Superabsorbent Polymer with Excellent Water/Salt Absorbency and Water Retention, and Fast Swelling Properties for Preventing Soil Water Evaporation

Haizhou Tian\textsuperscript{1,2} · Sha Cheng\textsuperscript{2} · Jianghong Zhen\textsuperscript{2} · Ziqiang Lei\textsuperscript{2}

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Abstract
In arid areas, the rapid evaporation of water leads to severe water shortage for plant growth. Superabsorbent polymers have the prospect of preventing water evaporation because of its excellent water absorbency. However, insufficient in salt resistance, water retention, and swelling rate limit its application. Herein, we fabricated Hydroxyethyl cellulose-g-(Acrylic acid-co-2-Acrylamido-2-methyl-1-propane sulfonic acid)/laterite (HEC-g-P (AA-co-AMPS)/laterite) with exceptional abovementioned performances by aqueous solution polymerization. Under optimal synthesis conditions, the water absorbency of the superabsorbent polymer were 1294 g/g, 177 g/g, and 119 g/g in distilled water, tap water, and 0.9 wt% NaCl solution, respectively. The water retention of the superabsorbent polymer was still as high as 97.7\% after 16 h at 25 °C, the water absorbency was up to 832 g/g after re-swelling for 5 times at 40 °C, and the water absorption reached swelling equilibrium was only 5 min. We investigated the effect of the mount of swollen hydrogel on the water evaporation rate in soil, and the results showed that hydrogels were effective in inhibiting soil water evaporation. Our study provides a new horizon for the application of superabsorbent polymer.

Keywords Superabsorbent polymer · Water absorbency · Water retention · Re-swelling property · Water evaporation

Introduction
Superabsorbent polymer, as a multi-functional polymer material [1], has excellent water absorption and water retention performance because of its slightly cross-linked three-dimensional network structure, and a large number of hydrophilic groups, such as hydroxyl and carboxyl groups [2–7]. It can absorb hundreds times or even thousands times of water higher than its own quality and swell into hydrogel, the absorbed water cannot removable under a certain range of pressure [8–10] and has repeated water absorbency capacity, safe and non-toxic, good processing and use performance [6]. Therefore, superabsorbent polymers have been widely used in agriculture and forestry [11–13], medical and health [8, 14], adsorption [7, 15–18], construction [10, 19–21] and petrochemical industry [22], etc. In particular, the use of superabsorbent polymer in soil not only increases the water-holding capacity of soil, but also firmly lock rainwater and irrigation water, slowly release stored water in soil to supply water to crops, thus enhancing water retention of soil [23–26]. It can also promote the formation of soil aggregate structure to improve soil permeability, improve soil structure, reduce the invalid evaporation and deep leakage of soil moisture and nutrients, and improve the utilization rate of water and fertilizer [27–29]. At present, there are still few reports on the evaporation performance of superabsorbent polymer in soil.

The researchers synthesized some superabsorbent polymers, such as P (AMPS), bio-based P (Itaconic acid),
chitosan derivative based superabsorbent polymers, and cellulose based superabsorbent polymers. The water absorbency of these materials is about 300 g/g to 600 g/g, and equilibrium rate of water absorption in distilled water is basically more than 1 h [5, 13, 30–34], which will limit the practical application of superabsorbent polymers. Considering practical application, it is necessary to fabricate superabsorbent polymer with excellent comprehensive properties. Among them, as an important performance factor, the water absorbency of superabsorbent polymer is restricted by many factors, including structure composition, cross-linking density, surface morphology, and solution properties. Therefore, improving the comprehensive properties of the polymer can be considered from the following aspects. I. Introducing diverse hydrophilic groups. According to the literature, although ionic superabsorbent polymer has excellent water absorbency capacity. The polymer of non-ionic hydrophilic monomer has low water absorbency, but its water absorption rate is fast, water absorbency is not affected by the external electrolyte. If superabsorbent polymer has both ionic hydrophilic groups (carboxyl, sulfonic acid group, tertiary amine group, etc.) and non-ionic hydrophilic groups (hydroxyl, amide group, ester group, etc.), its salt tolerance, and water absorption rate will be significantly improved [35]. II. Compound with inorganic components. The strength of inorganic materials is higher than that of polymers, and the price is low. However, inorganic hydrogels have some disadvantages, such as structural instability and irreversibility, but the salt resistance is generally better. Therefore, the composite of polymers and inorganic materials not only improve the gel strength, but also reduce its cost [36, 37]. III. Increase the specific surface area. Increasing the specific surface area of superabsorbent polymers can increase the contact area between water and polymer particles [38], but excessively reducing the particle size of polymer can have the opposite effect. If the superabsorbent polymers have multi-porous structure, it can increase the contact area with water to improve the water absorption rate [39].

Cellulose is a kind of water absorbent material containing multiple hydroxyl groups and has a certain water absorbency capacity. In addition, it has large specific surface area, biocompatible, biodegradable, non-toxicity, low cost and renewable [14, 16, 33]. AMPS is a strong anion water-soluble monomer with strong hydrophilic groups (amide group and sulfonic acid group), it has good salt resistance, acid and alkali resistance, and hydrolytic stability [38]. In addition, laterite from Lanzhou was used to produce organic-inorganic superabsorbent polymer, which could not only improve the water absorption capacity of the polymer, but also reduce the production cost, and promote the regional economic development and resource utilization. Herein, on the basis of the above strategies, HEC, AMPS and laterite were used as raw materials to fabricate a kind of superabsorbent polymer with excellent comprehensive properties, including water absorption, water retention, re-swelling ability and swelling rate. Based on the previous laboratory test, the influence of the ratio of laterite to loess on soil evaporation performance, the mixed soil of laterite and loess with mass ratio of 2:4 was selected. Hydrogels after completely swell of superabsorbent polymer were used to prepare the soil-based anti-evaporation composite materials to study the performance of hydrogels to inhibit soil water evaporation and showed that the hydrogel had a good inhibitory effect on soil water evaporation. Our study provides a strategy for improving the comprehensive performance of superabsorbent polymers, and provides an opportunity for the application and versatility of superabsorbent polymers.

### Experimental

#### Materials

Hydroxyethyl Cellulose (HEC),2-Acrylamido-2-methyl-1-propane sulfonic acid (AMPS) were obtained from Aladdin Reagent (Shanghai) Co., Ltd., Acrylic acid (AA) was obtained from Tianjin Damao Chemical Reagent Factory, Sodium hydroxide (NaOH) was obtained from Tianjin Yiwanda Chemical Co., Ltd., N,N-methylene-bis-acrylamide (MBA) was obtained from Chinese Drug Group Chemical Reagent Co., Ltd., Ammonium persulfate (APS) was obtained from Yantai Shuangshuang Chemical Co., Ltd., laterite was obtained from Lanzhou.

#### Preparation of HEC-g-P (AA-co-AMPS)/Laterite Superabsorbent Polymer

The dispersed solution was prepared by adding 12 wt% HEC and 30 mL distilled water into a 250 mL four-mouth flask with mechanical stirring, nitrogen line and condensing tube and stirring at 70 °C for 45 min. Then, the temperature was reduced to 50 °C and 5 mL aqueous solution containing 0.8 wt% APS was added under continuous stir. After 10 min, the mixed solution containing AA with a neutralization degree of 70%, 30 wt% AMPS, 0.08 wt% MBA and different weight percentages of laterite was added. The mixture was heated to 70 °C and reacted for 3 h. HEC-g-P (AA-co-AMPS) superabsorbent polymer was obtained except not containing laterite. The product was soaked in methanol for 1 h to remove the unreacted monomer, washed with distilled water for 3 times, and dried in an oven at 60 °C until constant weight. The fabricated products were crushed and screened for subsequent testing.
The reaction mechanism of HEC-g-P (AA-co-AMPS)/laterite superabsorbent polymer were shown in Scheme 1.

### Preparation of Soil-Based Anti-Evaporation Materials

Put 700 g sand (its function is to simulate the desertification area) into plastic boxes with the same specifications (20.5*13.2*6.5 cm), make the sand level in the plastic boxes, add 120 g distilled water, make the sand wet evenly. The different amounts of fully swollen hydrogel (optimum synthesis conditions) are spread over the sand. Then, a mixture of 200 g mixed soil (m_laterite:m_loess=2:4), 5 wt% of straw powder and 100 g of distilled water was uniformly stirred and spread out in a plastic box, respectively.

### Characterization of Materials

The infrared spectra of HEC and prepared samples were recorded by using Digilab FTS-3000 Fourier-transform Infrared Spectrometer in the range of 4000 – 400 cm⁻¹. The solid sample and KBr were mixed and ground into powder with the mass ratio of 1:100 and transparent sheet was formed by pressing method. The morphological changes of the samples were observed by Zeiss ULTRA plus thermal field emission scanning electron microscopy (SEM). Thermal stability analysis was carried out with TGA-DSC1 synchronous thermal analyzer by Mettler Toledo. Under nitrogen atmosphere, the temperature range was 30-1000 °C and the heating rate was 10 °C/min.

### Performance Test of Superabsorbent Polymer

#### Measurement of Swelling Behavior

0.1 g dry samples were accurately weighed and immersed in excess distilled water, tap water and 0.9wt % NaCl solution, respectively. After reaching water absorption balance for 4 h, the samples were sipped to remove excess water and weighed. Water absorption ratio is calculated according to formula (1):

\[ Q_{eq} = \frac{(M-M_0)}{M_0} \times 100\% \quad (1) \]

where, \( M(g) \) and \( M_0(g) \) are the masses of the sample reaching swelling equilibrium and the dry sample, respectively [40–42].

#### Determination of Water Retention at Different Temperatures

The 100 g swollen samples were placed in ovens at 25 °C, 35 °C, 45 °C and 60 °C, respectively. The samples were placed for 2, 4, 6, 8, 10, 12, 14, 16 h and weighed. The water retention of hydrogels is calculated according to formula (2):

\[ \text{Water retention} = \frac{W_i}{W_0} \times 100\% \quad (2) \]

where, \( W_i \) is the quality of the sample placed for different time at different temperatures, and \( W_0 \) is the mass of the fully swollen sample.

#### Re-Swelling Capacity Test at Different Temperatures

100 g fully swollen samples were placed in the oven at 40 °C, 60 °C, and 80 °C until the sample was completely dried, respectively. Then excessive distilled water was added to make it swelled again and weighed, and calculated the water absorption rate [43]. The above process was repeated several times, the water absorption rate is calculated according to formula (1).

#### Measurement of Swelling Kinetics

0.1 g sample under the optimum synthetic conditions was weighed and immersed in excess distilled water. Use a sieve to remove excess water at a set time interval (0.5, 1, 2, 3, 4, 5, 8, 10, 12, 15, 18, 20, 25, 30, 45, 60, 75, 90, 120, 150, 180, 210 and 240 min) and weighed it. The water absorption rate was calculated according to formula (1).

### The Water Evaporation Performance Test of Swollen Hydrogel in Soil

Under natural conditions, the mass of the anti-evaporation material was weighed every 204 h, and data were recorded. The calculation formula of evaporation rate is as follows:
The percentage of evaporated water = \((M_1 - M_2) / M_3 \times 100\%\) (3).

in which \(M_1\) is the total mass of the anti-evaporation material, \(M_2\) is the mass of the anti-evaporation material when \(t\), and \(M_3\) is the total mass of water in the anti-evaporation material.

**Results and Discussion**

**Morphological Analyses**

The porosity and average pore size of superabsorbent polymers play a significant role in its water absorption. The surface porous microstructure can increase specific surface area and capillary effect. Therefore, one of the most important properties of superabsorbent polymers is surface microstructure. Figure 1(a), (b) and (c) are SEM images of HEC, HEC-g-P (AA-co-AMPS) and HEC-g-P (AA-co-AMPS)/laterite, respectively. The surface morphology of HEC was relatively flat, smooth and dense. The surface of HEC-g-P (AA-co-AMPS) was rough and appeared many holes. However, the surface of the prepared superabsorbent polymer by adding laterite showed rough surface, multiple and evenly distributed pore structure. The such pore structure increased specific surface area, water- absorption sites, and capillary effect of the superabsorbent polymer, resulting in facilitating the diffusion of water molecules into the three-dimensional structure to improve the water absorption and absorbency rate of materials with laterite [31, 44]. Compared to the HEC-g-P (AA-co-AMPS), the prepared superabsorbent polymers with laterite had rough and multiple porous structure, the such microstructure can promote the water absorbency and swelling rate of the superabsorbent polymers (Fig. 2(f)). The results also indicated that laterite was involved in the polymerization, and the introduction of laterite had positive effect on improving the properties of materials.

**FTIR Spectroscopy**

In Fig. 1(d), the curve a was the infrared spectrum of HEC, the C-O-C stretching vibration peak (asymmetry and symmetry) at 1036 cm\(^{-1}\) and 915 cm\(^{-1}\) [45], and the plane of C-OH at 1384 cm\(^{-1}\), the vibration peak disappeared after the polymerization reaction; the aliphatic stretching vibration peak of C-H at 2925 cm\(^{-1}\) still existed in the curve b (HEC-g-P (AA-co-AMPS)) and curve c (HEC-g-P (AA-co-AMPS)/laterite (6 wt%)) [42, 46]; the O-H stretching vibration peak at 3433 cm\(^{-1}\), increased in intensity compared to the absorption peak in the b curve and c curve [15]; these results indicated that HEC was involved in the chemical reaction. In curve b and curve c, the asymmetric stretching vibration peaks of -COO- at 1404 cm\(^{-1}\) and 1402 cm\(^{-1}\) can be observed, respectively; the stretching vibration absorption peak of sulfonic acid groups O=S at 627 cm\(^{-1}\) and 669 cm\(^{-1}\), and the vibration absorption peaks at 1642 cm\(^{-1}\) and 1647 cm\(^{-1}\) were the stretching vibration peaks of C=O in the amide group [36, 47], indicated that the polyacrylic acid chain and AMPS have been grafted onto the HEC skeleton. In the curve c, we found the Si-O-Si bending vibration peak of the laterite at 554 cm\(^{-1}\) [37], indicated that the laterite was involved in the polymerization reaction. These results confirmed that HEC-g-P (AA-co-AMPS)/laterite were successfully synthesized.

**Thermal Properties**

The TG/DTG curves of HEC, HEC-g-P (AA-co-AMPS) and HEC-g-P (AA-co-AMPS)/laterite are shown in Fig. 1(e) and (f). The TG decomposition curve of HEC showed four steps, that is, 258\(^\circ\)C, 930\(^\circ\)C, 318\(^\circ\)C, and 884\(^\circ\)C, and weight loss was 7.67%, 58.36%, 20.94%, and 3.76%, respectively. Meanwhile, there were about three peaks of 53, 270, and 884\(^\circ\)C on the DTG curve, corresponding to the first three stages, indicated the maximum decomposition speed. The thermal decomposition of HEC-g-P (AA-co-AMPS) and HEC-g-P (AA-co-AMPS)/laterite were mainly divided into four processes, with mass loss of 11.09%, 46.29%, 30.63%, and 2.07%; 12.53%, 44.84%, 23.64% and 2.91%, respectively. The first stage occurred before 145\(^\circ\)C, which can be attributed to the decomposition of moisture and unreacted raw materials in the superabsorbent polymer [33, 48, 49]. The main mass loss occurred in the second stage from 145 to 481\(^\circ\)C, when the chain was broken to remove CO and CO\(_2\), and small molecules such as oligomers in the superabsorbent polymer began to decompose [11, 50]. In the third stage, the decomposition of HEC-g-P (AA-co-AMPS)/laterite was much slower than HEC-g-P (AA-co-AMPS). This is due to the elimination of water from the anhydride formed by two adjacent carboxyl groups on the polymer chain and the decomposition of branched chains in the polymer at 481\(^\circ\)C [51]. The decomposition of the fourth stage was between 917 and 1000\(^\circ\)C, which was due to the decomposition of polymer backbone and the destruction of the three-dimensional network [52]. Finally, the mass of the remaining samples of HEC-g-P (AA-co-AMPS)/laterite was 16.09%, which was higher than HEC (9.28%) and HEC-g-P (AA-co-AMPS) (9.92%). This was due to the partly decomposition of the product and inorganic salts. The results of TG/DTG indicated that the formation of networks in the samples, and there was a chemical reaction took place between HEC and laterite. The addition of...
laterite was conducive to the improvement of the thermal stability of the product [53].

The Effects of Synthesis Conditions on Water (salt) Absorbency of Polymer

Effect of HEC Content on Water (Salt) Absorbency of
showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and showed a trend of increased first and then decreased with the increase of HEC content, and the water (salt) absorbency reached the maximum when the HEC content was 12 wt%. HEC provided the polymerization skeleton and reaction site in polymerization, which can affect the reaction rate and the molecular weight of the material. When HEC content was low, the number of active sites generated in the system was small, and the monomer reaction was incomplete, which was not conducive to the formation of polymer skeleton and
However, when the content of HEC was high, the number of active sites increased and the reaction intensified, bringing about the decline of molecular weight of the product, which had an adverse effect on the improvement of its liquid absorption properties.

Effect of AMPS Content on Water (Salt) Absorbency of Polymer

Figure 2(b) showed the effect of AMPS content on water (salt) absorbency of superabsorbent polymer. As can be observed in the figure, as the AMPS content increased from 20 wt% to 30 wt%, the water (salt) absorption performance of the polymer improved; but water (salt) absorbency decreased when AMPS content was further increased. The reason might be that the increase of AMPS content, the number of hydrophilic groups (-CONH₂, -SO₃H, etc.) increased, at the same time, the synergistic effect of the network. However, when the content of HEC was high, the number of active sites increased and the reaction intensified, bringing about the decline of molecular weight of the product, which had an adverse effect on the improvement of its liquid absorption properties.

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hydrogen bonding between hydrophilic groups and water molecules and between various groups was enhanced [54, 55], thus increasing the water (salt) absorbency. However, when the AMPS content was higher than 30 wt%, there were overmuch hydrophilic groups, the intermolecular hydrogen bond interaction was large, and the polymer network shrunk, resulting in low water (salt) absorbency.

**Effect of Initiator Content on Water (Salt) Absorbency of Polymer**

The content of APS is the main factor affecting the length of polymer chain. The effect of APS content on water (salt) absorption performance is shown in Fig. 2(c). When the content of APS was lower than 0.8 wt%, few sites of active free radical were produced, which had less initiation effect on the reaction and reduced the molecular weight of the product, resulting in low water (salt) absorbency of the polymer. However, when the content of APS was higher than 0.8 wt%, the number of active free radicals generated increased [56]. Overabundant free radicals could cause intensifying of the reaction and termination of the growing molecular chains, resulting in shorter chain segments between the cross-linking sites of the polymer and making the network structure of the polymer more difficult to expand [57, 58]. Therefore, the water (salt) absorbency was decreased.

**Effect of Cross-linker Content on Water (Salt) Absorbency of Polymer**

According to Flory theory, cross-linking density has great influence on the water (salt) absorption performance of superabsorbent polymer [9]. Figure 2(d) shows the influence of MBA content on water (salt) absorbency of the polymer. With the augment of MBA content from 0.04 wt% to 0.08 wt%, the water (salt) absorbency of superabsorbent polymer increased. This is because when the cross-linker content was less, the formation of the network of the superabsorbent polymers were inefficient due to few crosslink sites, which results in the superabsorbent polymers were semi-soluble and hardly absorb water. Increasing the content of crosslinker to generate more cross-linking points generated for the system, leading to an increase in cross-linking density and better formation of the three-dimensional network structure as the increase of MBA content. When the content of MBA was higher than 0.08 wt%, its water (salt) absorption performance decreased, which can be attributed to the excessive MBA increased the cross-linking sites, resulting in the excessive cross-linking density inside the polymer, the shrinkage of network space [4, 59], the extension of polymer chain and the expansion of network structure were hindered [60].

**Effect of Neutralization Degree of AA on Water (Salt) Absorbency of Polymer**

Figure 2(e) shows the effect of the neutralization degree of AA on the water (salt) absorbency of the superabsorbent polymer. It can be apparently seen that when the neutralization degree of AA was less than 70%, the water (salt) absorbency of the superabsorbent polymer increased and reached the maximum water (salt) absorbency with the increase of the neutralization degree of AA. However, the water (salt) absorbency decreased when the neutralization degree of AA was further increased. After AA was neutralized by NaOH, the -COOH became -COO⁻ with negative charge. Due to the electrostatic repulsion in the network, the expansion capacity of the polymer and osmotic pressure were improved, which facilitates the penetration of water molecules [58]. When the neutralization degree of AA was higher than 70%, the excessive Na⁺ in the system would have shielding effect on -COO⁻, which would reduce the electrostatic repulsion [9] and hindered the expansion of the molecular chain, bring about the water (salt) absorbency decreased.

**Effect of Laterite Content on Water (Salt) Absorbency of Polymer**

The influence of the laterite content on the water (salt) absorbency properties of the superabsorbent polymer is shown in Fig. 2(f). The laterite content increased from 0 wt% to 6 wt%, the water (salt) absorbency of the superabsorbent polymer increased and reached maximum at the laterite content of 6 wt%, and its water absorbency were 1294 g/g, 177 g/g and 119 g/g in distilled water, tap water, and 0.9 wt% NaCl solution, respectively. As the laterite content further increased, the water absorbency decreased [61]. On the one hand, this is because a large amount of -OH on the surface of the laterite would polymerize with the polymer, appropriate rigid laterite could weaken the strong hydrogen bonding interaction and other physical intertwining between the polymeric chains, leading to strengthen the cross-linking effect, thereby increasing the water-absorbing chain and forming more effective water-absorbing network structure. On the other hand, the addition of laterite caused the composite polymer to form more pores and increase water-absorbing sites, resulting the water quickly entered the pores by capillary action and diffusion, so that the polymer was fast and sufficiently swollen, and the water absorbency and swelling rate were extremely increased. However, when the amount of laterite added was too much, the laterite content that cannot be effectively grafted increased, and this part of the laterite acted as a physical filling and will plug up some network voids. The role of the chemical bond was weak, and the laterite would be detached from the polymer under
the action of water, resulting in network structure collapsed and the water absorbency decreased [62].

**Performance Analysis of Superabsorbent Polymer**

**Water Retention Property of Superabsorbent Polymer at Different Temperatures**

The water retention properties at different temperatures and high temperatures have a significant effect on the application of superabsorbent polymers in various fields. The water retention of the swollen superabsorbent hydrogel was measured at different temperature. The water retention properties of the superabsorbent polymer at different temperatures are shown in Fig. 3(a). As the temperature and time increased, the water retention performance of the superabsorbent polymer decreased gradually. The water retention rates were 97.7%, 89.8%, 70.6%, and 62.6% after 16 h at 25°C, 35°C, 45°C, and 60°C, respectively. It is reported that the water contained in the superabsorbent polymer can be classified into free water, bound water, and half-bound water. Compared with free water, the water absorbed in the polymer interacted with through the van der Waals force and hydrogen bonding between the water molecules and the hydrophilic groups. This force made the water not easy to lose, so the superabsorbent polymer had a certain water retention property [51, 63, 64]. In addition, the increasing temperature could impair bond strength between water molecule and superabsorbent composite [58] and accelerated the movement of water molecules, thereby reducing the interaction between the polymer and the water molecules, resulting in the decrease of water retention capacity of the superabsorbent polymer as the temperature increased [65]. The superabsorbent hydrogel could retain more than 60% of the deionized water after being placed at 60°C for 16 h, which indicate that the fabricated material had excellent water retention capacity even under high temperature and can be used in practical applications.

**Re-Swelling Capability of Superabsorbent Polymer at Different Temperatures**

The re-swelling capacity of the superabsorbent polymers is a very significant factor in practical application. The excellent re-swelling ability can improve the service life of the superabsorbent polymer, and give a light of application prospect of the materials. The re-swelling properties of the superabsorbent polymer at different temperatures are shown in Fig. 3(b). As can be seen from the figure, the re-swelling performance of the superabsorbent polymer decreased with the increase of the temperature and re-swelling times. After re-swelling for 5 times, the water absorbency were 832 g/g, 754 g/g, and 601 g/g, respectively; reaching 64.30%, 58.27%, and 46.45% of the original water absorbency at 40°C, 60°C, and 80°C, respectively [66]. The superabsorbent hydrogel still maintained about 50% water absorption capacity even under high temperature of 80°C after 5 times swelling, which indicate that the material had excellent water retention capacity. It should be noted that when the swelling was repeated twice at 40°C and 60°C, the water absorbency was higher than the initial value; after that, the water absorbency was decreased. This can be attributed to the sufficient swelling of the polymer network structure, and the impurity ions were removed after the first swelling, resulting in increase in water absorption performance. However, after repeated use for a plurality of times, the main chain structure of the polymer may undergo a certain degree of change, and therefore caused the decrease of water absorption property [65, 67].

**Swelling Kinetics**

In order to study the water absorption dynamic mechanism of the superabsorbent polymer in the distilled water, the experimental data were fitted with the pseudo-second-order kinetic model and the Ritger-Peppas model. The pseudo-second-order kinetic model and Ritger-Peppas model are represented by Eqs. (4) and (5) respectively:

$$\ln \left( \frac{t}{q_t} \right) = \ln q_e - \ln q_e = kt$$

Where, \(q_e \) (g/g) and \(q_t \) (g/g) are the water absorption capacity of the product at equilibrium time and t time, respectively. \(K_2 \) (g·mg\(^{-1}\)·min\(^{-1}\)) is the rate constant of the pseudo-second-order model, and \(K_2 \) is the absorption percentage at time t, k is the structure coefficient, and n is the swelling index that determines the type of diffusion [68].

It can be seen from Fig. 3(c) that the superabsorbent polymer absorbed water quickly in the initial 5 min, reached the swelling equilibrium at 5 min, and presented a fluctuation trend after 5 min [69]. Superabsorbent polymer had such fast swelling rate was attributed to the rough, multiple and uniformly distributed pore structure. According to the swelling rate curve in the figure, the relationship between \(t/q_t \) and t can be well linearized, and the linear correlation coefficient \(R^2 = 0.99765 \), very close to 1. It showed that the pseudo-second-order kinetic model had a very good fitting result for the swelling behavior of the superabsorbent polymer in the distilled water, the swelling kinetics of the prepared product could obey with the pseudo-second-order equation very well, and the correlation coefficient between the calculated water absorption capacity and the experimental data was relatively high. Compared with the Ritger-Peppas model, the former had a higher correlation coefficient, which indicated that the swelling kinetic of the synthesized
Superabsorbent polymer was more consistent with the pseudo-second-order relationship.

For swollen hydrogel systems, according to the relative diffusion rate of water into the polymer matrix and the relaxation of the polymer chain, the diffusion mechanism of water molecules can be divided into five types: (1) $n<0.5$, pseudo-fickian diffusion; (2) $n=0.5$, Fickian diffusion; (3) $0.5<n<1$, non-fickian diffusion; (4) $n=1$, Case II transmission diffusion; (5) $n>1$, relaxation diffusion [32, 70]. The equation is suitable for the initial stage of swelling process [54]. As shown in Fig. 3 (d), $n>1$ occurred within 5 min of the beginning of swelling process, the movement of the chain controls the absorption rate. At $50240$ min, $n<0.5$, water molecule diffusion was the main factor of swelling [54]. Compared with the Ritger-Peppas model, the pseudo-second-order kinetic model had a higher correlation coefficient, indicated that the swelling kinetic of the synthesized superabsorbent polymer was more consistent with the pseudo-second-order relationship, and the water absorption process was mainly controlled by chemical absorptions [71].

### Prevent Water Evaporation Performance of Swollen Hydrogel in Soil

In agricultural and horticultural applications, the anti-evaporation performance of superabsorbent polymers for water in the soil are most worthy of investigation. Superabsorbent polymers can improve soil quality, slow down water evaporation, improve seedling survival ratios, and promote plant growth. Figure 4 shows the effect of the soil-based anti-evaporation materials with different fully swollen hydrogel quality on the percentage of evaporated water in soil. The effect of the ratio of mixed soil (mlaterite: mloess = 6:0, 5:1, 4:2, 3:3, 2:4, 1:5, 0:6) and the particle size of superabsorbent polymers (> 750 μm, 375–750 μm, 187.5–375 μm, 75–187.5 μm, < 75 μm) on the percentage of evaporated water in soil were previously investigated in our laboratory. Based on the best choice, mixed soil (mlaterite: mloess = 2:4) and superabsorbent polymer with particle size of 187.5–375 μm were selected as materials to fabricate soil-based anti-evaporation materials and the effect of hydrogel on water evaporation in soil was tested [72]. Hydrogel had a significant effect on the evaporation of moisture in soil, the percentage of water evaporation increases gradually with time, while the percentage of evaporated water decreased gradually with the increase of hydrogel content in the soil-based anti-evaporation materials. Generally speaking, when the soil-based anti-evaporation materials were placed for 125 h under natural conditions, the anti-evaporation effect of hydrogel on soil moisture was the most obvious. Compared with mixed soil (without hydrogel), the percentage of evaporated water decreased by 6.19%, 12.86%, 14.82%, 26.68%, 31.63%, 32.94%, and 34.71%, respectively. When the mass of hydrogel was 1000 ± 140 g, the percentage of evaporated water was not much different, this is because the soil contains a lot of inorganic components, such as Al₂O₃, Fe₂O₃ and SiO₂, etc., when the amount of the hydrogel added in the soil was high, the hydrogel occurred to de-swelling behavior under the influence of the inorganic components, which made the water absorbed by the hydrogel overflow to the surface of the soil, and increased the percentage of evaporated water at a certain degree. This results revealed that the soil-based anti-evaporation materials prepared by hydrogels had obvious effect on inhibiting water evaporation in soil, and the entrapped water in the superabsorbent polymer could be released gradually when the soil moisture decreased to maintain sustainability of the water into the soil and then by plants [73]. We believe that this study may significantly promotes the wide application of superabsorbent polymers in water retention, anti-evaporation, agriculture and forestry, and related researches.

### Conclusion

The application of superabsorbent polymers is limited due to inadequate salt resistance, water retention and swelling rate. Considering the performance requirements of practical application, HEC-g-P (AA-co-AMPS)/laterite superabsorbent polymers with excellent comprehensive properties were fabricated by aqueous solution polymerization, and the FTIR, SEM and TG/DTG were used to characterize the materials. The superabsorbent polymer under the optimized conditions had outstanding water/salt absorbency, water retention, re-swelling performance, and swelling rate: the water absorbency were 1294 g/g, 177 g/g, and 119 g/g in distilled water, tap water, and 0.9 wt% NaCl solution, respectively; the water retention rate was still reached 62.6% when placed at 60 °C for 16 h; the water absorbency was still reached 832 g/g, 754 g/g, and 601 g/g after repeatedly absorbing water for 5 times at 40 °C, 60 °C, and 80 °C, respectively. Besides, the water absorption kinetics of the obtained optimal product in distilled water was studied, and the swelling equilibrium was achieved at 5 min. We used the fully swollen hydrogel to fabricate the soil-based anti-evaporation composite, and studied its ability to inhibit water evaporation in soil. Compared with the mixed soil (mlaterite: mloess = 2:4), the evaporation rate of the aforementioned composite reduced by 6.19%, 12.86%, 14.82%, 26.68%, 31.63%, 32.94%, and 34.71% when placed for 125 h under natural condition, respectively, indicating that it had a good application prospect. We foresee further broadening of fabricate strategy of polymers with excellent integrative
properties in the development of superabsorbent polymers for practical applications.

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Declarations

Declaration of Competing Interest There are no conflicts to declare.

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