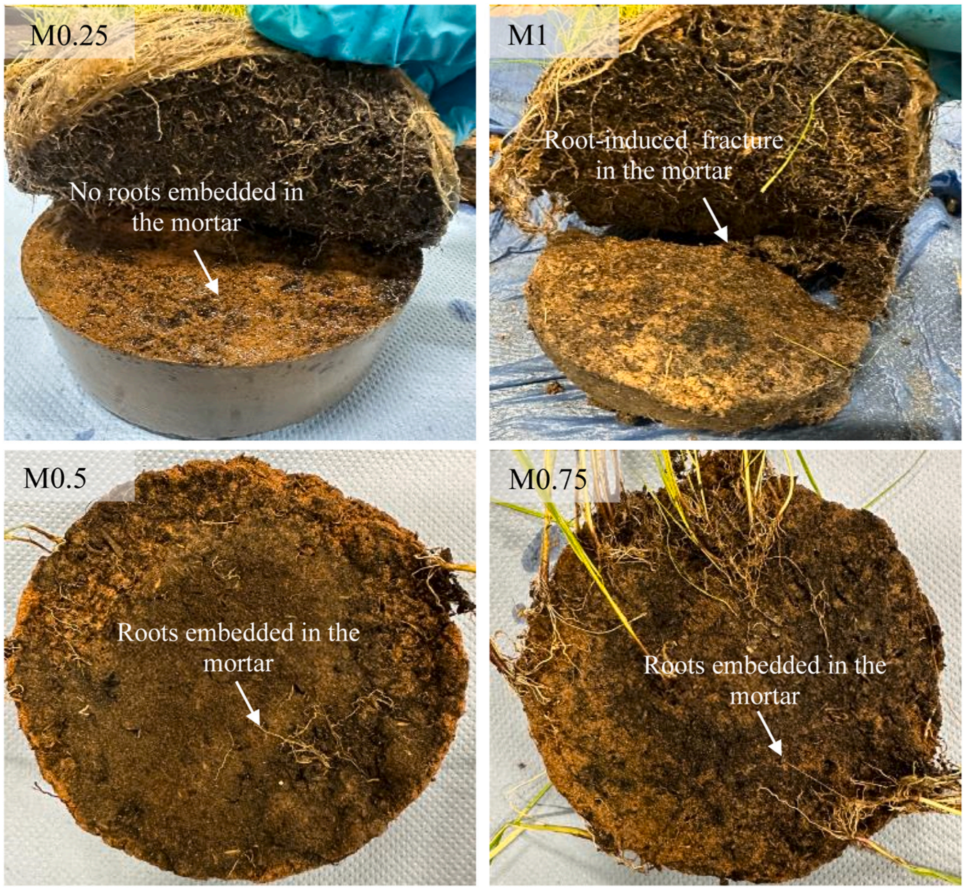

Fig. 23. Distribution characteristics of plant roots on mortar surface.

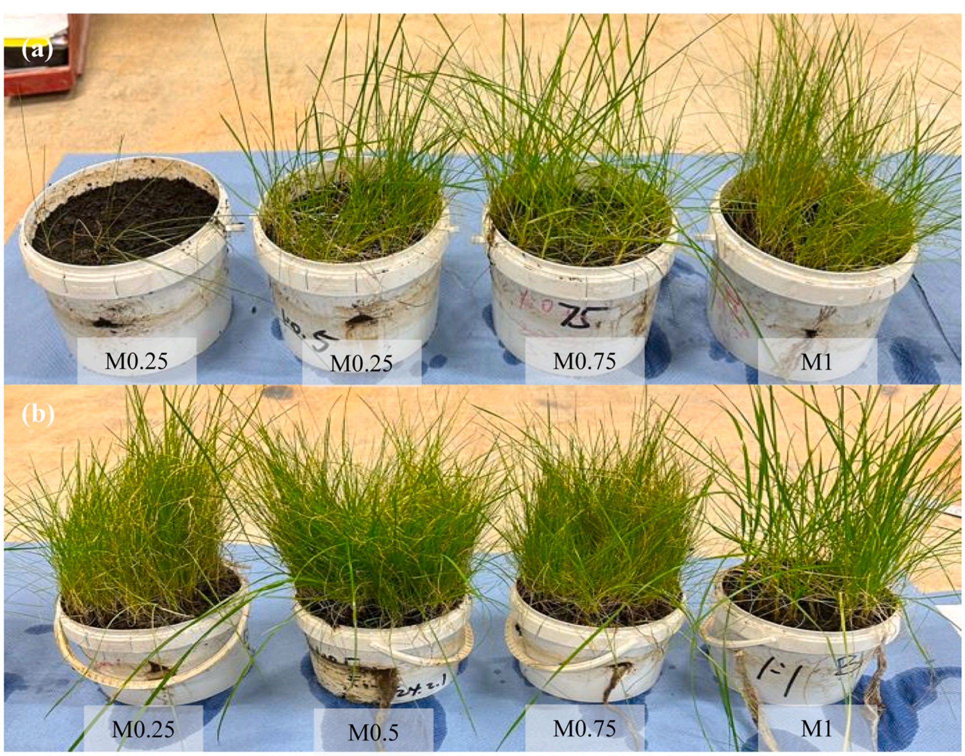

Fig. 24. Plant growth observation when (a) mixing seeds with mortar and (b) sowing seeds on mortar surface.

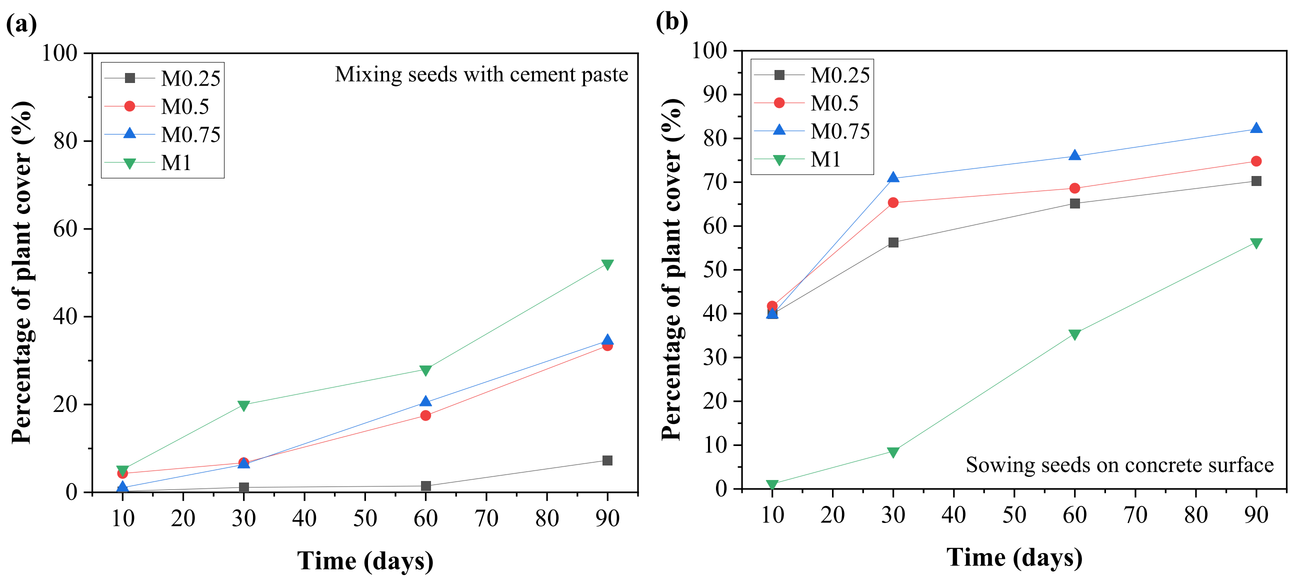

Fig. 25. Effects of planting methods on plant cover percentage (a) mixing seeds with mortar and (b) sowing seeds on mortar surface.

Data availability

Data will be made available on request.

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