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Improvement of Physical and Mechanical Property as well as Planting Property of Planting Concrete by Multi-Functional Synergy of Coal Gangue Characteristics

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Abstract

The environmentally friendly coal gangue planting concrete (CGPC) was prepared by leveraging the porous structure, nutrient reserves, potential reactivity, and solid waste characteristics of coal gangue. This provides an effective approach to comprehensively enhance the resource utilization of coal gangue solid waste and promotes ecological environmental governance. CGPC was prepared using activated coal gangue powder (ACGP) as a supplementary cementitious material and coal gangue as the aggregate. The influence of ACGP on the physical and mechanical property of CGPC was studied. Meanwhile, the influence of coal gangue powder as part of the guest soil on the planting property of CGPC was also studied. The results showed that low-content ACGP can fill the micropores in CGPC by micro-aggregate and pozzolanic effects, optimizing the structure of the interfacial transition zone between aggregate and paste, and significantly improves its mechanical property and frost resistance. The secondary hydration reaction of ACGP consumes a considerable amount of $Ca(OH)_2$, significantly reducing the alkalinity of CGPC and forming a more suitable environment for plant growth. Incorporation of 20% to 40% coal gangue powder into the guest soil effectively improves the growth status of the three plant species, especially Elymus dahuricus exhibits the most significant improvement.

Keywords
Planting concrete
Coal gangue powder
Physical and mechanical properties
Planting properties

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1. Introduction

With the development of global industry, urban hardening has resulted in significant ecological imbalances, manifesting as issues such as insufficient urban green space, blocked rainwater infiltration, and fragmentation of biological habitats (Huang et al., 2024; Jian et al., 2021). The application of planting concrete offers a new approach to solving this problem. As an emerging ecological material, planting concrete bonds coarse aggregates and cementitious materials into an integrated structure, forming a connected microporous structure. While maintaining sufficient strength, it can also provide suitable conditions for vegetation growth and rainwater internal circulation (Jin et al., 2024; Wu et al., 2024). Now, planting concrete is widely used in slope protection, riverbank restoration, urban green spaces, and ecological restoration. It can effectively reduce exposed slopes and soil erosion, improve the water environment, and alleviate the heat island effect (Gong et al., 2025).

At present, the main materials of planting concrete are mainly natural aggregates and ordinary Portland cement. Excessive mining of natural aggregates tends to cause ecological damage, and the cement production leads to high carbon emissions and large amounts of energy consumption. This will not meet the requirements of low-carbon and environmental protection. In addition, ordinary Portland cement shows relatively high alkalinity during hydration, and the dense structure of natural aggregates results in poor water retention. This is unfavorable to plant survival (Huang et al., 2025; Li et al., 2019; Li & Wang, 2019). Therefore, seeking new materials for planting concrete has become a top priority (Wu et al., 2023a, 2023b).

Nowadays, coal remains the main energy source in China and plays a key role in energy supply, industrial development and other fields. As a by-product of the coal industry, coal gangue has witnessed a steady increase in annual output (Gao et al., 2024, 2025; Wu et al., 2023a, 2023b). Its large-scale accumulation has caused problems such as land resource waste, vegetation destruction, and water pollution(Wang et al., 2025a, 2025b; Zheng et al., 2024). Coal gangue can be partially recycled for applications such as mine backfilling, road bases and beddings, but its overall utilization ratio remains relatively low (Li et al., 2024; Wu et al., 2022a, 2022b). Coal gangue presents a mineral composition similar to that of natural aggregates and possesses a certain strength basis. Coal

Table 1
Mix proportion design of CGPC.

Group	ACGP (kg)	Cement (kg)	Aggregate (kg)	Water (kg)	PVAP (kg)
AC0	0	280	1400	78	1.68 (0.6%)
AC10	28 (10%)	252	1400	78	1.68 (0.6%)
AC20	56 (20%)	224	1400	78	1.68 (0.6%)
AC30	84 (30%)	196	1400	78	1.68 (0.6%)
AC40	112 (40%)	168	1400	78	1.68 (0.6%)

Note: AC10 represents the mass percentage of ACGP in total cementitious materials.

gangue is used as aggregate in concrete is an efficient approach for its resource utilization (Li et al., 2024; Wu et al., 2023a, 2023b; Zhao et al., 2023). However, the layered structure and high water absorption of coal gangue can also easily lead to poor mechanical property and durability of concrete, which make it difficult to largely replace natural aggregates in concrete (Qiu et al., 2020; Wu et al., 2022b). Wang et al. (2025a, 2025b) believed that the water absorption and expansion of coal gangue weakened the bonding property of concrete, while coal gangue with high kaolinite and quartz showed a dense surface and bonded more firmly with concrete. Zhu et al. (2024) suggested that coal gangue could be regarded as a damage factor and only had the feasibility for use at low dosages to replace natural aggregates in concrete. Therefore, the use of coal gangue aggregates in ordinary concrete has certain limitations. As a structural material with low performance requirements, planting concrete, when combined with the characteristics of coal gangue aggregates, exhibits good compatibility with the two.

During the crushing process of coal gangue, 20% coal gangue powder (CGP) is formed, and its low pozzolanic activity limits its effective utilization (Xu et al., 2025). Studies have shown that when the coal gangue powder is activated by chemical or physical methods, it can be used as a supplementary cementitious material (Arulkumar et al., 2025; Su et al., 2022; Yin et al., 2025; Zhu et al., 2024). However, chemical activation is challenging to promote and apply on a large scale due to its high energy consumption and significant environmental pollution. In contrast, physical ball milling has the advantages of low energy consumption and no pollution emissions. It breaks down the mineral crystal structure of coal gangue powder through impact and friction, creating lattice defects or amorphous phases, thereby enhancing its cementitious activity (Chen et al., 2023; Yuan et al., 2024; Zhou et al., 2025). Chen et al. (2025) suggested that mechanical activation improved the reactivity of coal gangue powder by inducing structural disorder and increasing surface area, which promotes the hydration process.

In addition, coal gangue powder exhibits a certain particle size gradient. By regulating soil texture, it can significantly enhance soil aeration as well as water-holding and nutrient-retention capacity (He et al., 2016). Coal gangue is rich in mineral elements such as P, K, Ca, Mg and organic matter. It can effectively enhance soil fertility and promote the healthy circulation of soil ecosystem by slowly releasing nutrients and regulating soil pH (Han et al., 2021; Zheng et al., 2022). These characteristics endow coal gangue powder with the potential as a planting substrate.

Therefore, in the study, coal gangue was used as the aggregate, physically activated coal gangue powder (ACGP) was used as the supplementary cementitious material, and coal gangue powder (CGP) was incorporated to replace guest soil for preparing the planting substrate. The effects of ACGP on the mechanical properties, permeability, water retention, frost resistance, porosity and pore solution pH of Coal gangue planting concrete (CGPC) were studied, while the mechanism of ACGP on the cement hydration and interface of CGPC was revealed. Meanwhile, the effects of CGP on the growth of three plant species were explored. This study aimed to realize comprehensive resource utilization of coal gangue from aggregate to powder, providing theoretical support for the full-scale utilization of coal gangue.

2. Materials and test methods

2.1 Raw materials

The raw materials for the test include ordinary Portland cement, coal gangue aggregates, coal gangue powder (CGP), activated coal gangue powder (ACGP), polyvinyl alcohol powder (PVAP), water reducing agent, etc. Coal gangue was crushed and sieved to obtain coal gangue aggregates with a particle size of 10-20 mm. CGP with a particle size smaller than 4.75 mm was added to guest soil for preparing planting substrate. Particles smaller than 2 mm accounted for 75% in CGP. ACGP was obtained by mechanical activation of CGP via ball milling. The particle size of ACGP was mainly distributed between 5 μm and 20 μm, and the activity index is 67.7%. The specific parameters, preparation processes and characterization parameters of the above-mentioned materials are shown in the the Supplementary Information (SI) of the Supplementary Material.

2.2 Preparation and characterization of CGPC

To ensure that planting concrete (PC) has high porosity and low alkalinity while meeting certain strength requirements, coal gangue aggregates with a particle size of 10 to 20 mm and ACGP were used to replace OPC in this experiment. The water-binder ratio was fixed at 0.28, and the water-reducing agent was fixed at 1%. The specific mix design is shown in **Table 1**.

The specific preparation process and performance test of CGPC are provided by Supplementary Information (SI) of the Supplementary Material. Performance tests include compressive strength, split tensile strength, water permeability, water retention, porosity, pore pH and frost resistance. The phase, hydration products and interfaces of CGPC were characterized and analyzed by X-ray diffractometer (Smart Lab) and scanning electron microscope (CLARA). The leaching content of heavy metals in CGPC (ACGP: 20%) was tested by using inductively coupled plasma optical emission spectrometer (ICP-OES).

2.3 Plant selection and testing

Based on the factors such as climatic conditions, temperature, humidity, and plant resistance in the northwest region, Elymus dahuricus, Festuca elata, and Alfalfa were selected for planting experiments. The planting substrates mainly included guest soil and mixture of guest soil with CGP. The basic physical and chemical properties of guest soil are shown in **Table S4**. 600 plant seeds were evenly scattered on the CGPC specimens' surface of 300 × 200 × 100 mm, and then covered with a 2 cm thick substrate. Regular watering and maintenance were performed to monitor plant growth conditions at each stage. Planting property was evaluated based on plant coverage, plant height and root length.

3. Results and discussion

3.1 Effect of ACGP on mechanical property of CGPC

The effect of ACGP on mechanical properties of planting concrete is shown in **Fig. 1**. When the dosage of ACGP increased from 0 to 40%, both the 7-day and 28-day compressive strengths and splitting tensile strengths of CGPC first increased slowly and then decreased significantly. At an ACGP dosage of 20%, the 7-day and 28-day compressive strengths

and splitting tensile strengths of CGPC all reached the maximum values, The 7-day and 28-day compressive strengths were 7.5 MPa and 9.5 MPa, while the 7-day and 28-day splitting tensile strengths were 0.9 MPa and 1.3 MPa, respectively. Compared with CGPC without ACGP, its 28-day compressive strength and splitting tensile strength were increased by 8.0% and 8.3%, respectively.

After ball milling treatment, the particle size of ACGP was significantly refined, with its distribution concentrated between 5 and 15 μm. Meanwhile, some stable crystal structures of SiO_2 and Al_2O_3 were disrupted and transformed into reactive amorphous SiO_2 and Al_2O_3, thereby endowing ACGP with pozzolanic activity (Chen et al., 2025; Zhou et al., 2025). Within the low dosage range, $Ca(OH)_2$ generated by cement hydration can fully activate the amorphous silica-alumina components in ACGP, promoting their participation in the hydration reaction and the formation of cementitious hydration products (such as C-S-H gel). Additionally, the fine particles of ACGP can fill the tiny pores within the CGPC paste and in the transition zone between aggregates and paste, significantly improving compactness and reducing porosity, thus enhancing mechanical properties (Tong et al., 2023). With the increase of ACGP dosage, the efficiency of its secondary hydration reaction and filling effect fails to compensate for the performance loss caused by the reduction of cement content, resulting in the decline of mechanical properties of CGPC (Su et al., 2022). The influence of ACGP on the porosity of CGPC can be found in Section 3.3, which is also an important cause of the changes in the mechanical property of CGPC.

3.2 Effects of ACGP on water permeability and water retention of CGPC

The effect of ACGP on water permeability and water retention of CGPC is shown in **Fig. 2**. As observed in **Fig. 2(a)**, the permeability coefficient of CGPC decreased as the ACGP content increased, ranging from 10.29 mm/s to 9.78 mm/s. All values remained higher than the requirement for K8 grade (≥ 8 mm/s) specified in the standard, enabling effective resistance to infiltration pressure from stormwater runoff. As shown in **Fig. 2(b)**, with the increase of ACGP dosage, the water retention capacity improved steadily, with its 7-day water retention rate increasing from 11% to 34%.

The water permeability of CGPC is influenced by its connected porosity. As noted in Section 3.3, the connected porosity of CGPC decreases with increasing ACGP content, which corresponds to the trend in permeability coefficient. Due to its large specific surface area and porous nature, ACGP exhibits high water absorption capacity. ACGP will absorb part of the mixing water, resulting in a reduction in the effective free water content in the system and a decrease of water-binder ratio of paste. The viscosity of the paste increases with the increase in ACGP content, leading to a significant decline in paste fluidity. This high-viscosity paste tends to form a thicker microporous coating layer on the surface of aggregate particles, which fills some of the connected pore channels between aggregates. This causes a decrease in connected porosity and leads to a reduction in the permeability (Zhang et al., 2024). Meanwhile, the high-water absorption capacity of ACGP and the microporous coating on the surface of the aggregate endow CGPC with remarkable water absorption property. So, the increase in ACGP has led to a decrease in the permeability of CGPC while an increase in its water retention ratio. CGPC with a 20% ACGP not only ensures excellent water and air permeability but also maintains a certain water retention capacity. Meanwhile, it can meet the requirements of different growth characteristics of plants, achieving a

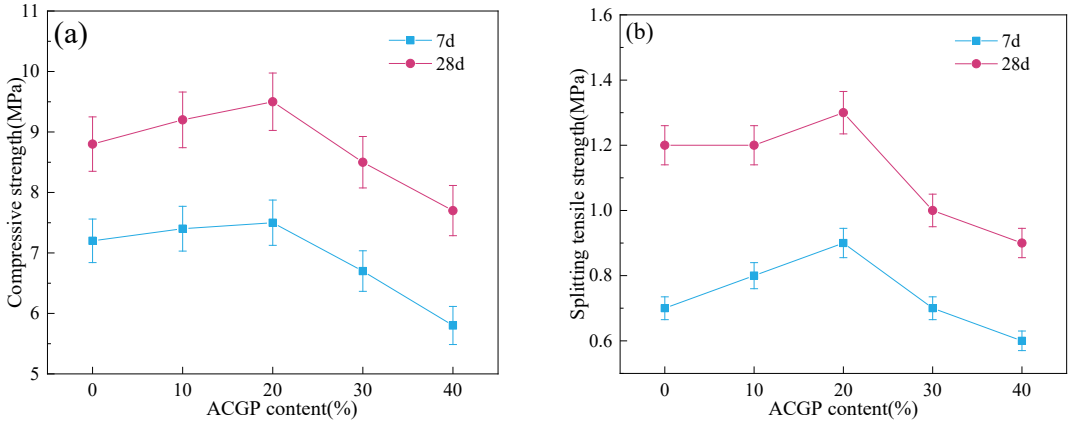


Fig. 1
Effect of ACGP on the compressive strength and splitting tensile strength of CGPC.

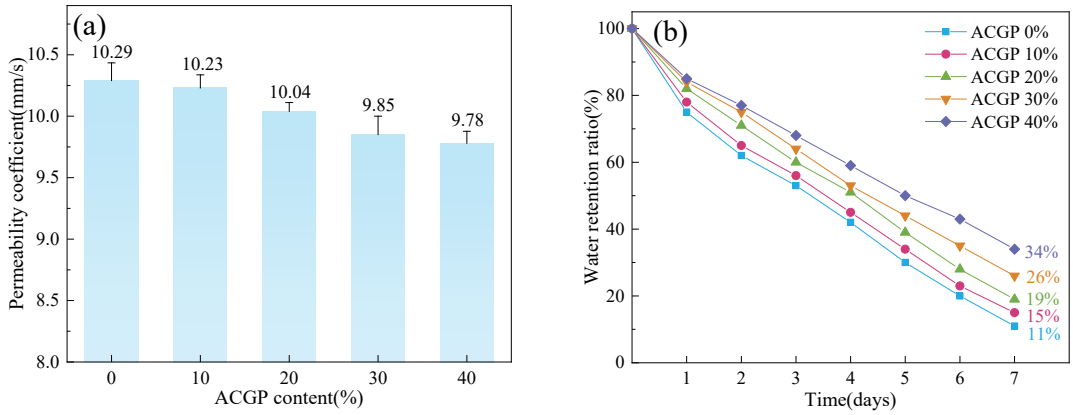


Fig. 2
Effect of ACGP on water permeability and water retention of CGPC.
(a) Permeability coefficient; (b) Water retention ratio.

coordinated balance between water permeability and water retention.

3.3 Effect of ACGP on porosity of CGPC

The effect of ACGP on total porosity and continuous porosity of CGPC is shown in **Fig. 3**. It can be seen that as ACGP content of increased, the total porosity of the CGPC first decreased slowly and then increased rapidly, ranging from 33.8% to 35.6%. In contrast, the connected porosity decreased with increasing ACGP content, ranging from 27.9% to 25.2%. Across all ACGP dosages tested, the total porosity of CGPC was 22.6% to 41.3% higher than the connected porosity, indicating that a greater number of unconnected pores exist, which have an adverse impact on the water permeability of CGPC.

When the ACGP content was less than 20%, the synergistic effect of generated cementitious substances and fine particles effectively filled some micropores inside CGPC, resulting in a decrease in both total porosity and connected porosity. However, when the ACGP content is excessively high, its high fineness leads to an increase in mixture viscosity, causing CGPC to form a large number of micropores during the molding process and resulting in a significant rise in its total porosity. Meanwhile, the uneven distribution of the paste also causes a decrease in connected porosity.

3.4 Effect of ACGP on frost resistance of CGPC

Coal gangue has a high-water absorption rate and the high porosity of CGPC makes it vulnerable to freeze-thaw damage caused by water flow. Therefore, frost resistance is crucial for the durability of CGPC. The influence of ACGP content on frost resistance of CGPC is shown in **Fig. 4**. As observed in the figure, as ACGP content increased, the mass loss rate and strength loss rate of CGPC first decreased slowly and then increased significantly. Compared with the CGPC without ACGP, the CGPC with ACGP content of 10% and 20% had better frost resistance, whereas those with 30% and 40% ACGP showed poorer performance. At an ACGP content of 20%, the frost resistance of the CGPC was the best. Compared with the CGPC without ACGP, its mass loss rate and strength loss rate decreased by 7.8% and 9.7% respectively. When the ACGP content was 40% (with all aggregates being coal gangue), the mass loss rate and strength loss rate of CGPC after 30 freeze-thaw cycles were 4.12% and 15.35% respectively, representing increases of 25.2% and 31.5% compared with the ACGP-free group. Nevertheless, it still meets the requirements ((a mass loss rate of less than 5% and a strength loss rate of less than 20% after 25 freeze-thaw cycles) of the Chinese standard JC/T 2557-2020 "Green-growing concrete".

A low dosage of ACGP facilitates the enhancement of frost resistance, primarily because the micro-aggregate effect and gels generated by the pozzolanic reaction can fill micropores within the CGPC paste. This reduces capillary water migration and alleviates frost heave-induced damage (Lu et al., 2025). Meanwhile, the interface transition zone (ITZ) between aggregates and paste undergoes particle filling and gelation, minimizing microcracks and enhancing the bonding strength between aggregates and paste (Guo et al., 2025). Additionally, K^+ and Na^+ ions leached from ACGP can lower the freezing point of the pore solution by 1 to 2 °C, slowing its freezing ratio.

At excessively high ACGP dosages, the formation of early hydration products is insufficient, leading to a loose structure and increased porosity in the CGPC paste. Unhydrated coal gangue particles, due to the high organic carbon content, are adsorbed onto the surface of hydration products, forming a water-absorbing and water-retaining network. This increases capillary porosity and accelerates water penetration. During freeze-thaw cycles, greater frost heave stress from ice crystals is generated, exacerbating freeze-thaw damage.

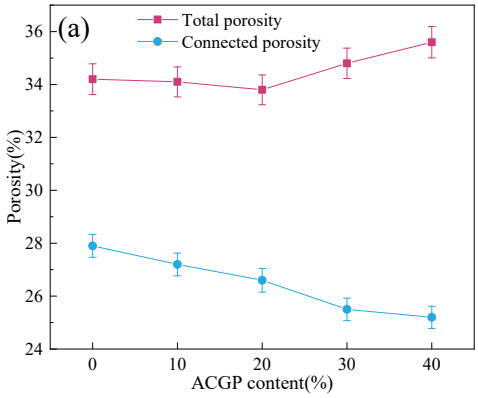


Fig. 3
Effect of ACGP on total porosity and connected porosity of CGPC.

3.5 Effect of ACGP on microstructure of CGPC

3.5.1 XRD analysis of hydration products of CGPC

XRD patterns of CGPC paste after 28 days of hydration at different ACGP contents are shown in **Fig. 5**. It can be seen that the phase composition mainly consisted of portlandite ($Ca(OH)_2$), a small amount of ettringite (AFt), quartz, and unhydrated C_2S and C_3S. As ACGP content increased, the diffraction peak intensity of calcium hydroxide ($Ca(OH)_2$) gradually decreased. This is because when ACGP replaces part of the OPC, the content of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) in the cement clinker decreases, leading to reduced $Ca(OH)_2$ formation. Furthermore, active silica-alumina components in coal gangue undergo a secondary hydration reaction with $Ca(OH)_2$ from cement hydration, consuming $Ca(OH)_2$ and generating calcium silicate hydrate (C-S-H) and calcium aluminate

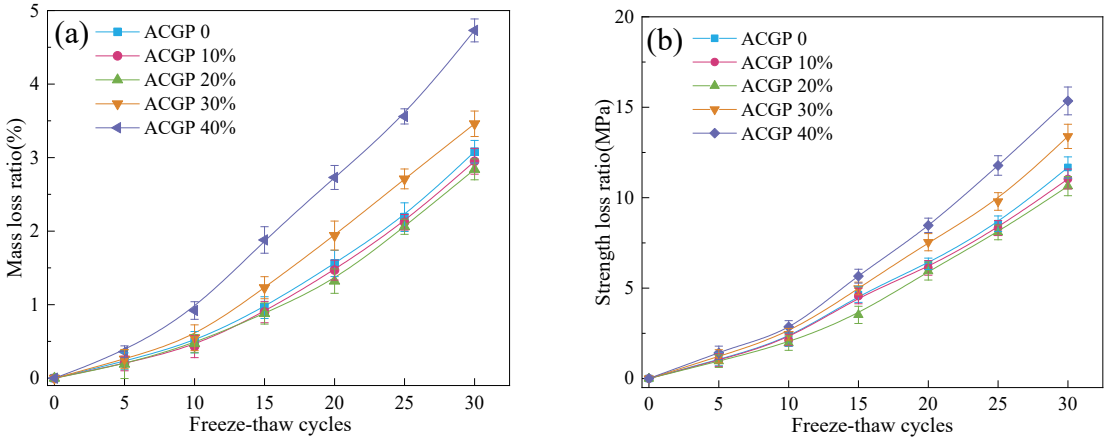


Fig. 4
Effect of ACGP on frost resistance of CGPC.

hydrate (C-A-H) gels (Yin et al., 2025). The diffraction peak intensity of AFt also decreased as ACGP content increased. This is primarily due to reduced cement usage and lower alkalinity of the system, which increased the instability of AFt and may cause partial decomposition of AFt. With increasing ACGP content, more quartz was introduced, resulting in an increase in the diffraction peak intensity of quartz.

3.5.2 SEM analysis of CGPC

Microscopic morphology of CGPC after 28 days of hydration with different ACGP contents are shown in **Fig. 6**. It can be observed that numerous needle-like AFt crystals formed on the paste surface, interweaving with hydrated gels to form a network structure. As shown in in **Figs. 6(a)** to **6(c)**, the ITZ between the paste and aggregate gradually densifies at low ACGP dosages (10% and 20%) due to filling by AFt and C-S-H gel materials. At 20% ACGP content, the filling and densification effects on the CGPC paste surface and ITZ were optimal. EDS line scan results for CGPC without ACGP addition are shown in **Fig. 6(a_3)**. In the 0-12.5 μm region, silicon and aluminum contents were relatively high, which were the main components of coal gangue aggregates, while in the 15.2-21 μm region, calcium predominated, characteristic of cement hydration product distribution. The range of 12.5-15.2 μm was the ITZ. For CGPC with 20% ACGP (**Fig. 6(c_3)**), the ITZ was within the range of 6.8-9.2 μm. Compared with **Fig. 6(a_3)**, after the addition of ACGP, the ITZ was narrowed, with the cracks filled by hydration products and improved interface compactness. The microscopic structural characteristics were consistent with the changes in mechanical property (Li et al., 2023; Su et al., 2022). Comparison of EDS line scan results reveals that ACGP addition significantly increased silicon and aluminum contents in the cement paste. This is primarily attributed to the active silica and alumina components introduced by ACGP, which participated in secondary hydration reactions to form C-S-H gel.

3.6 Planting property of CGPC

3.6.1 Effect of ACGP on alkalinity of pore solution of CGPC

The alkaline environment in the pores of CGPC significantly impacts the growth of plant roots and stems. It determines whether plants can take root and grow normally in CGPC and also affects the balance of the internal micro-ecosystem of CGPC. Therefore, pH value has become a key indicator for evaluating the planting performance of CGPC (Yang et al., 2025). The influence of ACGP content on the alkalinity of pore solution in CGPC is shown in **Fig. 7**. As shown in the figure, the pH of the pore solution of the CGPC at 3, 7 and 28 days all decreased with increasing ACGP content. The effect of ACGP on the pH value of CGPC at 3 and 7 days was relatively small, while the pH at 28 days decreased significantly, from 11.5 to 9.7.

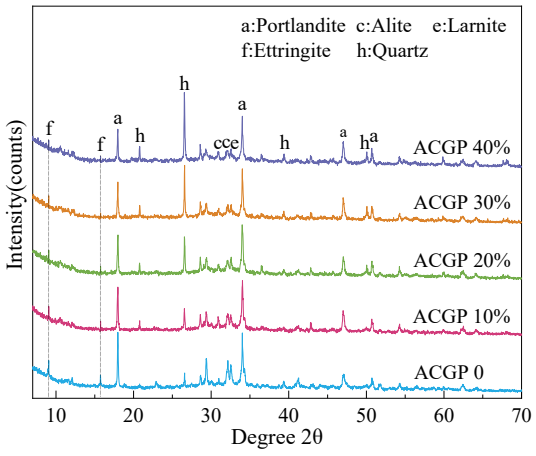


Fig. 5
XRD analysis of CGPC with different ACGP content.

Consistent with the XRD analysis in Section 3.5.1, the incorporation of ACGP reduces cement content, directly decreasing the generation of $Ca(OH)_2$ during cement hydration. Moreover, the hydration of active components of ACGP also consumes $Ca(OH)_2$. In the later stage, with the participation of some ACGP, free $Ca(OH)_2$ in the concrete is significantly consumed, resulting in a reduction in the overall alkalinity of the CGPC (Liu et al., 2024).

3.6.2 Plant coverage

Coal gangue powder (CGP) has significant advantages in improving soil porosity and enhancing air permeability. Additionally, the minerals it contains are released slowly, which can provide some trace elements for plants. To promote greater consumption of CGP, this study mixed 20% and 40% CGP with guest soil to serve as planting substrates. By observing the growth of three plant species, the feasibility of using coal gangue powder as a planting substrate was explored. The growth coverage of the three plants at four instants is shown in **Fig. 8**, and the coverage data is shown in **Fig. 9**.

From the growth status of the three plant species in the substrate without CGP addition, Festuca elata exhibited the best adaptability to CGPC, with 42-day plant coverage reaching 91%. This was followed by Alfalfa and Elymus dahuricus, with coverage rates of 88% and 68%, respectively. Festuca elata is a drought-tolerant and infertile species. Its fibrous root system can penetrate into the pores of CGPC through multiple branches to absorb water and nutrients, demonstrating strong adaptability to scarce environments. Elymus dahuricus has moderate barren resistance and higher demands for water and nutrients, with its photosynthetic rate and biomass accumulation easily inhibited when substrate nutrients are insufficient. Alfalfa is a nitrogen-fixing taproot plant, it can fix atmospheric nitrogen through rhizobia to adapt to low-nitrogen environments but exhibits weak drought tolerance. Therefore, under the experimental condition of sufficient water, Festuca elata and Alfalfa show good adaptability to CGPC due to their inherent nutrient supply advantages, while Elymus dahuricus has moderate adaptability. After CGP addition, the coverage rates of the three plants in the early and late stages all increased significantly, especially that of Elymus dahuricus, which saw the most remarkable improvement. When 20% and 40% CGP were incorporated, the 42-day coverage rate of Elymus dahuricus increased by 23.5% and 17.6%, respectively. For Alfalfa, the 42-day coverage rate increased by 4.5% and 8.0% respectively. For Festuca elata, the 42-day coverage rate increased by 4.4% at 20% CGP content, whereas it decreased by 13.2% at 40% CGP content. These results indicate that Festuca elata and Alfalfa are more suitable for growing in CGPC, and the addition of CGP to guest soil can effectively improve the growth state of Elymus dahuricus and Alfalfa.

3.6.3 Plant height and root length

Plant stems and roots are key indicators for evaluating healthy plant growth. Among them, root length determines whether the plant can penetrate CGPC to absorb nutrients from beneath, which is critical for assessing plant compatibility with CGPC. The stem and root lengths of the three plants species after 42 days of growth is shown in **Fig. 8**, while plant height and root length date at each stage are shown in **Figs. 10** and **11**. As observed in **Fig. 10**, the incorporation of CGP was beneficial to the growth of the three plants, with relatively little variation across CGP contents. Specifically, 20% CGP had the best effect on promoting the growth of Elymus dahuricus, increasing its plant height from 11 cm to 17 cm (without CGP incorporation). According to **Fig. 11**, CGP content significantly affected root length, high CGP content (40%) promoted root growth in Elymus dahuricus, while low dosage (20%) enhanced root growth in Festuca elata and Alfalfa. Notably, 40% CGP was even detrimental to alfalfa root growth.

When a small amount of CGP is added, its porous characteristics and particle size gradient enable it to fill the gaps between soil particles,

improving water retention and air permeability. This effectively alleviates clay compaction and enhances soil water retention capacity in arid regions (He et al., 2016). Meanwhile, it is rich in elements such as potassium, silicon, aluminum, calcium, and organic carbon, which are slowly released after weathering or decomposition to continuously provide nutrients for plants (Han et al., 2021; Zheng et al., 2022). Therefore, a small amount of CGP promotes the growth of the three plant species. As shown in **Fig. 10**, when the CGP content reaches 40%, its weak alkalinity reduces the bioavailability of trace elements such as phosphorus, iron, and manganese in the substrate, leading to nutrient deficiency symptoms (e.g., leaf chlorosis) in Alfalfa and slowed growth rate in Festuca elata, while Elymus dahuricus remains unaffected. Additionally, according to **Fig. 11**, the small amount of silicon and aluminum oxides in CGP slightly inhibits the rhizobial activity of Alfalfa, thereby impairing its nitrogen fixation efficiency and adaptability. But it has little impact on the root growth of fibrous-rooted plants with no significant inhibitory effect.

In summary, Festuca elata showed favorable growth state in terms

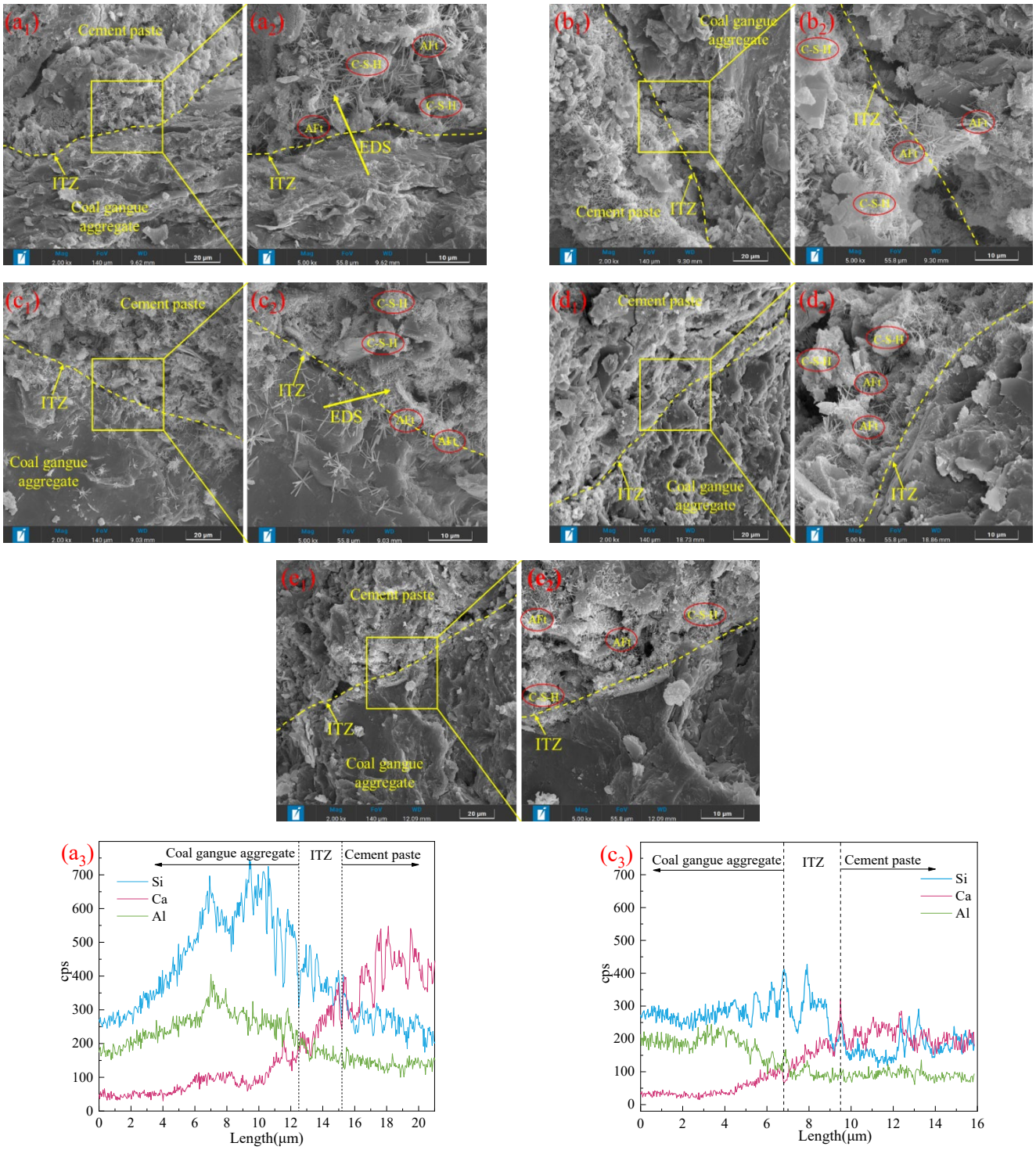


Fig. 6

Microstructure of CGPC under different ACGP content.

(a_1): ACGP 0; (b_1): ACGP 10%; (c_1): ACGP 20%; (d_1): ACGP 30%; (e_1): ACGP 40%, SEM images at 2000 magnification; (a_2): ACGP 0; (b_2): ACGP 10%; (c_2): ACGP 20%; (d_2): ACGP 30%; (e_2): ACGP 40%, SEM images at 5000 magnification; (a_3): ACGP 0; (c_3): ACGP 20%, EDS line scanning.

of coverage rate, plant height and root length, making it particularly suitable for growth in CGPC. Alfalfa also showed good planting property in CGPC. However, when CGP content increased to 40%, the growth of root system was significantly inhibited. Elymus dahuricus had relatively weak compatibility with CGPC, but its growth status could be significantly improved after incorporating CGP into the planting substrate. Therefore, when coal gangue is entirely used as aggregate and 20% ACGP is incorporated as a cementitious material to prepare concrete. 20%-40% CGP was added to guest soil, it can serve as an excellent planting substrate, especially suitable for growing Festuca elata or Alfalfa.

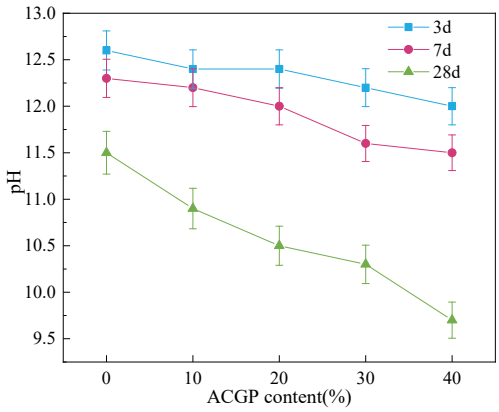


Fig. 7
pH of pore solution of CGPC.

3.7 Environmental implication and research limitations

Coal gangue contains small amounts of heavy metals, so the heavy metal leaching test of CGPC (ACGP: 20%) was carried out to verify its environmental implication. The concentrations of various heavy metals in the leachate are as shown in **Table S5**. it can be shown that heavy metals leaching concentration meet the safety limit requirements specified in Chinese standard GB 5085.3-2007 "Identification standards for hazardous wastes - Identification for extraction toxicity". However, whether the leached heavy metals can transfer into plant tissues and thereby affect plant growth needs further investigation.

When high content ACGP is incorporated to prepare CGPC, the alkalinity of CGPC decreases, which reduces its carbonation resistance. Compared with ordinary concrete, planting concrete has lower requirements for resistance to carbonation. On the other hand, ACGP with low activity presents a micro-aggregate effect, which can improve the compactness of the paste. This is beneficial to enhancing the carbonation resistance, although the improvement effect is limited. The water absorption ratio of 3.9% of coal gangue aggregate makes CGPC have the risk of drying shrinkage. Before preparing the CGPC, the coal gangue aggregate is pre-wetted to effectively prevent it from absorbing the mixing water of the cement paste. Moreover, during the drying period, the moisture absorbed by the coal gangue aggregate can migrate to the cement paste, compensating for the water loss of the paste and alleviating the drying shrinkage. The carbonation and shrinkage of CGPC was insufficiently studied in the study, and further research will be conducted.

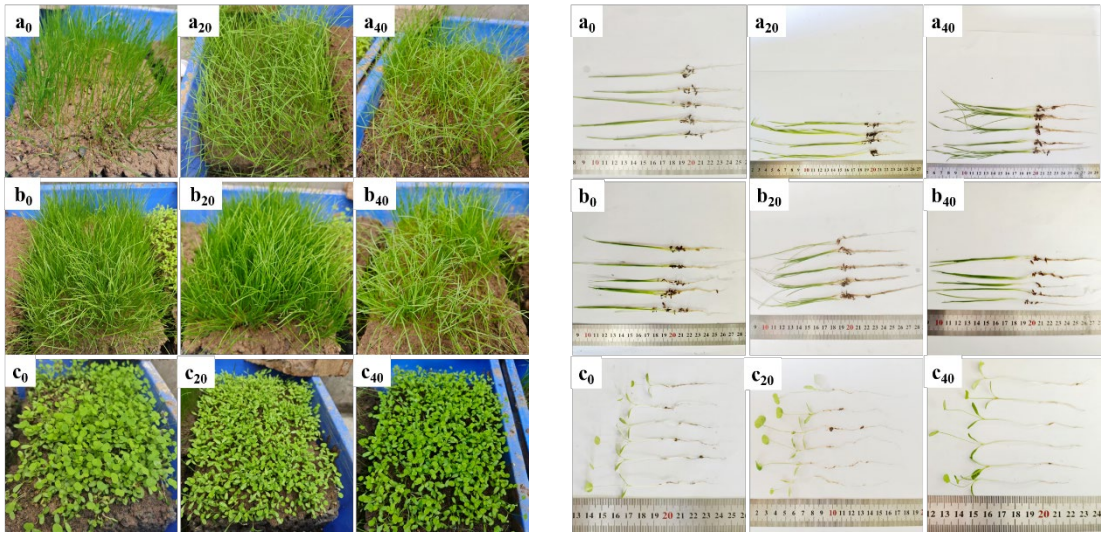


Fig. 8
The plant coverage, growth height and root length of three plants at 42 days (the subscript data indicates the dosage of CGP).
(a): Elymus dahuricus; (b): Festuca elata; (c): Alfalfa.

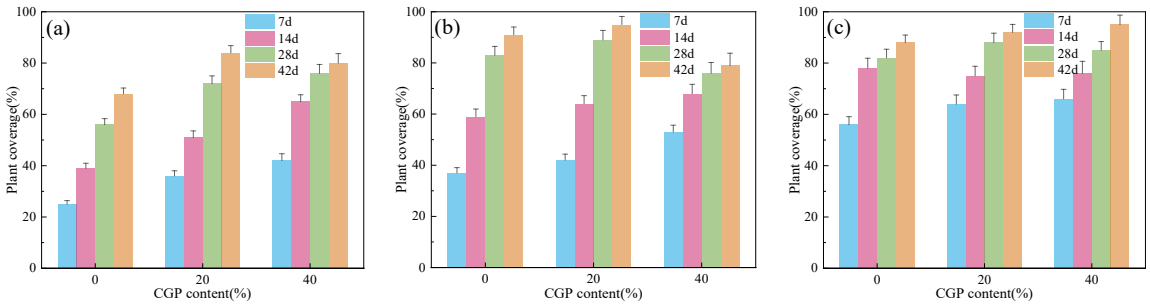


Fig. 9
Plant coverage ratios.
(a): Elymus dahuricus; (b): Festuca elata; (c): Alfalfa.

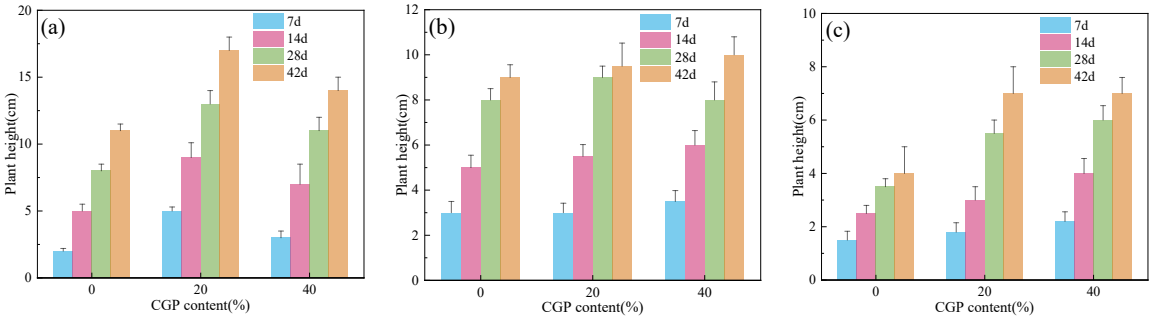


Fig. 10
Growth height of three plants in each stage.
(a): Elymus dahuricus; (b): Festuca elata; (c): Alfalfa.

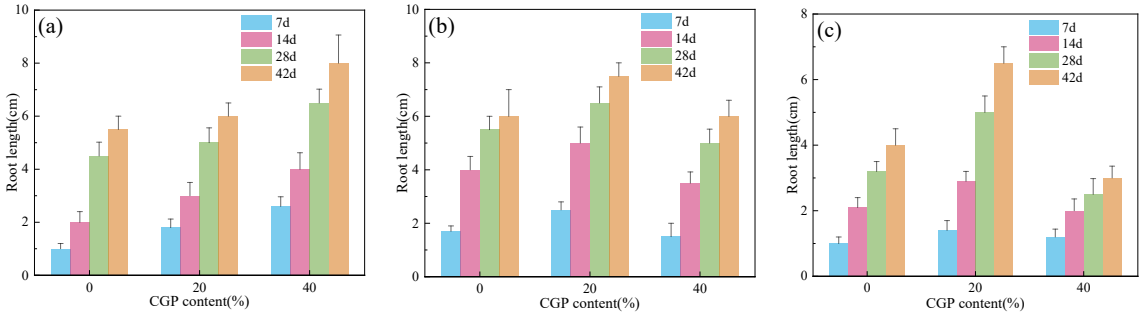


Fig. 11
Root length of three plants in each stage.
(a): Elymus dahuricus; (b): Festuca elata; (c): Alfalfa.

4. Conclusions

(1) As the ACGP content increased from 0 to 40%, the mechanical properties of CGPC first increased and then decreased, while connected porosity and water permeability decreased and water retention capacity increased. At an ACGP content of 20%, CGPC exhibited superior performance, the 28-day compressive strength and splitting tensile strength achieved 9.5 MPa and 1.3 MPa, respectively, and the mass loss ratio and strength loss ratio during freeze-thaw cycles were as low as 2.84% and 10.64%, respectively.

(2) After ball milling and activation, the particle size of ACGP was significantly refined and the reactivity was greatly enhanced. The participation in the secondary hydration reaction consumed the cement hydration product $Ca(OH)_2$, and significantly reduced the alkalinity of the CGPC system. Hydration products of C-S-H (C-A-S-H) gel and unhydrated inert micro-fillers in ACGP acted synergistically to effectively fill the micro-cracks in the paste and improve the performance of the ITZ.

(3) Low content ACGP effectively enhanced the mechanical property of CGPC through the secondary hydration and micro-aggregate filling effect, in synergy with cement hydration. At relatively high ACGP content, the efficiency of the secondary hydration reaction and the filling effect could not compensate for the performance loss caused by reduction in cement content, resulting in a significant decrease in the mechanical property of CGPC. CGPC prepared with 20% ACGP effectively achieved a coordinated balance of mechanical property, water permeability, water retention and frost resistance.

(4) The porosity of coal gangue aggregates, the potential activity of ACGP and the nutrient-rich characteristic of CGP endow CGPC with excellent performance as a planting carrier, especially suitable for the cultivation of Festuca elata and Alfalfa. Adding 20%-40% CGP to the guest soil can effectively improve plant growth property. When 20% CGP was incorporated, the coverage ratio of Elymus dahuricus, Festuca elata and Alfalfa are 84%, 95% and 92%, respectively.

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Conflicts of competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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