Water-Absorption Characteristics of Organic–Inorganic Composite Superabsorbent Polymers and Its Effect on Summer Maize Root Growth

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ABSTRACT: Adding inorganic materials in SAPs to synthesize organic–inorganic composite superabsorbent polymers (OICSAPs) can effectively improve salt-tolerance, gel strength, thermal stability, and water retention. However, most researches mainly focus on synthesizing process optimization and new multifunctional products, lacking reports on how ions affected water-absorption characteristics and mechanism of OICSAPs and its influence on summer maize root growth. On the basis of these, we set up laboratory experiments and field cultivation experiment, using environmental scanning electron microscopy (ESEM) and fractal theory to study the questions above. Results show that OICSAPs have better salt-tolerance, while cations and concentration affected its water-absorption characteristics significantly. With higher cation valence, larger ionic radius, and concentration, its water-absorption rate reduced remarkably as $Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Fe^{2+} < Fe^{3+} < Al^{3+} < Cu^{2+}$, while the effects of anions could be neglected. The OICSAPs presented typical honeycomb membrane-like 3D crosslinked network structure, but Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+}, and Cu^{2+} would damage the structure (Cu^{2+} with the most significant effect) in local microdomain, and changed the complexity of pores. In the experiment, higher concentration could reduce water-absorption rate without changing micromorphological characteristics. Applying OICSAPs will reduce total length, surface area, and volume of summer maize root, while promoting absorbing and transmitting ability by larger root diameter and the proportion of root <0.5 cm. All these results will provide a theoretical basis on application, marketing, and product development of OICSAPs. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 000: 000–000, 2012

Key words: OICSAPs; water-absorption characteristics; root growth; summer maize; micromorphology structure

INTRODUCTION

Enhancing effective use of rainfall and irrigation water in farmland, improving storage capacity of soil reservoir, and reducing steam consumption are becoming key points of remitting global water shortage and frequent droughts. Therefore, using chemicals, such as SAPs, to keep soil moisture are getting more attention. SAPs can absorb hundreds to thousand times as its own weight to increase water storage capability and provide water to plants through "absorb–release–absorb" process and release nutrients and pesticides absorbed with water around root slowly. Compared to other technologies, SAPs have advantages of simpler, lower cost, quicker reaction and easier in industrialization, generalization, etc., and it is expected to be a new way to increase water use efficiency significantly.

SAPs primarily rely on its 3D network to store abundant free water. Water-absorption capacity of SAPs is decided by both extension caused by ionic charge repulsion of macromolecular electrolyte and expansion resistance caused by crosslinked structure and hydrogen bond. The internal micromorphology of SAPs directly affects its water-absorption characteristics and mechanism.[1] Some researchers have reported on the structural feature of SAPs hydrogel.[2,3] We used the fractal theory to analyze the structure of SAPs dry gel and hydrogel.[1] However, researches nowadays still focus on acrylic and polyacrylamide SAPs, lacking quantitative description of hydrogels in different ion solutions and concentration. Besides, SAPs were commonly weak in salt-tolerance and therefore lost practicality. In the recent years, some researchers have found that adding inorganic minerals, such as attapulgite clay, in SAPs to synthesize organic–inorganic composite superabsorbent polymers (OICSAPs) can improve its combination property. In fact, soil is a typical multisystem containing large amounts of Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, etc. But comprehensive reports on how typical

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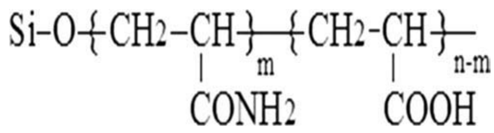

$$\mathrm{Si{-}O{-}[CH_2{-}\underset{\displaystyle CONH_2}{CH}]_m{-}[CH_2{-}\underset{\displaystyle COOH}{CH}]_{n-m}}$$

Figure 1 Constitutional formula of the OICSAPs.

ions and different concentration affect the OICSAPs and micromorphological structure as well as fractal characteristics are limited. Meanwhile, OICSAPs absorb nutrients along with water, forming a microdomain, but how the changed microenvironment would affect summer maize root growth was unknown.

Considering all these mentioned earlier, we selected one of the most representative OICSAPs and set up the detailed laboratory experiments and field cultivation experiment, using environmental scanning electron microscopy (ESEM) and fractal theory to study water-absorption characteristics and microstructure of OICSAPs in different ions and concentration, while analyzing its influence on summer maize root growth. All these results are aiming at providing theoretical basis on application, promotion, and technical support for developing new products of OICSAPs.

MATERIALS AND METHODS

Experimental materials

The OICSAPs selected were produced by HUAYE New Material in Dongying, Shandong Province, China, through adding attapulgite clay in polyacrylamide-acrylic crosslinked polymer. Its constitutional formula is shown in Figure 1 and flow chart in Figure 2.

The chemical agents, such as NaCl, KCl, $CaCl_2$, $MgCl_2$, $FeCl_2$, $FeCl_3$, $CuCl_2$, $AlCl_3$, KNO_3, K_2SO_4, and K_3PO_4, were manufactured by Beijing Chemical Analysis Company. The deionized water used in the experiment was provided by Beijing KEBANZHENGYE.

Water-absorption characteristics of OICSAPs

Water-absorption characteristics of OICSAPs were tested by Filtering method of 100-mesh. Add 1.00 g OICSAPs into solutions till equilibrium (determined by the pretest) and filtrate with 100-mesh, weigh OICSAPs hydrogels, and get water-absorption multiplying factor. Equation (1) shows how to calculate the multiplying factor of OICSAPs.

$$S = (W_t - W_d)/W_d \qquad (1)$$

where S denotes multiplying factor, W_t denotes mass of OICSAPs hydrogel at the moment of t in time, and W_d denotes the mass of dry gel of OICSAPs. The relative water-absorption multiplying factor is calculated by dividing water-absorption multiplying factor in solutions to that in deionized water. To eliminate the effect of particle size, OICSAPs were sieved in three classes before experiment according to diameter that were 1.0–2.0, 2.0–3.0, and more than 3.0 mm, respectively, among which particles between 1.0 and 2.0 mm were in proportion of about 79.43%. Specific experiment methods were introduced in the following sections.

Influence of particle size and repeated absorbing

Add OICSAPs particles sized in 1.0–2.0, 2.0–3.0, and >3.0 mm into deionized water till equilibrium, which were 50, 160, and 220 min, respectively. Weight OICSAPs hydrogels and put in culture dish in diameter of 120 mm. Heat the dish in oven under 60°C till 8.00 g ± 0.50 g. Take it out in case it damages the network structure. Swelling and then weight OICSAPs hydrogels again.

Influence of soils ions and their concentration

Considering common ions in soil, and taking ion concentration tested in experimental soil as reference, preparing NaCl, KCl, $CaCl_2$, $MgCl_2$, $FeCl_2$, $FeCl_3$, $CuCl_2$, $AlCl_3$, KNO_3, K_2SO_4, and K_3PO_4 solutions, among which the concentration of monovalent ions, divalent ions, and trivalent ions was 6.0, 3.0, and 2.0 mmol/L, respectively. Furthermore, select KCl, $CaCl_2$, and $MgCl_2$ solutions and put them in four concentrations in 3.0, 6.0, 12.0, 24.0mmol/L, and 1.5, 3.0, 6.0, and 12.0 mmol/L (the latter two).

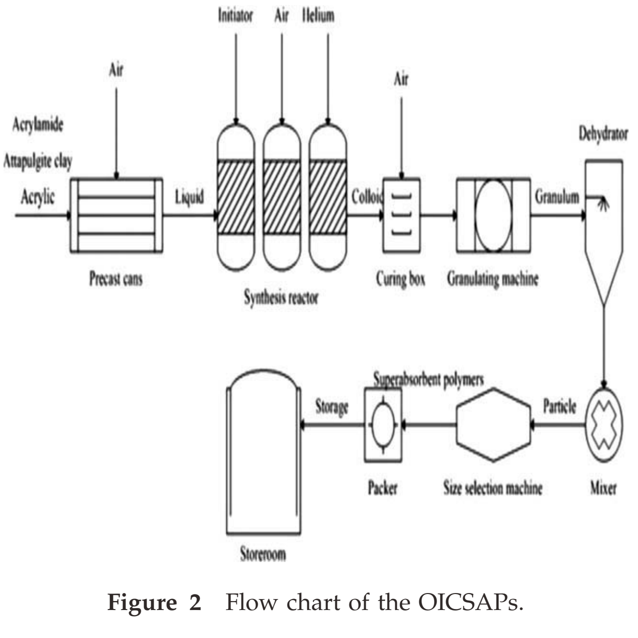

Figure 2 Flow chart of the OICSAPs.

TABLE I
Basic Physical and Chemical Properties of Soil Used in the Experiment

Particle content (%)			Saturated water ratio (g/g)	Soil water rate (g/g)	Volume-weight (g/cm^3)
Sand	Silt	Clay			
60.4	26.6	13.0	0.319	0.197	1.37
TN (%)	TP (mg/kg)	Available P (mg/kg)	NH_4^+-N (mg/kg)	NO_3^--N (mg/kg)	EC (mg/kg)
0.075	751.0	7.68	34.40	1.93	13.5
Na^+ (mg/kg)	K^+ (mg/kg)	Mg^{2+} (mg/kg)	Ca^{2+} (mg/kg)	Cl^- (mg/kg)	SO_4^{2-} (mg/kg)
54.65	33.69	61.36	90.61	102.55	112.16

Put OICSAPs with diameter between 1.0 and 2.0 mm in different solutions to swell.

Scanning internal micromorphology features of OICSAPs hydrogels

Use FEI Quanta 200 ESEM for observation. Select the internal profile of OICSAPs dry gel and hydrogels tested above and place them on the observation platform of FEI Quanta 200 ESEM. Observe in low-vacuum condition with vacuum degree of 130 Pa and acceleration voltage of 20 kV. Considering the problems of unclear contrast and polarized light in obtained images, each one was 1024 × 678 pixels and transferred into an eight-level grayscale image.

Calculating pore network boundary fractal dimension

Fractal geometry deals with substantial unsmoothed and irregular geometric shapes in nature and in nonlinear system and tries to describe the complex shapes quantitatively, which are hard to discuss by the classical Euclidean geometry. Fractal dimension quantitatively describes the fractal complexity, and it is a characteristic quantity in describing fractal.

The island analysis was used to calculate fractal dimension of pore cross-sectional boundary of internal structure of OICSAPs hydrogels. The island analysis is a method for calculating fractal dimension based on measurement relationship. Mandelbrot pointed out[4]:

$$\alpha_D(\varepsilon) = \frac{L^{\frac{1}{D}}(\varepsilon)}{A^{\frac{1}{2}}(\varepsilon)} \tag{2}$$

where L denotes the pore perimeter, A denotes the pore area, and D denotes the fractal dimension; $\varepsilon = \eta/L_0$, where η denotes the absolute measurement scale and L_0 denotes the initial perimeter of the image; with constant scale of η, α_D $(\varepsilon)$is a constant while α_D (ε) is only related to the selected scale, and it is not related to the image size. Take logarithm for both sides of Equation (2) and obtain the following equation:

$$\lg L(\varepsilon) = D \lg \alpha_D(\varepsilon) + \frac{D}{2} \lg A(\varepsilon) = C + \frac{D}{2} \lg A(\varepsilon) \tag{3}$$

where C is a constant. Use Image-pro software to analyze each ESEM image after binarization processing and measure the area and perimeter of every pore on surface. The fractal dimension D is twice the slope of the double-log curve between area and perimeter.

Effects of OICSAPs on summer maize root growth

The experiment carried out in Shixia soil erosion monitoring stations, conducted by Beijing Soil and Water Conservation Station, in Gaoling, Miyun County. Basic soil physicochemical property was shown in Table I. The crops were summer maize (varieties ND108), sowed on May 6, 2010, and the ground was reconditioned before seeding. Using flat-bed planting method, excavated a trench with 15 cm in depth at first and mixed a small amount of soil with OICSAPs well, after which broadcasted, backfilled, sowed, backfilled soil again, and irrigated enough water. Set a high and low dosage treatment of OICSAPs, which were 45.0 and 22.5 kg/hm^2, labeled SAPH and SAPL. A CK treatment was set without OICSAPs. Irrigation, fertilization, and other agricultural processes of experimental treatments were consistent with the surrounding areas. Select three maize crops during heading stage (July 26) and mature stage (August 16) each treatment. Wash the roots from soil and spread on a plastic film carefully and quickly, especially avoiding overlap. Use EPSON root image analysis system to analyze the total length, total surface area, total volume, average diameter and other related parameters of maize roots, take the average value as test results, and the proportion of maize root in each limited ranges statistically.

RESULTS AND ANALYSES

Water-absorption characteristics and micro-morphology of OICSAPs in deionized water

Water-absorption characteristics in deionized water of OICSAPs in different size were tested by filtering method using 100-mesh sieve. Results show that water-absorption rate of OICSAPs after first swelling was 221, 192, and 181 g/g, followed by 169, 150, and

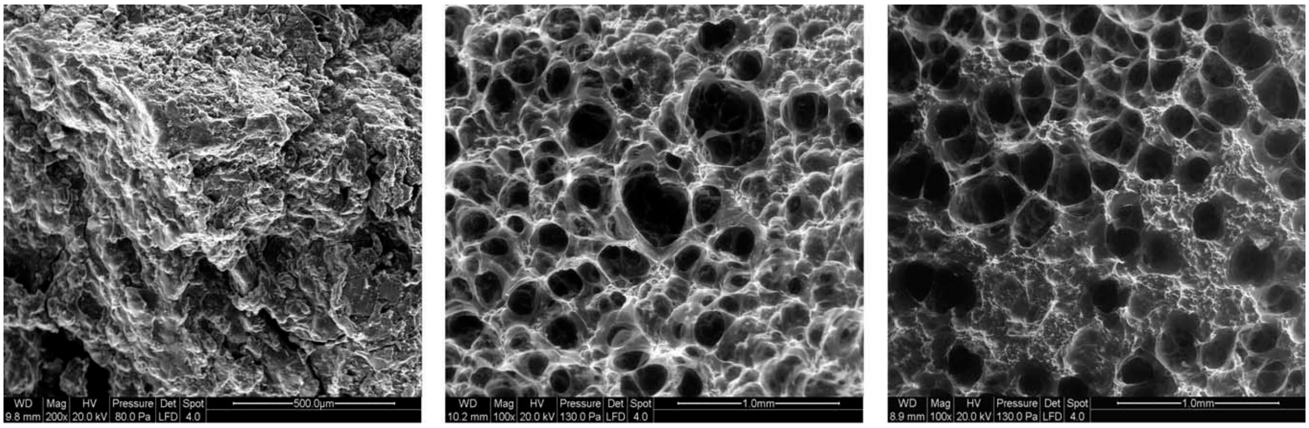

Figure 3 ESEM images of dry gel and hydrogels after first and second swelling.

136 g/g after second swelling. Water-absorption capacity of OICSAPs in different sizes showed lower power in larger size, which mainly due to smaller contact surface between larger particle and water. Water-absorption rate in second swelling decreased rapidly, only 75.1–78.1% that of the first time, but the difference in decay-rate between different sizes can be neglected.

Use FEI Quanta200 ESEM to observe micromorphology features of dry gel and hydrogels of OICSAPs between 1.0 and 2.0 mm after first and second swelling in deionized water, which were shown in Figure 3. The OICSAPs dry gel showed a complex irregular structure [Fig. 3(a)], in which there were lots of folds, pits, etc., while hydrogels showed significant honeycomb membrane-like 3D crosslinked network structure [Fig. 3(b)], including large numbers of pores related to water-absorption capability. Micromorphology features of hydrogels after first and second swelling had some difference, and the latter represented a certain degree of damage [Fig. 3(c)] along with lower water-absorption, but kept basic structure and a good capacity of water-absorption and water-retention, which reflects better reusability.

Water-absorption characteristics and micro-morphology of OICSAPs in solutions of common soil ions

Water-absorption rates of OICSAPs in Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, Cu^{2+}, Al^{3+}, Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-} solutions were shown in Table II, which were significantly different, and only reached 20.00–62.35% of that in deionized water. The different effects of cations were much greater than anions and reduced as $Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Fe^{2+} < Fe^{3+} < Al^{3+} < Cu^{2+}$, from which we concluded that lower water-absorption rate was related to higher cation valence and lager ionic radius. Specially, Cu^{2+} had the most remarkable influence. However, water-absorption rates in four anion solutions reduced as $PO_4^{3-} < SO_4^{2-} < Cl^- < NO_3^-$, showing that lager valence resulted in smaller impact on swelling, but the deviation of different anions was within 5%, which could be ignored.

Figures 4(a–k) and 5 (a–k) showed micromorphology features and fractal dimension of OICSAPs hydrogels after swelling in different solutions, and all samples had typical honeycomb membrane-like 3D crosslinked network structure, while the relation between area and perimeter of pores represented excellent linear correlation ($R^2 \geq 0.96$), which means obvious fractal characteristics. But impact of different solutions was inconsistent, higher cation valence and lager ionic radius caused more changes in membrane structure as well as fractal dimensions, which were consistent with the result of water-absorption rates. Hydrogels in Na^+ and K^+ solutions were similar to that in deionized water, with fractal dimensions deviated within just 2.7%, slightly differed in pore size and structure; but Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+}, and Cu^{2+} seriously damaged the 3D crosslinked network, especially large area was damaged in solution of Cu^{2+}. The fractal dimension of hydrogel in Cu^{2+} increased 18.1% in comparison with that

TABLE II
Water-Absorption Ratio of OICSAPs in Solutions of Different Ions

Solutions	NaCl	KCl	$CaCl_2$	$MgCl_2$	$FeCl_2$	$FeCl_3$	$CuCl_2$	$AlCl_3$	KNO_3	K_2SO_4	K_3PO_4
Water absorption ratio (g/g)	137.8	127.6	105.4	115.3	59.7	57.5	44.2	53.6	117.1	125.8	129.5
Relative water absorption velocity (%)	62.35	57.74	47.69	52.17	27.01	26.02	20.00	24.25	52.99	56.92	58.60

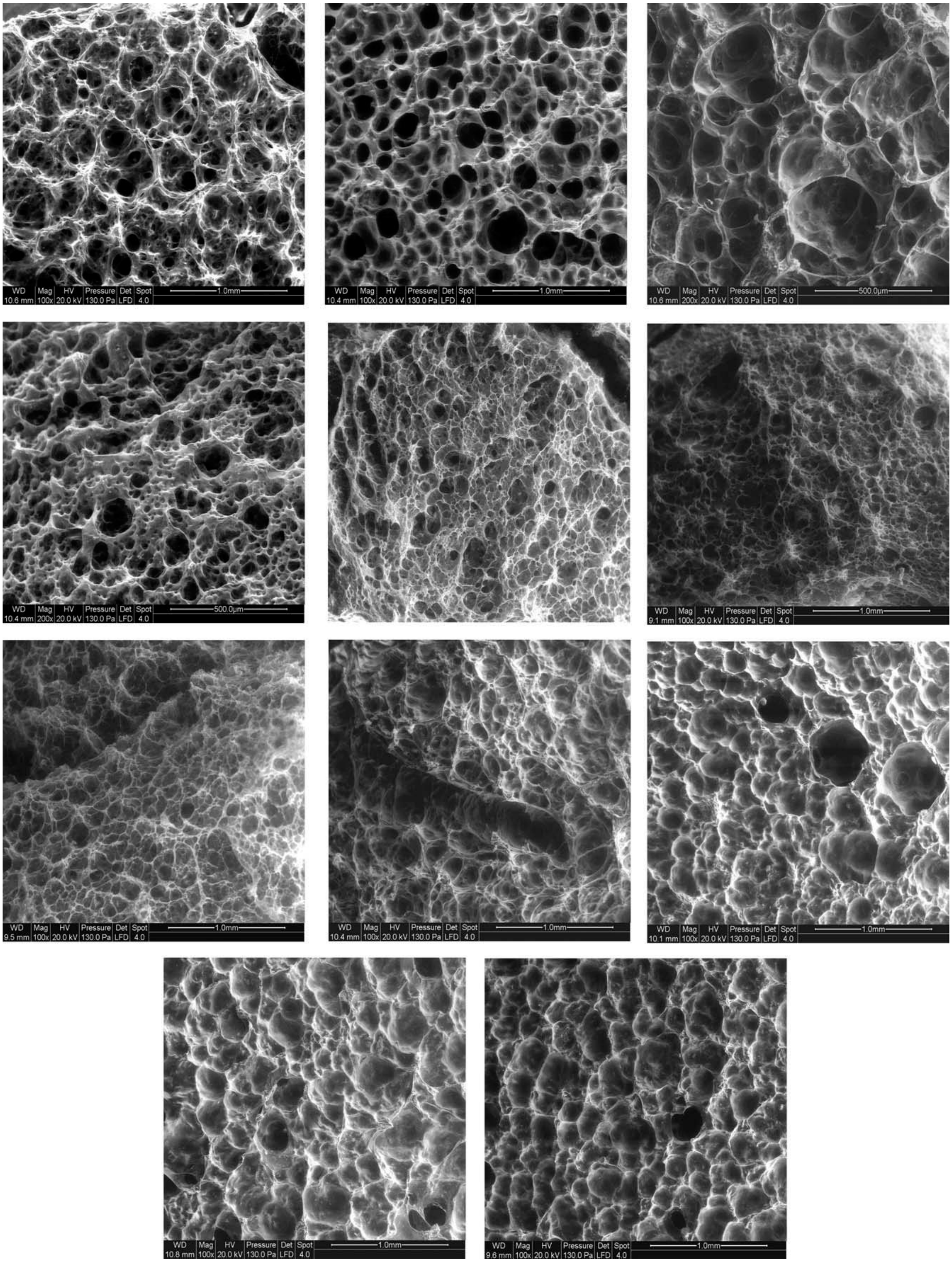

Figure 4 ESEM images of hydrogels after swelling in solutions of different ions.

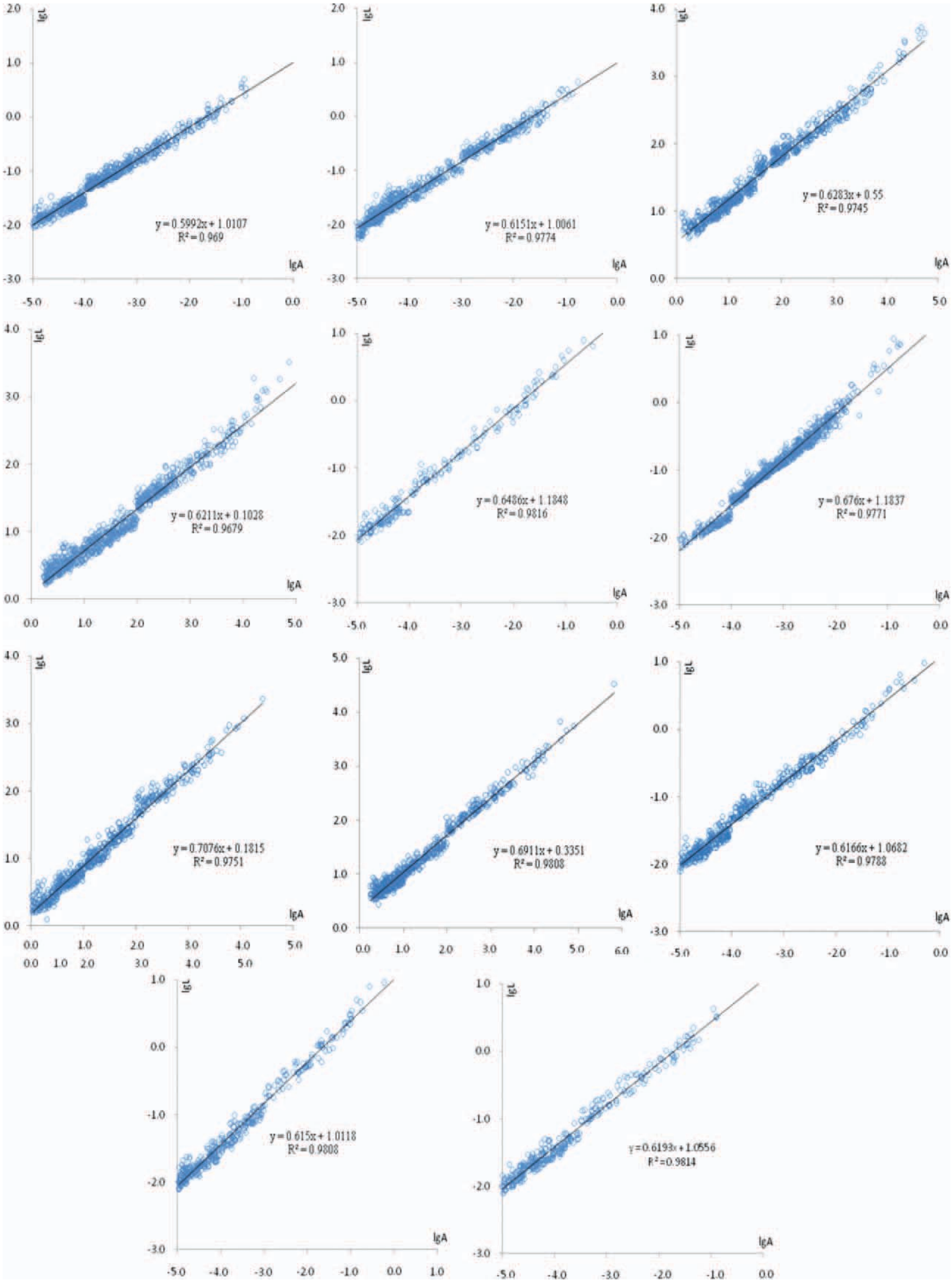

Figure 5 Calculation of fractal dimension of hydrogels after swelling in solutions of different ions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE III
Water-Absorption Ratio of OICSAPs in Solutions of Different Concentrations

	Concentration of KCl (mmol/L)				Concentration of $CaCl_2$ (mmol/L)				Concentration of $MgCl_2$ (mmol/L)			
Solutions	3.0	6.0	12.0	24.0	1.5	3.0	6.0	12.0	1.5	3.0	6.0	12.0
Water absorption ratio (g/g)	157.2	127.6	104.2	78.3	141.2	105.4	83.1	41.9	137.2	115.3	58.9	41.7
Relative water absorption velocity (%)	71.13	57.74	47.15	35.43	63.98	47.69	37.60	18.96	75.66	52.17	26.65	18.87

in Na^+. As for PO_4^{3-}, SO_4^{2-}, Cl^-, and NO_3^-, hydrogels morphology was similar with each other, and fractal dimension deviated within only 0.7%, which was negligible.

Effects of ions concentration on water-absorption characteristics and micro-morphology of OICSAPs

Table III showed water-absorption rates in different concentration of KCl, $CaCl_2$, and $MgCl_2$ solutions, which represents a clear decreasing trend with higher concentration. Under high concentration, water-absorption rate reached 41.0 g/g in minimum (only 18.6% of that in deionized water) with a linear decreasing variation. In contrast, changes in Mg^{2+} solutions were most remarkable. Micromorphological features of hydrogels under different treatments were shown in Figures 6–8. The micromorphological characteristics of OICSAPs in different concentration were relatively similar, and concentration had relatively small effects on micromorphological characteristics, but pore size reduced significantly.

Using fractal theory to analyze the lgA–lgL correlation of pores on hydrogels surface in different concentration, results were in Figures 9–11, which showed that different concentrations of cations (K^+, Ca^{2+}, Mg^{2+}) seriously affected its water-absorption rate, but changes in surface characteristics were relatively small. Under different concentrations, the fractal dimensions changed in 2.63, 2.49, and 3.01%, respectively, which were negligible and meant

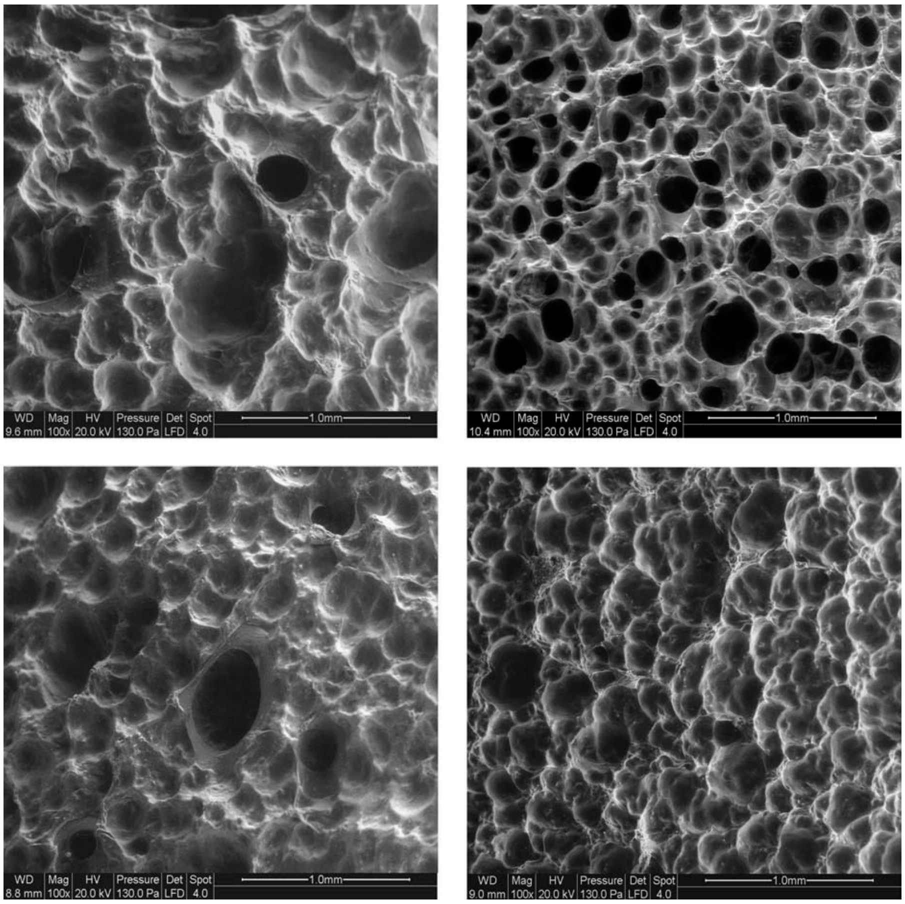

Figure 6 ESEM images of hydrogels in different concentration of KCl.

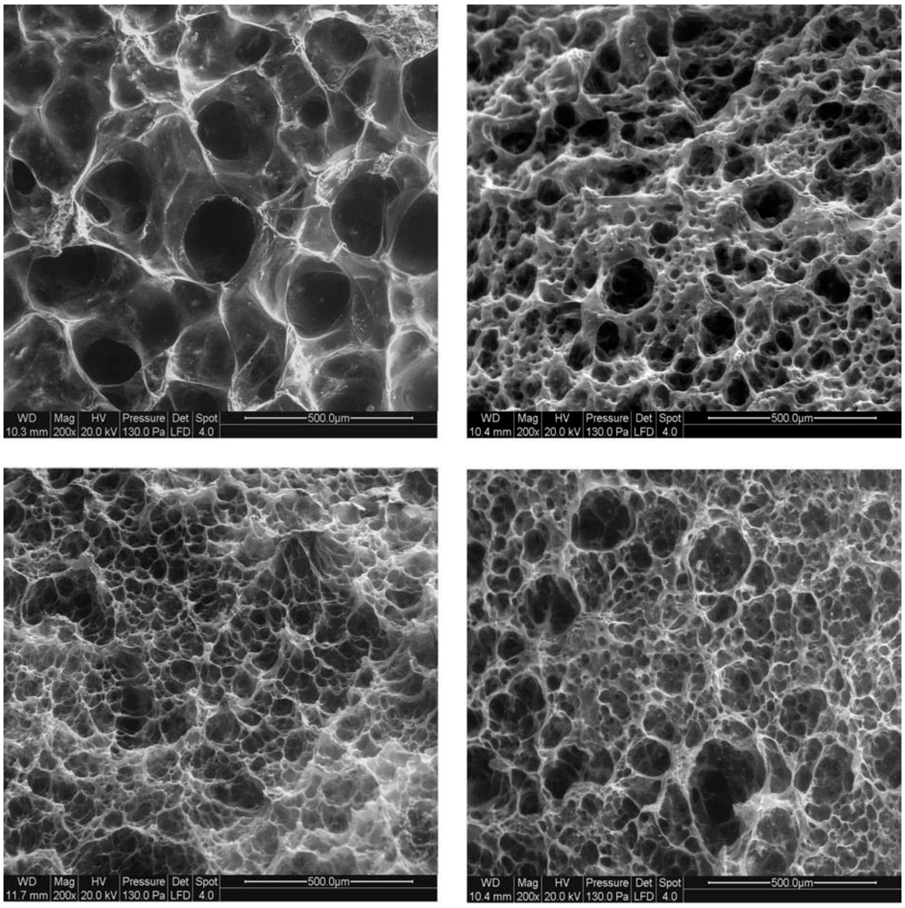

Figure 7 ESEM images ofhydrogels in different concentration of $CaCl_2$.

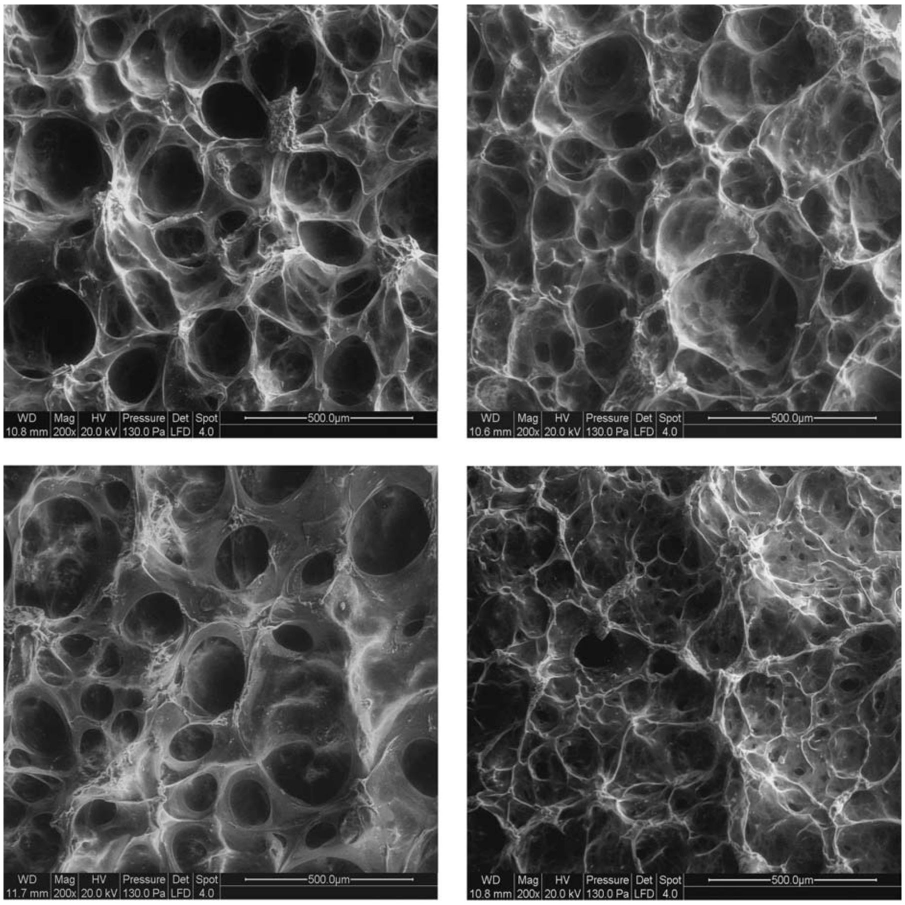

Figure 8 ESEM images of hydrogels in different concentration of $MgCl_2$.

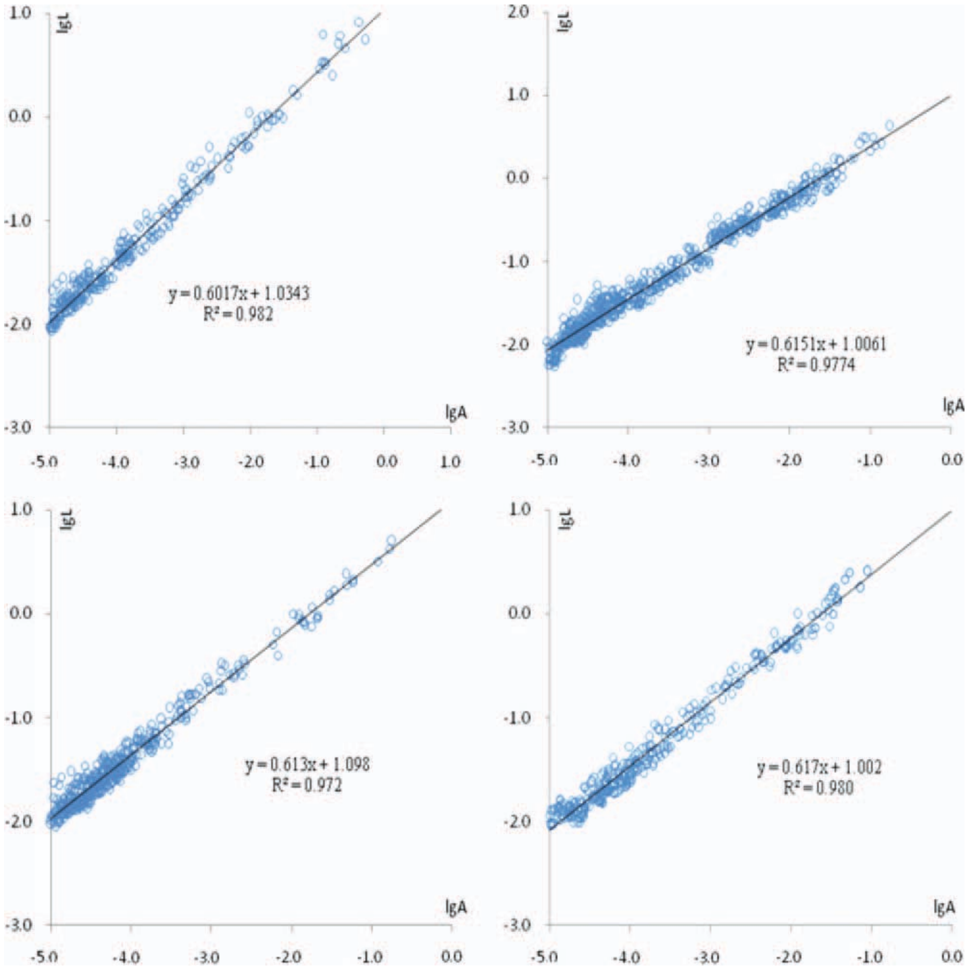

Figure 9 Calculation of fractal dimension of hydrogels after swelling in different concentration of KCl. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

different concentrations only changed water-absorption rates with smaller changes in the complexity of morphology and microporous.

Effects of OICSAPs on summer maize root growth

Statistical results in Table IV figured out that total length, total surface area, and total volume of maize root decreased with the application of higher concentration of OICSAPs, while average diameter increased in contrast. Overall, the maize roots mainly were fibrous roots, which were shorter than 0.5 cm. Applying OICSAPs could significantly change the proportion of maize root that were <0.5, 0.5–2.0, 2.0–3.5, and >3.5 cm, increasing the proportion of root that were shorter than 0.5 cm, while higher concentration result in more apparent trend.

DISCUSSION

Water-absorption characteristics and mechanisms of SAPs had been concerns of numerous researchers, manufacturers, and customers, among whom acrylic and acrylamide SAPs occupied the market. However, acrylic SAPs have large water-absorption rate but poor in salt-tolerance and acrylamide SAPs on the contrary. Using organic–inorganic hybrid technology, adding inorganic materials in SAPs synthesizing OICSAPs could improve water-absorption rate, salt-tolerance, and reduce costs,[5] which has become a shining direction in research and development of SAPs.

OICSAPs was a hydrophilic polymer, usually acquired by hydroxyl, carboxyl, or amino hydrophilic monomer reacting with initiator or cross-linking agents through polymerization, hydrolysis, cross-linking, and form a 3D network, which was insoluble but highly swelling in water. The polymers absorb water quickly and store it in the network, which indicate the main reason for absorbing and maintaining water. Hydrogels showed typical honeycomb membrane-like 3D crosslinked network structure after absorbing enough water under ESEM observation. The effects of second swelling and different ions and concentration on structure were relatively small when compared with the conventional

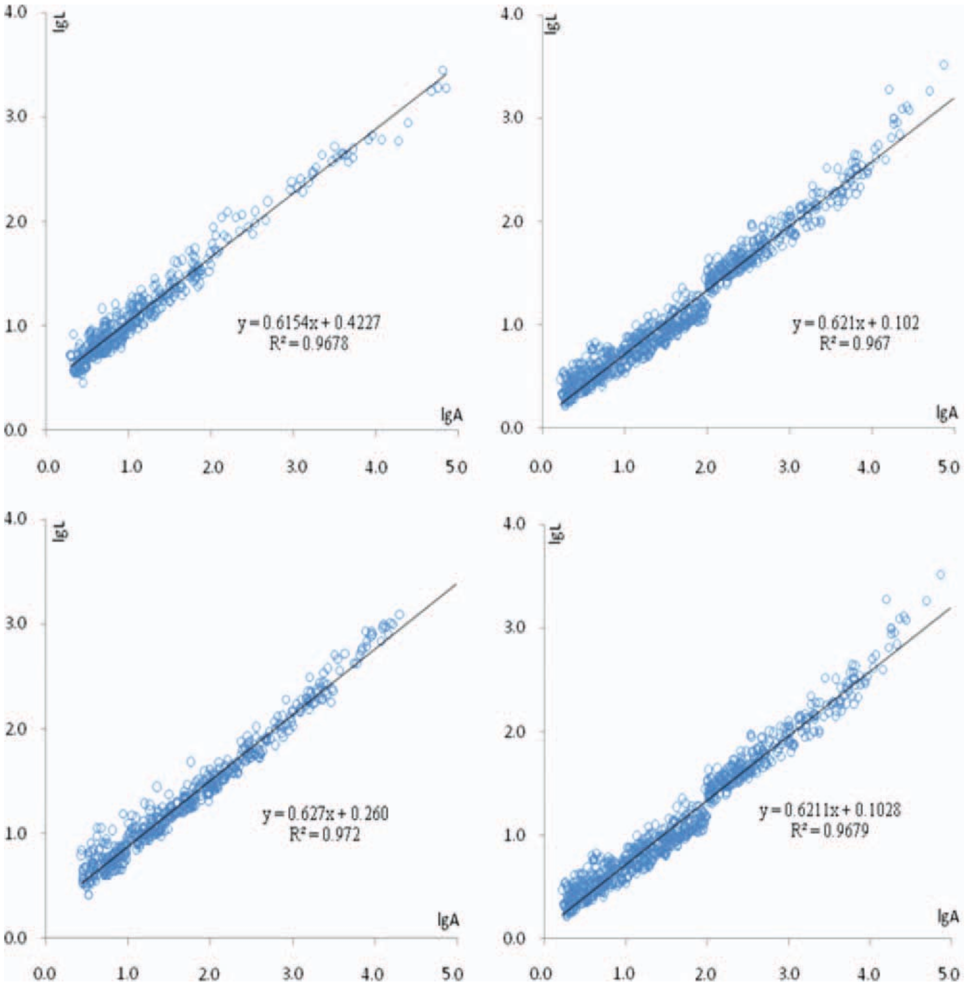

Figure 10 Calculation of fractal dimension of hydrogels after swelling in different concentration of $CaCl_2$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

SAPs. After all, the OICSAPs had a better capability of water-absorption, water-retention, and reusability.

Na^+, K^+, Mg^{2+}, Ca^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+}, Cu^{2+}, ${PO_4}^{3-}$, SO_4^{2-}, ${NO_3}^-$, and Cl^- are common ions in soil. Under general condition, there are quantities of Ca^{2+} and Mg^{2+} in soil, followed by ${NO_3}^-$, but ${NH_4}^+$ and ${PO_4}^{3-}$, especially the latter, are relatively less. In different kinds of soil solutions, the maximum concentration of common ions could reach about 40 mmol/L.[6–10] We found that 12 common ions in soil had significant but different impact on water-absorption characteristics of OICSAPs, only reached 20.00–62.35% of that in deionized water, but still higher than that of traditional SAPs under the same treatment.[5] And the result was consistent with micromorphology features. OICSAPs relied on its 3D network in storing abundant free water. Water-absorption capacity of OICSAPs was decided by both extension caused by ionic charge repulsion of macromolecular electrolyte and expansion resistance caused by crosslinked structure and hydrogen bond. After swelling, OICSAPs dissociated to carboxylic acid and inorganic ions, and inorganic ions moved in the water while the carboxyl anion connected to the chain. Therefore, the network of main chain, mainly consisted of negatively charged carboxyl groups, expended through exclusion, and inorganic ions, although being active, could only exist in the network due to the attraction and restriction of negative charges, so that the concentration internal was much larger than that external, thus generating osmotic pressure, and water could be poured into the network in a short time. With the penetration of water, some positive and negative ions dissolved and inorganic ions diffused to the solution, resulting in expanding among chains, then water entered more easily under restrict of network structure and the hydrogen bonding. These two actions above eventually reached balance. Therefore, concentrations of inorganic ion inside and outside network reduced with ion concentration increased, along with the osmotic pressure and equilibrium time and water-absorption rate. Its 3D crosslinked network structure was more likely to be damaged. Water-absorption rate of the OICSAPs was

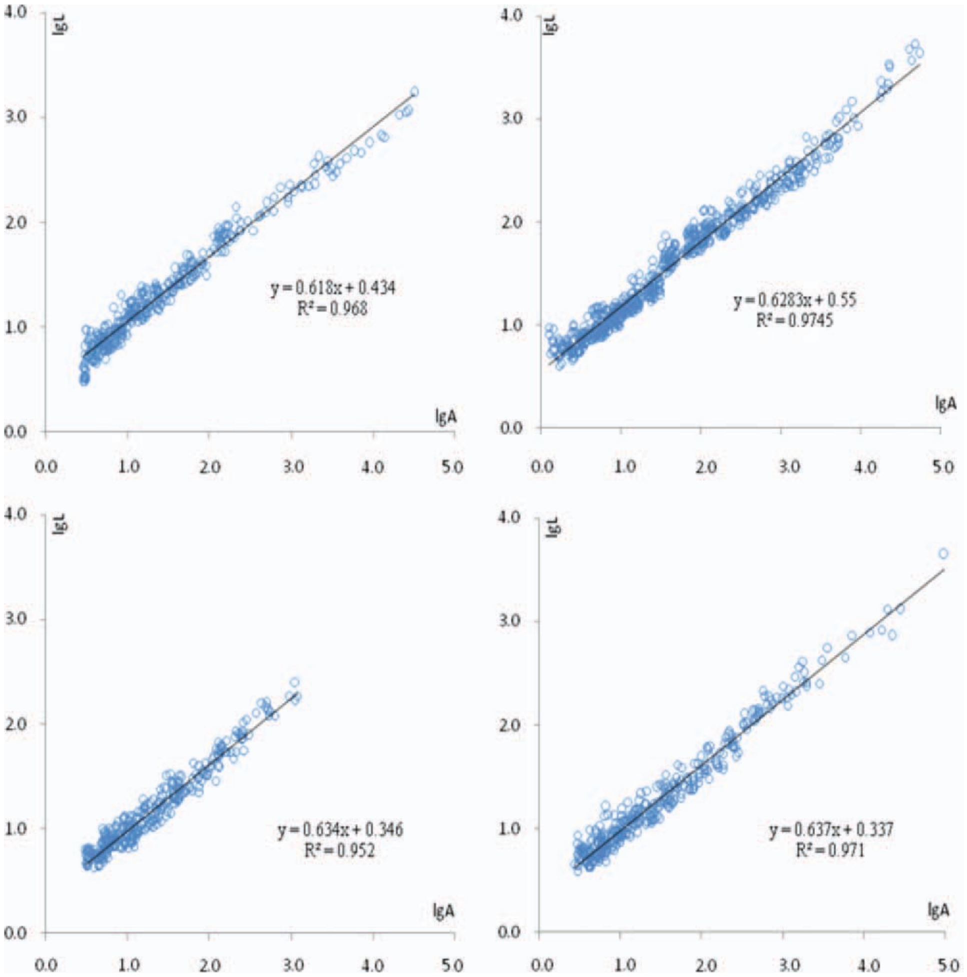

Figure 11 Calculation of fractal dimension of hydrogels after swelling in different concentration of $MgCl_2$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

significantly higher than conventional SAPs, mainly because more acid in conventional polymers resulting in more evident "anti-ion shielding" effect, that was, a reaction counter ions (Na^+) to —COO^-.

Water-absorption capacity of SAPs is greatly affected by temperature, salt concentration, salt type, pH, and other factors.[11,12] Ion type and concentration played the most important role in water-absorption characteristics and microstructures of OICSAPs. Researchers have found that valence had significantly impact on SAPs, and this work found that surface morphology of OICSAPs hydrogel had obvious fractal characteristics in different solutions. Higher cation valence and lager ionic radius result in the decreased as $Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Fe^{2+} < Fe^{3+} < Al^{3+} < Cu^{2+}$, and fractal dimension showed the same variation. Among all these ions, Cu^{2+} had the most outstanding effect, but the mechanism needs further research. Although water-absorption rate of OICSAPs decreased with higher concentration, much smaller changes in fractal dimension, indicating that the concentration only affected the pore sizes and quantity of hydrogels, but much less on its micromorphology and complexity of pores. However, the influence of anions could be ignored. In conclusion, OICSAPs performed much better in salt-tolerance and reusability than SAPs, which offered a much more ideal, expansive space for research and development.

Root is an important organ for crop to uptake, synthesis, fix, and support, through which to absorb water and nutrients in soil, also directly affects water and nutrients usage. On the other hand, they have "trend to water" and "trend to fertilizer," so water and nutrients in soil have a significant effect on their growth.[13] OICSAPs absorbed water and nutrients in soil forming a coupled microdomain around roots and slowly released them to support the absorption and utilization of whole plant, which would have an impact on root growth. But reports on root growth after the application of SAPs were sporadic. In this work, we found that total length, total surface area, and total volume of maize root significantly decreased after

TABLE IV
Statistics on Growth of Maize Roots in Different Concentrations of OICSAPs

Date	Treatment	Total length (cm)					Total surface area (cm^2)					Total volume (cm^3)					Average diameter (mm)
			Proportion (%)					Proportion (%)					Proportion (%)				
		Total	<0.5	0.5–2.0	2.0–3.5	>3.5	Total	<0.5	0.5–2.0	2.0–3.5	>3.5	Total	<0.5	0.5–2.0	2.0–3.5	>3.5	Total
Heading stage	SAPH	**1902.53**	92.90	5.23	1.32	0.55	**111.76**	57.55	23.70	10.38	8.37	**5.08**	10.97	20.95	27.31	40.78	**0.300**
	SAPL	**2930.49**	91.01	7.04	0.66	1.29	**175.16**	63.34	28.18	5.39	3.09	**8.77**	19.82	37.49	21.84	20.85	**0.282**
	CK	**3575.41**	90.90	8.58	0.41	0.11	**217.37**	73.84	24.74	1.09	0.33	**16.45**	41.31	56.58	7.27	3.94	**0.243**
Mature stage	SAPH	**2108.94**	92.85	11.70	0.13	0.00	**94.42**	71.24	27.14	1.58	0.04	**5.15**	34.26	56.11	9.24	0.39	**0.346**
	SAPL	**3325.66**	87.69	11.70	0.53	0.08	**151.08**	56.59	36.31	5.50	1.60	**11.67**	18.57	49.10	21.76	10.57	**0.312**
	CK	**3363.88**	85.81	12.88	1.02	0.29	**174.64**	48.95	36.79	9.35	4.91	**19.26**	11.31	36.87	26.09	25.73	**0.241**

the application of OICSAPs, but the average diameter increased. The more OICSAPs applied, the more obvious this trend would be. This was mainly because OICSAPs kept enough water around the root, so that roots only need focused on a small area to absorb water, thus lowered demand for penetration and its amount, which were consistent with the result of Li Luhua's[14] research about the influence of soil moisture on root growth. Meanwhile, lager root diameter mainly due to the distribution of photosynthetic products, the length of root in OICSAPs made the growth of photosynthetic products trend to grow in lateral. At the same time, OICSAPs significantly altered the distribution of root system in different stages including that <0.5, 0.5–2.0, 2.0–3.5, and >3.5 cm, increasing proportion of active roots that were short than 0.5 cm, thus improving the capacity of absorbing water and fertilizer. Combined with the water and nutrients condition, they used water and fertilizer more efficiently, enhancing crop growth while reducing the risk of nutrition loss into groundwater. That was the reason why OICSAPs could save water and increase production.

As a whole, the detailed laboratory experiments and ESEM were set in this work to discuss the water-absorption characteristics and mechanisms of the OICSAPs as well as its effect on summer maize root growth and finally drew some conclusions. However, the experiments were carried out in deionized water and ions solutions, which were quite different from the complex soil environment, including the physical, chemical, biological, and other environmental conditions and the competition of multiple ions. Researches on water-absorption characteristics and mechanisms of OICSAPs in different soils were in greater demand.

CONCLUSIONS

Three categories of conclusions were achieved based on the research in this work:

1. Water-absorption rates of the OICSAPs in deionized water tested reached 221 g/g at maximum, while higher cation valence, larger ionic radius, and higher ion concentration result in lower water-absorption rate as $Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Fe^{2+} < Fe^{3+} < Al^{3+} < Cu^{2+}$, OICSAPs had better salt-tolerance and reusability, but anions' effect could be ignored;
2. The internal morphology features of OICSAPs integrated response to its water-absorption characteristics, which showed typical honeycomb membrane-like 3D crosslinked network structure after swelling, as well as obvious fractal characteristics. Metal cations had significant

influence on its original structure or even cause damage. In contrast, anions and ion concentration only changed pore size and number of OICSAPs, but relatively small changes in complexity of its network structure, so fertilizer containing high valence cations is unfit for mixing with OICSAPs.

3. Applying OICSAPs would reduce the total length, total surface area, and total volume of summer maize root, but increased the average diameter, while changing the proportion of root in different stages, especially increased exuberant fibrous roots that were <0.5 cm and significantly improved the capacity of absorbing and transporting capability, indicating the origin of OICSAPs in saving water and increasing production.

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