Novel superabsorbent polymer composites based on α-cellulose and modified zeolite: synthesis, characterization, water absorbency and water retention capacity

Enfa Fu · Sijia Zhang · Yu Luan · Yuting Zhang · Summaira Saghir · Zhenggang Xiao

Received: 31 May 2021 / Accepted: 16 December 2021 / Published online: 27 January 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract Most superabsorbent polymers (SAPs) are prepared based on synthetic polymers (from petroleum resources), making them costly, nondegradable, and not ecofriendly. To overcome these drawbacks, biodegradable and renewable natural materials are proposed as additions into SAPs. In this article, a new SAP composite was synthesized by using AA, AM, α-cellulose, and modified zeolite (MZE). The prepared SAP composites were analysed by FTIR spectroscopy, XRD, SEM and TGA. Then, their water absorbency and water retention capacity results were evaluated. AA and AM were successfully grafted to the α-cellulose chains, and MZE was uniformly dispersed in the SAP composite matrix as an inorganic filler, which endowed the SAP composites with a more undulant and coarser surface along with more abundant hydrophilic groups. In contrast with poly(AA-co-AM), the water absorbency of the prepared SAP composites increased by 93.88% in distilled water and 89.58% in 0.9 wt.% NaCl solution. Additionally, the water retention time of these SAP composites was 11.2 h when evaluated at 50 °C, which was a 71.79% increase. Moreover, both the $T_{\text{onset}}$ and $T_{\text{peak}}$ of the prepared SAP composites slightly increased compared with those of α-cellulose-poly(AA-co-AM), showing that the introduction of MZE could slightly improve the thermal stability of the SAP composites. These novel SAP composites with their excellent water absorbency and retention capacity could be applied to the agricultural and horticultural fields as water-keeping materials.

Keywords Superabsorbent polymer composites · Cellulose · Modified zeolite · Water absorbency · Water retention capacity

Introduction

As a soft material, superabsorbent polymers (SAPs) can absorb a large amount of water and retain it at a certain pressure (Islam et al. 2015). Thus, SAPs have potential applications in hygiene (Wu et al. 2008), horticulture (Khan et al. 2009), agriculture (Seki et al. 2014), and biological and tissue engineering (Divakaran et al. 2015). However, most SAPs are fully based on synthetic polymers (from petroleum resources), which are costly, nondegradable, and not ecofriendly (Guilherme et al. 2015; Wang et al. 2010). To overcome these drawbacks, many biodegradable and renewable materials have been proposed by many
researchers for use as co-components in SAPs (Feng et al. 2014; Dong et al. 2008).

Cellulose is an abundant biopolymer consisting of a linear chain of hundreds to thousands of $\beta$ (1 → 4)-linked D-glucose units (Petroudy et al. 2018). It will become the primary chemical resource in the future as novel cellulose-based functional materials are currently being developed for a variety of applications (Nogi and Yano 2008; Yuan et al. 2016). Additionally, cellulose has drawn considerable attention for preparing hydrogel materials due to its biodegradability, ease of availability, and nontoxicity (Dai and Huang 2017; Wang 2019). Moreover, the abundant reactive surface of cellulose is beneficial for further surface modification and allows it to be easily grafted with acrylic acid (AA) and acrylamide (AM) to prepare cellulose-based SAPs (Li et al. 2013). Cellulose-based SAPs exhibit excellent performance, such as good biocompatibility, low toxicity, and notable biodegradability (Wu et al. 2012; Marcı` et al. 2006). Despite these advantages, the poor mechanical properties and low gel strength that results from the inadequate hygroscopic swelling behaviour of cellulose-based SAPs strictly limit their application (Haraguchi et al. 2005). Recently, the introduction of clay material has been proven to be a method to produce SAPs that exhibit better swelling behaviour, higher mechanical strength, and excellent water absorbency, while also having a lower production cost (Chen et al. 2016a, b; Lu et al. 2015; Darder et al. 2017; Zhang et al. 2007a, b). Different clays, such as diatomite, rectorite, and sepiolite, have been used in the preparation of SAPs. Despite this, there are just a few studies on the use of zeolite in SAP composites. Zeolite is a well-known clay mineral (inorganic filler) (Saghir and Xiao 2021) with many unique advantages, including a lower cost and higher thermal stability (Yadav and Rhee 2012; Anbusagar et al. 2014; Saghir et al. 2020). After modification by NaOH solution, modified zeolite (MZE) has a larger surface area, stronger adsorption capacity, and more reactive hydroxide radical groups on the surface, contributing to strong interfacial interactions with the polymers in SAP composites (Fu et al. 2016). The introduction of MZE into cellulose-based SAPs may lead to better water absorbency, appropriate swelling behaviour and higher thermal stability.

Therefore, in view of the advantage of cellulose-based hydrogels as well as the exceptional structural properties of MZE, the novelty of this research work comprises the synthesis of crosslinked hydrogel composites of cellulose with MZE and the feasibility of its use as a regenerative, energy-efficient and cost-effective SAP to hold water. Initially, the hydrogel of cellulose is grafted with AA and AM, and MZE is further embedded in the parental hydrogel (SAP) matrix. The prepared SAP composites are analysed by Fourier transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM) and thermal gravimetric analysis (TGA). The water absorbency of the SAP composites is investigated in 0.9% NaCl solution and distilled water. Additionally, the swelling kinetics and water retention capacity of these SAP composites are studied. As expected, the obtained SAP composites exhibit outstanding water absorbency and water retention capacity.

**Experimental section**

**Materials**

Acrylamide (AM, 99%), acrylic acid (AA, 99%), hydrochloric acid (HCl, 36–38%), sodium hydroxide (NaOH, 96%), potassium persulfate (KPS, 99.5%), N,N$\text{-}$methylenebisacrylamide (MBA, 99%) and zeolite (ZE) were purchased from Shanghai Aladdin Industrial Corporation. The chemical formula of zeolite is $(\text{SiO}_2)_{x}(\text{Al}_2\text{O}_3)_y$, and the CAS number is 1318-02-1. The molecular weight of the used zeolite was 218.24, and its size was 5 mm. The inhibitor in AA was removed by reduced pressure distillation before use. Cellulose powder (α-cellulose, average particle diameter of 25 μm) was supplied by Shanghai Mackin Biochemical Co., Ltd. All other chemicals were of analytical grade and used without purification.

**Pretreatment of modified zeolite (MZE)**

To prepare modified zeolite (MZE), 10 g of ZE was placed in a vacuum oven for 20 h at 100 °C. Then, ZE was dispersed in 100 mL of NaOH solution in a dried flask with a magnetic stir bar. Then, the mixture was heated at 80 °C for 4 h and washed six times with deionized water. Finally, MZE was ground and sieved through a 140-mesh sieve with an average particle diameter of 5 μm before being saved in a desiccator for future use.
Preparation of the SAP composites (α-cellulose-g-poly(AA-co-AM)/MZE)

Briefly, 5 g of AA was neutralized with 50 mL of NaOH solution in an ice-water bath. Then, 1.5 g of AM and a certain amount of MZE were ultrasonically dispersed in the mixed solution for 20 min. Moreover, approximately 0.35 g of α-cellulose was dispersed in 100 mL of distilled water at 75 °C and allowed to swell for 4 h. The AM, AA, and MZE mixed solution was transferred into the swollen α-cellulose for premixing at 40 °C for 90 min in a N₂ atmosphere. The mixture was heated to 55 °C, and then 0.02 g of KPS was added. After 0.5 h, 0.0025 g of crosslinking agent MBA was added into the former mixture. Then, the mixture was heated to 65 °C for 4 h in a N₂ atmosphere and repeatedly washed with deionized water. The product was dried at 50 °C for 100 h. Finally, the dry SAP composites were cut for further characterization. All drying treatments occurred in a vacuum environment.

Characterization

The samples were analysed by FTIR spectroscopy (Nicolet iS10) using the KBr disk method (Saghir et al. 2020). The wavenumber range was 4000–500 cm⁻¹, and 32 scans with a resolution of 4 cm⁻¹ were averaged to obtain each spectrum.

The morphology of the samples was observed by SEM (Hitachi S-4800). The glass slides containing samples were covered with a layer of gold, making them conductive under the electron beam.

The crystal form of the samples was analysed in the range of 2θ = 5°–50° (interval of 0.05°) by XRD (Bruker D8) with a Cu Kα radiation source.

The thermal stability of the samples was estimated by TGA (PerkinElmer SDTQ600). The samples were heated in a N₂ atmosphere from 50 to 600 °C at a heating rate of 10 °C/min.

Water absorbency experiment

Briefly, 0.1 g of the SAP composites were immersed in distilled water or salt solution at room temperature to reach swelling equilibrium. Then, SAP composites were extracted from the solution, and the water absorbency (Q) of the SAP composites was measured with Eq. (1).

\[
Q(\text{g/g}) = \frac{M_t - M_d}{M_d} \tag{1}
\]

where \( M_t \) and \( M_d \) are the weights of the swollen and dry SAP composites, respectively. Five parallel tests were carried out for each sample.

Water retention study

The water retention capacity of the SAP composites was evaluated at 50 °C by the auto mass measurement experiment developed by our group (Chen et al. 2016a, b). All samples were analysed during the release from fully swelled SAP hydrogels by using the above swelling method. The water retention (WR) of the SAP composites was calculated by Eq. (2).

\[
WR(\%) = \left( \frac{W_i}{W_0} \right) \times 100\% \tag{2}
\]

where \( W_i \) and \( W_0 \) are the weights of the SAP composites at time \( t \) (min) during the water retention test and swollen SAP composites, respectively. Five parallel tests were carried out for each sample.

Results and discussion

Formation mechanism of the SAP composites

The proposed reaction mechanism of the SAP composites is shown in Fig. 1. First, the α-cellulose is swollen in distilled water. KPS, a free radical initializing agent, forms sulfate anion radicals that can cleave H⁺ from the hydroxyl group of α-cellulose to form alkoxy radicals. The alkoxy radicals initiate the polymerization of AA and AM, leading to a grafted copolymer of poly(AA-co-AM) onto α-cellulose chains. During graft polymerization, the crosslinker (MBA) forms a crosslinked network between the growing polymer chains by the end vinyl groups. Additionally, modified zeolite (MZE) has a highly active silanol (Si–OH) group, and it reacts with the carboxylic acid (–COOH) group to facilitate MZE particles to join the composite network. Moreover, MZE serves as a crosslinked point to increase the intensity of the crosslinked network. In general, SAP composites are prepared by grafting copolymerized AA and AM onto α-cellulose chains with the introduction of MZE as an inorganic filler; a similar
reaction mechanism has been illustrated in previous
studies (Pourjavadi et al. 2007; Mukerabigwi et al.
2015; Dai and Huang 2017).

FTIR spectroscopy analysis

Figure 2 displays the FTIR spectroscopy results of the
prepared samples. In the FTIR spectrum of MZE, the
absorption peak at 970 cm\(^{-1}\) is attributed to the
stretching vibration of the Si–O–Si group, and the
absorption peak at 522 cm\(^{-1}\) reflects the bending
vibration of Si–O–Al (Zhang et al. 2007a, b). Regard-
ing \(\alpha\)-cellulose, the stretching vibrations of the C–H
and C–O–C groups appear at 2850 cm\(^{-1}\) and
1032 cm\(^{-1}\), respectively. The absorption peaks at
approximately 3372 cm\(^{-1}\) and 1310 cm\(^{-1}\) are
assigned to the bending and stretching vibrations of
the –OH group (Saghir and Xiao 2021). The absorption
peak at 1053 cm\(^{-1}\) is related to the \(\beta\)-(1,4)
glycosidic bonds of cellulose. Regarding poly(AA-co-
AM), the absorption peak at 2941 cm\(^{-1}\) is ascribed to
the stretching vibration of the C–H group. The
absorption peaks at approximately 1541 cm\(^{-1}\) and
1415 cm\(^{-1}\) appear due to the asymmetrical and
symmetrical stretching vibration of the –COO\(^{-}\) group.
The absorption peak at 1669 cm\(^{-1}\) is characteristic of
the presence of carboxamide (Bao et al. 2011).
Comparing curve (d) with curve (a–c) in Fig. 2, the characteristic absorption peaks of MZE, \( \alpha \)-cellulose, and poly(AA-co-AM) all appear in the spectra of the SAP composites. The absorption peaks at 1550 cm\(^{-1} \) and 1404 cm\(^{-1} \) are strengthened, which is attributed to the asymmetric stretching vibration of a large amount of C=O groups. Additionally, the absorption peak at 1670 cm\(^{-1} \) is obviously strengthened because of the reaction between the –COOH group of \( \alpha \)-cellulose–poly(AA-co-AM) and the –OH group of MZE (Bao et al. 2011). The results suggest that the desired product (SAP composites) is successfully synthesized. Moreover, the broad characteristic peak at 3450–3310 cm\(^{-1} \) is ascribed to the vibration stretching of the abundant hydrophilic groups on the SAP composites (Fig. 2).

**XRD analysis**

The crystalline pattern of the prepared samples was determined with XRD, as displayed in Fig. 3. \( \alpha \)-Cellulose displays obvious peaks at 15.3° and 22.9°, which are related to cellulose I in nature (French 2014). These peaks of \( \alpha \)-cellulose disappear in the patterns of \( \alpha \)-cellulose-g-poly(AA-co-AM), indicating that the original crystal structure of \( \alpha \)-cellulose is destroyed during graft polymerization; thus, \( \alpha \)-cellulose forms an amorphous state to achieve better water absorbency. Regarding SAP composites, the weak diffraction peak at 21.9°–24.1° is attributed to the change in the crystalline phase (Mukerabigwi et al. 2015). Moreover, the characteristic diffraction peaks of MZE disappear in the SAP composites, indicating that MZE is uniformly dispersed in the SAP composite matrix (Dai and Huang 2017).

**SEM analysis**

The surface morphologies of the ZE, MZE, \( \alpha \)-cellulose, \( \alpha \)-cellulose-g-poly(AA-co-AM), and SAP composites are shown in Fig. 4. As shown in Fig. 4a, b, MZE has a rougher and looser surface with a high specific surface area than ZE. The clear layered structure with gaps in MZE is conducive to the absorption of water molecules. The \( \alpha \)-cellulose shows a long-strip structure, promoting its use as the target macromolecule for grafting and copolymerizing with monomers in the presence of the initiator. Compared with Fig. 4a–d, due to the introduction of MZE, the SAP composites have a coarser and undulant surface, which endows the SAP composites with a larger superficial area to enhance its water absorption capacity.

**Water absorbency**

The water absorbency of the samples was measured with distilled water and 0.9 wt.% NaCl solution, as displayed in Fig. 5. As seen from Fig. 5, the water absorbency of the SAP composites is better than that of other samples in distilled water and 0.9 wt.% NaCl solution, respectively. It is clearly observed that the water absorbency of samples in 0.9 wt.% NaCl solution is apparently lower than that of distilled water. Na\(^+ \) mainly causes this phenomenon in the solution (the penetration of Na\(^+ \) into the crosslinked network decreases the water absorbency of these samples). After the introduction of MZE and \( \alpha \)-cellulose, the water absorbency of the SAP composites increases by 93.88% (from 350.28 ± 3.16 g/g to 679.13 ± 5.49 g/g) in distilled water, while it increases by 89.58% (from 46.65 ± 1.78 g/g to 88.46 ± 2.36 g/g) in 0.9 wt.% NaCl solution compared with poly(AA-co-AM). Combined with SEM, it is found that the SAP composites have a larger superficial area and a large number of hydrophilic groups after the introduction of MZE and \( \alpha \)-cellulose, which improve the surface adsorption capacity (Zhang et al. 2007a, b). In summary, the water absorbency of

![Fig. 3 XRD patterns of the MZE, \( \alpha \)-cellulose, \( \alpha \)-cellulose-g-poly(AA-co-AM) and SAP composites](image-url)
the SAP composites is obviously improved after the introduction of MZE and α-cellulose.

Figure 6 shows the water absorbency of the SAP composites with different MZE contents. As displayed in Fig. 6, the water absorbency of the SAP composites first increases and then decreases as the MZE content is increased. The highest water absorbencies of these SAP composites in distilled water and in 0.9 wt.% NaCl solution are achieved almost synchronously when the MZE content is 6 wt.%. The large number of pores in MZE accommodate more water molecules due to the increasing internal pore volume. Additionally, MZE can serve as a crosslinked point, which promotes the formation of the crosslinked network to enhance water absorbency (Li et al. 2015). When the content of MZE exceeds the optimal value, MZE may agglomerate, which will result in steric hindrance between the polymer chains and make it difficult for the reactants to evenly disperse in the SAP composites (Liang et al. 2009). The results show that the optimal content of MZE in the SAP composites for achieving an obviously enhanced water absorbency is 6 wt.%.

Fig. 4 SEM images of the a ZE, b MZE, c α-cellulose, d α-cellulose-g-poly(AA-co-AM), and (e) SAP composites
Therefore, SAP composites with an MZE content of 6 wt.% were prepared and used for further studies on the swelling kinetics, water retention capacity and TGA.

Swelling kinetics

The swelling process of the samples in distilled water is represented in Fig. 7. It is evident that the time for reaching the swelling equilibrium of SAP composites is shorter than that of poly(AA-co-AM) and \( \alpha \)-cellulose-g-poly(AA-co-AM). The swelling rate of the SAP composites rapidly increases within the first 30 min and then slowly increases to 679.13 ± 5.49 g g\(^{-1}\) until equilibrium is reached (55 min). Moreover, the swelling rate of the SAP composites is remarkably increased compared with that of \( \alpha \)-cellulose-g-poly(AA-co-AM) (440.23 ± 3.56 g g\(^{-1}\) at 55 min) and poly(AA-co-AM) (350.60 ± 1.28 g g\(^{-1}\) at 55 min). The results show that the addition of MZE and \( \alpha \)-cellulose affects the swelling kinetics of the SAP composites (which is related to the surface area and swelling ability (Zhang et al. 2006)). Moreover, the –OH groups increase the affinity of SAP composites to water molecules. The results show that the introduction of MZE and \( \alpha \)-cellulose affects the swelling kinetics of the SAP composites (which is related to their surface area and swelling ability (Zhang et al. 2006)). Additionally, the large amount of –OH groups increases the affinity of the SAP composites to water molecules. MZE also strengthens the crosslinked network of the SAP composites, providing more free volume for penetrating water molecules.

The swelling kinetics can be calculated by Eq. (3), which is based on the Voigt-based viscoelastic model (Kabiri et al. 2003; Irani et al. 2013):

\[
S_t = P(1 - e^{-r t})
\]  

(3)

where \( S_t \) (g g\(^{-1}\)) is the swelling property of the samples at some moment, \( P \) (g g\(^{-1}\)) is the power parameter, and \( r \) (min) is the rate parameter (the time required for the sample to reach 63% of its final swelling).

As shown in Fig. 7, the curves of the swollen samples are consistent with the experimental results. The \( P \)-value reflects better water absorbency, and the \( r \)-value reflects the swelling rates (Wang and Wang 2009). For SAP, \( r \) is 9.57 min and \( P \) is 681.16 g g\(^{-1}\),
for α-cellulose-g-poly(AA-co-AM), \( r \) is 17.22 min, and \( P \) is 465.34 g g\(^{-1}\), while for poly(AA-co-AM), \( r \) is 23.79 min and \( P \) is 397.10 g g\(^{-1}\). The swelling rate is higher when \( r \) is lower and \( P \) is higher. The results indicate that the SAP composites provide better water absorbency and a greater swelling rate after the introduction of MZE and α-cellulose owing to the increase in surface area.

**Water retention capacity**

The water retention capacity of the samples was evaluated at 50 °C by using an auto mass measurement experiment, as displayed in Fig. 8. It is notable that the water absorption rate decreases gradually with increasing time. Compared with α-cellulose-g-poly(AA-co-AM) and poly(AA-co-AM), the SAP composites possess a better water retention rate within the same interval. After 5 h, the weight loss of water in swollen SAP composites is approximately 51.1%, while α-cellulose-g-poly(AA-co-AM) is approximately 73.9% and poly(AA-co-AM) is approximately 92.8%. In contrast with poly(AA-co-AM), the water retention time of the SAP composites increases from 6.5 to 11.2 h, increasing by 71.79%. The results show that the water retention capacity of the SAP composites improves. The introduction of MZE and α-cellulose can resist the shrinkage of the SAP composite matrix. Moreover, the absorbed water is locked in the crosslinked network of the SAP composites, and more energy is needed to release the absorbed water, contributing to the enhanced water retention capacity (Li et al. 2004).

**Thermal behaviour analysis**

The effect of the introduction of MZE on the thermal performance of the SAP composites was further investigated by TGA; the analysis results are shown in Fig. 9 while the corresponding values are listed in Table 1.

Four mass loss stages are observed for α-cellulose-g-poly(AA-co-AM). The initial decomposition of both samples is due to the presence of moisture in the samples (Seki et al. 2014). The second loss stage between 105 and 346 °C is attributed to the decomposition of α-cellulose (Fu et al. 2016; Etminani-Isfahani et al. 2020). The third mass loss stage between 346 °C and 410 °C reflects the decomposition of some of the short or straight chains of α-cellulose-g-poly(AA-co-AM) (Liang et al. 2009). The fourth mass loss stage between 410 and 510 °C is ascribed to the degradation of the grafted chains in the crosslinked network (Bee et al. 2014). The TGA curve of the SAP composites contains four stages similar to α-cellulose-g-poly(AA-co-AM). However, the \( T_{10\%} \), \( T_{50\%} \) and \( T_{peak} \) (the temperatures at the maximum decomposition rate of each step) of the SAP composites increase compared with α-cellulose-g-poly(AA-co-AM), respectively. The above results indicate that the introduction of MZE, with its higher thermal stability, can slightly improve that of the SAP composites. As crosslinked points, MZE has strong interactions with the polymers in the SAP composites to enhance the strength of the crosslinked networks, thereby delaying the thermal decomposition of the SAP composites (Li et al. 2015; Etminani-Isfahani et al. 2020). Furthermore, the additional content of MZE is only 6 wt.%; thus, its effect on the thermal stability of the SAP composites is not significant.

**Conclusion**

A new SAP composite was successfully synthesized by grafting AA and AM onto α-cellulose chains with the introduction of MZE as an inorganic filler. In
contrast with poly(AA-co-AM), the prepared SAP composites had an undulant and coarse surface with abundant hydrophilic groups, and their water absorbency increased by 93.88% (from 350.28 ± 3.16 g/g to 679.13 ± 5.49 g/g) in distilled water and 89.58% (from 46.65 ± 1.78 g/g to 88.46 ± 2.36 g/g) in 0.9 wt.% NaCl solution. The swelling kinetic mechanism of the SAP composites was consistent with the Voigt-based viscoelastic model, and the results showed that the swelling rate was higher. Additionally, the water retention capacity increased by 71.79%. Moreover, the addition of MZE could slightly improve the thermal stability of the SAP composites. The excellent water absorbency and water retention capacity of the SAP composites demonstrate that this method for α-cellulose-g-poly(AA-co-AM)/MZE is appropriate for a variety of other inorganic fillers and polymer composite systems to prepare more SAP composites.

Acknowledgments  This work was supported by the National Natural Science Foundation of China (No. 22075146).

![Graph showing TG and DTG curves of α-cellulose-g-poly(AA-co-AM) and SAP composites](image)

**Table 1** Different characteristic temperatures in the TG and DTG experiments

| Sample                      | TG   | DTG   |
|-----------------------------|------|-------|
|                             | $T_{\text{onset}}/^\circ\text{C}$ | $T_{10\%}/^\circ\text{C}$ | $T_{50\%}/^\circ\text{C}$ | Residual rate/% | $T_{\text{peak}}/^\circ\text{C}$ |
| α-cellulose-g-poly(AA-co-AM) | 63.5 | 75.1  | 461.8  | 32.9 | 64 | 318 | 369 | 439 |
| SAP composites              | 63.8 | 77.2  | 476.7  | 34.5 | 63 | 330 | 372 | 450 |

![Table 1](image)
Authors’ contributions EF, SZ and YL contributed equally to this work. EF conceived the idea and designed the experiments. SZ contributed to the material fabrication. YL conducted the thermal property measurements and analysed the corresponding results. YZ and SS were responsible for the SEM images and FTIR measurements. EF, SZ and YL cowrote and revised the manuscript. All authors commented on the final manuscript.

Declarations

Conflicts of interest The authors declare that there are no financial or personal relationships with other people or organizations that could inappropriately influence their work in this paper. All the authors listed have approved the enclosed manuscript.

Ethical approval All authors state that they adhere to the Ethical Responsibilities of Authors.

Human or animal rights This study has followed compliance with ethical standards. There were no animal studies or human participants involvement in this study.

References

Anbusagar NRR, Giridharan PK, Palanikumar K (2014) Effect of nanomodified polyester resin on hybrid sandwich laminates. Mater Des 54:507–514. https://doi.org/10.1016/j.matdes.2013.08.025
Bao Y, Ma J, Li N (2011) Synthesis and swelling behaviors of sodium carboxymethyl cellulose-g-poly(AA-co-AM-co-AMPS)/MMT superabsorbent hydrogel. Carbohydr Polym 84(1):76–82. https://doi.org/10.1016/j.carbpol.2010.10.061
Bee S-T, Ratnam CT, Sin LT, Tee T-T, Hui D, Kadhum AAH, Rahmat AR, Lau J (2014) Effects of electron beam irradiation on mechanical properties and nanostructural–morphology of montmorillonite added polyvinyl alcohol composite. Compos B Eng 63:141–153. https://doi.org/10.1016/j.compositesb.2014.03.021
Chen J, Zhang W, Li X (2016a) Preparation and characterization of konjac glucomannan-acrylic acid-diatomite composites. Polym Compos 37(12):3384–3390. https://doi.org/10.1002/pc.23536
Chen M, Zhang Y, Dong C, Xiao Z (2016b) On-line auto mass measurement of residual solvent mass and its influence on mechanical properties of propellants. Propellants, Explos Pyrotech 41(6):972–977. https://doi.org/10.1002/prep.201600053
Dai H, Huang H (2017) Enhanced swelling and responsive properties of pineapple peel carboxymethyl cellulose-g-poly(acrylic acid-co-acrylamide) superabsorbent hydrogel by the introduction of carclazyte. J Agric Food Chem 65(3):565–574. https://doi.org/10.1021/acs.jafc.6b04899
Darder M, Matos CRS, Aranda P, Gouveia RF, Ruiz-Hitzky E (2017) Bionanocomposite foams based on the assembly of starch and alginate with sepiolite fibrous clay. Carbohydr Polym 157:1933–1939. https://doi.org/10.1016/j.carbpol.2016.11.079
Divakaran AV, Torris At A, Lele AK, Badiger MV (2015) Porous poly(ethylene glycol)-polyurethane hydrogels as potential biomaterials. Polym Int 64(3):397–404. https://doi.org/10.1002/pi.4802
Dong H, Xu Q, Li Y, Mo S, Cai S, Liu L (2008) The synthesis of biodegradable graft copolymer cellulose-graft-poly(L-lactide) and the study of its controlled drug release. Colloid Surf B-Biointerface 66(1):26–33. https://doi.org/10.1016/j.colsurfb.2008.05.007
Etminani-Isfahani N, Mohammadbagheri Z, Rahmati A (2020) 4-(6-Aminohexyl) amino-4-oxo-2-butenoic acid as a novel hydrophilic monomer for synthesis of cellulose-based superabsorbents with high water absorption capacity. Carbohydr Polym 250:116959. https://doi.org/10.1016/j.carbpol.2020.116959
Feng E, Ma G, Wu Y, Wang H, Lei Z (2014) Preparation and properties of organic-inorganic composite superabsorbent based on xanthan gum and loess. Carbohydr Polym 111:463–468. https://doi.org/10.1016/j.carbpol.2014.04.031
French A (2014) Idealized powder diffraction patterns for cellulose polymorphs. Cellulose 21(2):885–896. https://doi.org/10.1007/s10570-013-0030-4
Fu L, Cao T, Lei Z, Chen H, Shi Y, Xu C (2016) Superabsorbent nanocomposite based on methyl acrylic acid-modified bentonite and sodium polyacrylate: fabrication, structure and water uptake. Mater Des 94:322–329. https://doi.org/10.1016/j.matdes.2016.01.014
Guilherme MR, Aouada FA, Fajardo AR, Martins AF, Paulino AT, Davi MFT, Rubira AF, Muniz EC (2015) Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: a review. Eur Polym J 72:365–385. https://doi.org/10.1016/j.eurpolymj.2015.04.017
Haraguchi K, Li HJ, Matsuda K, Takehisa T, Elliott E (2005) Mechanism of forming organic/inorganic network structures during in-situ free-radical polymerization in PNI-PA—clay nanocomposite hydrogels. Macromolecules 38(8):3482–3490. https://doi.org/10.1021/ma047431c
Irani M, Ismail H, Ahmad Z (2013) Preparation and properties of linear low-density polyethylene-g-poly (acrylic acid)/organo-montmorillonite superabsorbent hydrogel composites. Polym Test 32(3):502–512. https://doi.org/10.1016/j.polymertesting.2013.01.001
Islam MS, Rahaman MS, Yeumi JH (2015) Electrospun novel super-absorbent based on polysaccharide-polyvinyl alcohol-montmorillonite clay nanocomposites. Carbohydr Polym 115:69–77. https://doi.org/10.1016/j.carbpol.2014.08.086
Kabiri K, Omidan H, Hashemi SA, Zohuriaan-Mehr MJ (2003) Synthesis of fast-swelling superabsorbent hydrogels: effect of crosslinker type and concentration on porosity and absorption rate. Eur Polym J 39(7):1341–1348. https://doi.org/10.1016/s0014-3057(02)00391-9
Khan F, Tare RS, Orefio ROC, Bradley M (2009) Versatile biocompatible polymer hydrogels: scaffolds for cell growth. Angew Chem Int Ed 48(5):978–982. https://doi.org/10.1002/anie.200804096
Li A, Wang A, Chen J (2004) Studies on poly(acrylic acid)/attapulgite superabsorbent composite. I. Synthesis and characterization. J Appl Polym Sci 92(3):1596–1603. https://doi.org/10.1002/app.20104

Li Y, Huang G, Zhang X, Li B, Chen Y, Lu T, Lu TJ, Xu F (2013) Magnetic hydrogels and their potential biomedical applications. Adv Funct Mater 23(6):660–672. https://doi.org/10.1002/adfm.201201708

Li J, Corma A, Yu J (2015) Synthesis of new zeolite structures. Chem Soc Rev 44(20):7112–7127. https://doi.org/10.1039/c5cs00023h

Li Y, Huang G, Zhang X, Li B, Chen Y, Lu T, Lu TJ, Xu F (2015) Synthesis of new zeolite structures. Li J, Corma A, Yu J (2015) Porous 3D network rectorite/chitosan gels: preparation and adsorption properties. Appl Clay Sci 107:21–27. https://doi.org/10.1016/j.clay.2015.01.020

Marci G, Mele G, Palmisano L, Pulito P, Sannino A (2006) Environmentally sustainable production of cellulose-based superabsorbent hydrogels. Green Chem 8(5):439–444. https://doi.org/10.1039/b515247j

Mukerabigwi JF, Lei S, Wang H, Luo S, Ma X, Qin J, Huang X, Lu Y, Chang PR, Zheng PV, Ma X (2015) Porous 3D network rectorite/chitosan gels: preparation and adsorption properties. Appl Clay Sci 107:21–27. https://doi.org/10.1016/j.clay.2015.01.020

Petroudy SRD, Ranjbar J, Garmaaroody ER (2018) Eco-friendly superabsorbent polymers based on carboxymethyl cellulose strengthened by TEMPO-mediated oxidation wheat straw cellulose nanofiber. Carbohydr Polym 197:565–575. https://doi.org/10.1016/j.carbpol.2018.06.008

Pourjavadi A, Barzegar S, Zeidabadi F (2007) Synthesis and properties of biodegradable hydrogels of κ-carrageenan grafted acrylic acid-co-2-acrylamido-2-methylpropylsulfonic acid as candidates for drug delivery systems. React Funct Polym 67(7):644–654. https://doi.org/10.1016/j.reactfunctpolym.2007.04.007

Saghir S, Xiao Z (2021) Hierarchical mesoporous ZIF-67@LDH for efficient adsorption of aqueous Methyl Orange and Alizarine Red S. Powder Technol 377:453–463. https://doi.org/10.1016/j.powtec.2020.09.006

Saghir S, Fu E, Xiao Z (2020) Synthesis of CoCu-LDH nanosheets derived from zeolitic imidazole framework-67 (ZIF-67) as an efficient adsorbent for azo dye from waste water. Microporous Mesoporous Mater 291:110010. https://doi.org/10.1016/j.micromeso.2020.110010

Sekić Y, Altunisik A, Demircioglu B, Tetik C (2014) Carboxymethylcellulose (CMC)-hydroxyethylcellulose (HEC) based hydrogels: synthesis and characterization. Cellulose 21(3):1689–1698. https://doi.org/10.1007/s10570-014-0204-8

Wang D (2019) A critical review of cellulose-based nanomaterials for water purification in industrial processes. Cellulose 26(2):687–701. https://doi.org/10.1007/s10570-018-2143-2

Wang W, Wang A (2009) Preparation, characterization and properties of superabsorbent nanocomposites based on natural guar gum and modified rectorite. Carbohydr Polym 77(4):891–897. https://doi.org/10.1016/j.carbpol.2009.03.012

Wang J, Wang W, Wang A (2010) Synthesis, characterization and swelling behaviors of hydroxyethyl cellulose-g-poly(acrylic acid)/attapulgite superabsorbent composite. Polym Eng Sci 50(5):1019–1027. https://doi.org/10.1002/pen.21500

Wu L, Liu M, Rui L (2008) Preparation and properties of a double-coated slow-release NPK compound fertilizer with superabsorbent and water-retention. Bioresour Technol 99(3):547–554. https://doi.org/10.1016/j.biortech.2006.12.027

Yadav M, Rhee KY (2012) Superabsorbent nanocomposite (alginate-g-PAMPS/MMT): synthesis, characterization and swelling behavior. Carbohydr Polym 87(4):2519–2525. https://doi.org/10.1016/j.carbpol.2011.11.028

Yuan N, Xu L, Zhang L, Ye H, Zhao J, Liu Z, Rong J (2016) Superior hybrid hydrogels of polyacrylamide enhanced by bacterial cellulose nanofiber clusters. Mater Sci Eng C 67:221–230. https://doi.org/10.1016/j.msec.2016.04.074

Zhang J, Li A, Wang A (2006) Study on superabsorbent composite. VI. Preparation, characterization and swelling behaviors of starch phosphate-graft-acylamide/attapulgite superabsorbent composite. Carbohydr Polym 65(2):150–158. https://doi.org/10.1016/j.carbpol.2005.12.035

Zhang J, Qin W, Wang A (2007a) Synthesis and characterization of chitosan-g-poly(acrylic acid)/attapulgite superabsorbent composites. Carbohydr Polym 68(2):367–374. https://doi.org/10.1016/j.carbpol.2006.11.018

Zhang J, Wang L, Wang A (2007b) Preparation and properties of chitosan-g-poly(acrylic acid)/montmorillonite superabsorbent nanocomposite via in situ intercalative polymerization. Ind Eng Chem Res 46(8):2497–2502. https://doi.org/10.1021/ie061385i

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.