Journal of Polymer Science and Engineering (2023) Volume 6 Issue 1
doi: 10.24294/jpse.v6i1.2892

ORIGINAL RESEARCH ARTICLE

Polymer gel amended sandy soil with enhanced water storage and extended release capabilities for sustainable desert agriculture

Mohan Raj Krishnan[*], **Edreese Housni Alsharaeh**[*]

College of Science and General Studies, AlFaisal University, Riyadh 11533, Saudi Arabia

* **Corresponding authors**: Mohan Raj Krishnan, mkrishnan@alfaisal.edu; Edreese Housni Alsharaeh, ealsharaeh@alfaisal.edu

ABSTRACT

Herein, we report a facile preparation of super-hydrophilic sand by coating the sand particles with cross-linked polyacrylamide (PAM) hydrogels for enhanced water absorption and controlled water release aimed at desert agriculture. To prepare the sample, 4 wt% of aqueous PAM solution is mixed with organic cross-linkers of hydroquinone (HQ) and hexamethylenetetramine (HMT) in a 1:1 weight ratio and aqueous potassium chloride (KCl) solution. A specific amount of the above solution is added to the sand, well mixed, and subsequently cured at 150 °C for 8 h. The prepared super-hydrophilic sands were characterized by Fourier-transform infrared spectroscopy (FT-IR) for chemical composition and X-ray diffraction (XRD) for successful polymer coating onto the sand. The water storage for the samples was studied by absorption kinetics at various temperature conditions, and extended water release was studied by water desorption kinetics. The water swelling ratio for the super-hydrophilic sand has reached a maximum of 900% (9 times its weight) at 80 °C within 1 h. The desorption kinetics of the samples showed that the water can be stored for up to a maximum of 3 days. Therefore, super-hydrophilic sand particles were successfully prepared by coating them with PAM hydrogels, which have great potential to be used in sustainable desert agriculture.

Keywords: super-hydrophilicity; sand; polyacrylamide; hydrogels; water absorption

ARTICLE INFO

Received: 19 September 2023
Accepted: 22 October 2023
Available online: 7 November 2023

1. Introduction

Polymer hydrogels are otherwise known as superabsorbent polymers (SAPs) with unique three-dimensional networks of hydrophilic polymers that can absorb and retain large amounts of water within their networks[1–4]. The very high water absorption capacity of the hydrogel is due to the inherent thermodynamic affinity of the hydrophilic polymers for water molecules. Due to this excellent water absorption property, hydrogels are prime candidates for various applications such as tissue engineering, wound dressing, drug delivery systems, sensors, and agriculture[5–11]. In general, sand is an abundant natural resource in desert land and has a low water storage capacity, which makes sustainable agriculture highly challenging in these dry lands. However, some of the current methods used to overcome desertification involve various water irrigation systems, such as sprinkling, trickling, and/or micro-irrigation of water. However, these methods are expensive to install and also require constant maintenance. The cultivation of arid dunes needs a huge amount of water and frequent irrigation. This is due to the low water-holding capacity of the sand, which results in rapid infiltration and quick surface evaporation of water. Therefore, hydrogels have been widely employed to enhance the water-holding capacity of sandy soils to realize desert agriculture[12–27]. Among various hydrogels, anionic polyacrylamides (PAMs) are the most commonly used system for infiltration control, erosion management, and aggregate stabilization in soil[22,28–38]. Since the 1990s, there has been a rapid advancement in PAM hydrogel-based agricultural and environmental technologies. The ease of processing and the remarkable potency of absorbing huge amounts of water with excellent network integrity largely improve the overall efficiency and economies of agricultural and environmental processes[24,39,40]. In addition, the PAM hydrogels are inexpensive and highly recyclable.

Therefore, we report a facile preparation of PAM-coated sand for improved water absorption with controlled water release aimed at desert agriculture. The PAM-coated sand samples were prepared by mixing the sand particles with a 4 wt% aqueous PAM solution that is pre-mixed with organic cross-linkers of HQ and HMT in a 1:1 weight ratio and aqueous KCl solution, and subsequent curing at 150 °C for 8 h. The PAM-coated sand samples were then characterized in detail by FT-IR and XRD for surface coverage. The water absorption of the samples was studied by absorption kinetics at various temperatures, and the water release was analyzed by water desorption kinetics. The water swelling ratio for the PAM-coated sand has reached a maximum of 900% at 80 °C within 1 h. The desorption kinetics of the PAM-coated sand showed that the water can be stored for up to 72 h.

2. Materials and method

2.1. Materials

Polyacrylamide (PAM) with a Mol. wt. of 550,000 g/mol was purchased from Flotek. The cross-linkers, such as hydroquinone, HQ (99% purity), and hexamethylene tetramine, HMT (99% purity), were purchased from Loba Chemie. The potassium chloride, KCl, was purchased from Scharlau. The sand particles were collected from the deserts of Saudi Arabia.

2.2. Method

The sand particles were coated with PAM hydrogel using an in-situ method. The weight percentages of PAM, organic crosslinkers (HQ and HMT), and salt were taken from our previous optimized condition[22,31,41]. 4 wt% PAM solution, 0.3 wt% of HQ and HMT, as well as 2 wt% of KCl. The weights were all based on the amount of water used to dissolve the PAM. Hence, the PAM solution required to coat the sand was prepared by mixing a specified amount of PAM in DI water for 1 h. Then, the required amount of organic crosslinkers and KCl were added and mixed further for another 15 min. Finally, the prepared PAM solution was mixed with the sand. Afterwards, the sand mixed with PAM solution was cured at 150 °C for 48 h. FTIR and XRD studies were performed to analyze the chemistry of the sand-PAM gels. The water absorption capacity of the prepared sand-PAM gels was studied by immersing the dried sand-PAM gel beads in water for 48 h.

2.3. Characterization

Fourier transform infrared spectroscopy (FT-IR, Thermo Scientific Nicolet-iS10) spectra were used to study the chemical structure and surface interaction of sand-PAM hydrogel using attenuated reflectance (ATR) mode. The FT-IR spectra for the samples were recorded in the range of 4000–500 cm^{-1} wavenumbers[40,42–50]. The XRD (Rigaku MiniFlex 600) was used to characterize the successful surface coating of PAM hydrogel onto the sand[51–53]. The XRD of the samples was measured with Cu radiation [40 kV, 15 mA, Kα radiation (1.54 A°)] and recorded in the range of 5–80°[40,46,54,55].

3. Results and discussion

3.1. Surface interaction of PAM with sand

The reaction chemistry and mechanism for the formation of PAM hydrogel can be found in our previous works[22,31]. The surface interaction between the sand and the PAM matrix, i.e., the success of the sand being coated by the PAM hydrogel, was investigated using XRD and ATR-FTIR techniques. **Figure 1** depicts the XRD patterns of the PAM-coated sand in comparison to neat-sand and neat-PAM. The neat-sand attained sharp peaks with high intensity, indicating crystalline structure[56]. Meanwhile, the XRD patterns of the neat-PAM did not show the presence of sharp peaks as a result of the amorphous structure of the PAM[57]. Hence, the success of the sand coating was evaluated based on the peak intensities depicted for the sand-PAM gels with respect to neat-sand and neat-PAM. The absence of some of these peaks of sand and their corresponding decrease in intensities indicates the successful coating of the PAM hydrogel matrix onto the sand surface.

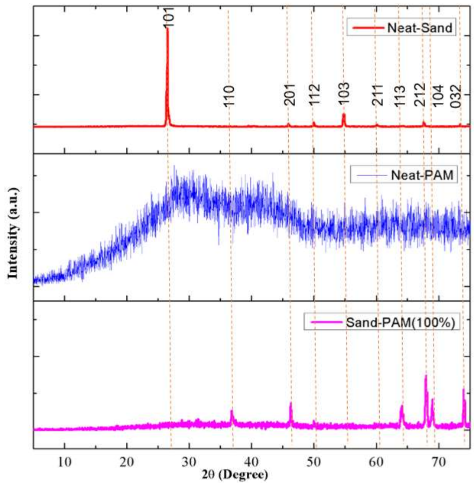

Figure 1. The XRD patterns of neat-sand, neat-PAM, and PAM-coated sand.

Figure 2 illustrates the ATR-FTIR spectrum of the PAM-coated sand in comparison to neat-sand[58] and neat-PAM[59]. The neat-PAM depicted the characteristic peaks of PAM, i.e., the C = O bond detected at 1642 cm^{-1} and the OH group at 3382 cm^{-1}. At a lower coating thickness, i.e., 5 wt% of the PAM coating thickness, the ATR-FTIR spectra of the sand-PAM gel resembled the neat sand, indicating that the amount used to coat the sand was not sufficient. Meanwhile, increasing the coating thickness to 15 wt% further, the attained ATR-FTIR peaks were similar peaks that resembled the neat-PAM. This shows that the sand particles were successfully coated with the PAM matrix.

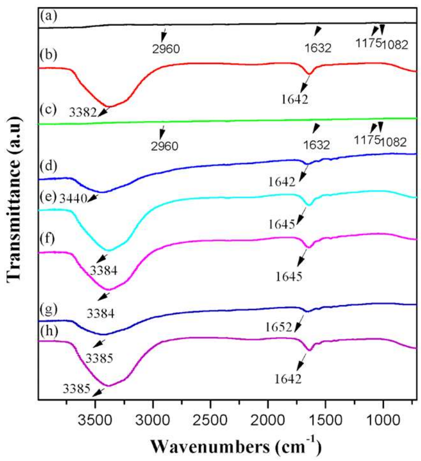

Figure 2. The FTIR spectrum of the PAM-coated sand at different coating thicknesses (a) neat sand, (b) neat PAM, (c) 5wt%, (d) 15wt%, (e) 25wt%, (f) 30wt%, (g) 50wt%, and (h) 100wt% of PAM to sand.

In addition, the peaks detected for the sand-PAM gel shifted slightly compared to the neat-PAM. For instance, the C = O bond detected at 1642 cm^{-1} for the neat-PAM was seen to slightly shift to 1645 cm^{-1} (i.e., 15 wt% PAM), 1645 cm^{-1} (i.e., 25 wt% PAM), 1645 cm^{-1} (i.e., 30 wt% PAM), 1652 cm^{-1} (i.e., 50 wt% PAM), and 1642 cm^{-1} (i.e., 100 wt% PAM). Meanwhile, the OH group of the neat-PAM at 3382 cm^{-1} shifted to 3440 cm^{-1} (i.e., 15 wt% PAM), 3384.48 cm^{-1} (i.e., 25 wt% PAM), 3384 cm^{-1} (i.e., 30 wt% PAM), 3384 cm^{-1} (i.e., 50 wt% PAM), and 3385 cm^{-1} (i.e., 100 wt% PAM). This redshift (i.e., increased in wavelength) indicates there is some kind of interaction between the sand and the PAM molecules, thus confirming the successful functionalization of the sand-PAM hydrogel.

3.2. Water absorption

The water absorption of the sand-PAM hydrogel was evaluated by immersing the dried samples in excess water for 48 h. The swelling ratio of the samples was calculated from the ratio of the weight of the swollen sample to that of the initial sample (Equation (1)).

$$Swelling\ Ratio(\%) = \frac{w_2 - w_1}{w_1} \times 100 \quad (1)$$

where w_2 (g) and w_1 (g) are the weights of samples before and after the absorption process, respectively. The results obtained are depicted in **Figure 3**. As evident from the figure, the swelling ratio for the neat PAM hydrogel is found to be as high as 12,000%. From the results obtained, it was seen that the water swelling ratios of the sand-PAM gel increased with an increase in PAM thickness, i.e., the water swelling was directly proportional to the amount of PAM coated on the sand particles. This suggested that the more PAM was used to coat the sand, the greater the gel's water absorption capacity due to the PAM's affinity for the water molecules.

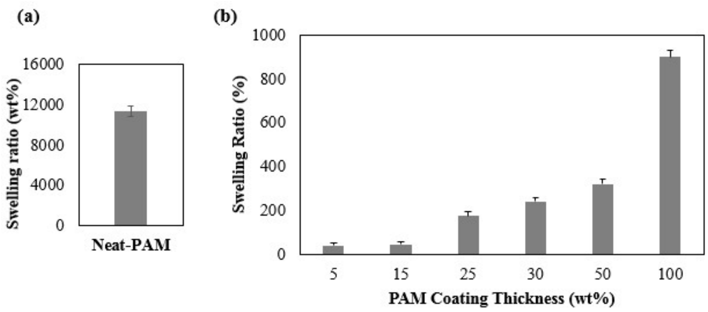

Figure 3. Water absorption of **(a)** neat-PAM and **(b)** PAM-coated sand at different PAM thicknesses after 48 h of swelling.

3.3. Water absorption kinetics

Kinetics analyses of water absorption by sand-PAM hydrogels are beneficial in elucidating the mechanism of the absorption process. **Figure 4** illustrates the absorption kinetic curves for the sand-PAM 100wt% at different temperatures of 25 °C, 50 °C, and 80 °C. The kinetic curves were obtained by plotting the swelling ratio as a function of contact time for the samples at the respective temperatures. As shown in **Figure 4**, the swelling ratio initially increases rapidly with contact time and reaches saturation in about 2 h then remains almost constant for up to 6 h. It can be distinctively concluded from the obtained kinetic curves that the observed kinetic trends are quite similar for the samples at different temperatures. Interestingly, it was observed that the swelling ratio increased with an increase in the temperature. The swelling ratio for sand-PAM 100wt% reached as high as 900% at 80 °C whereas the swelling ratio was found to be only 500% and 200% at 50 °C and 25 °C, respectively.

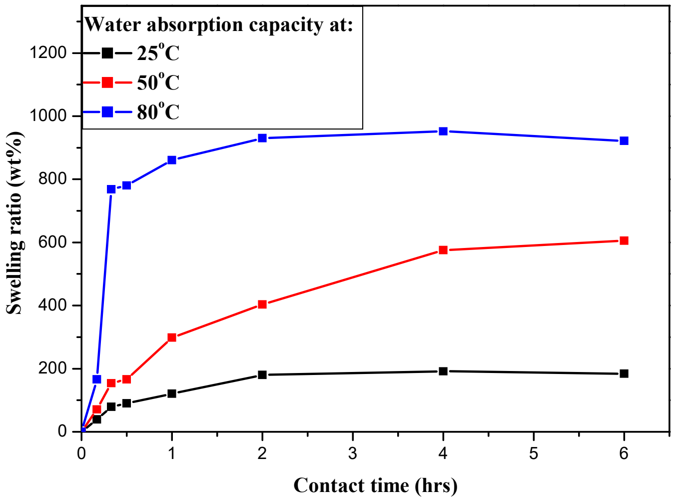

Figure 4. Water absorption kinetics of the PAM-coated sand at different temperatures.

3.4. Water desorption kinetics

Figure 5 illustrates the desorption kinetic curve for sand-PAM at 100 wt% at a temperature of 25 °C. The kinetic curve was obtained by plotting the deswelling ratio as a function of time for the sample at the respective temperature. As shown in **Figure 5**, the swelling ratio initially decreased at faster rates and reached saturation in about 25 h then remained almost constant for up to 70 h. This experiment was carried out in open air and under ambient conditions. Interestingly, the fabricated sand-PAM hydrogels have the potential for excellent water storage, with the most desirable characteristic being extended water release for several hours.

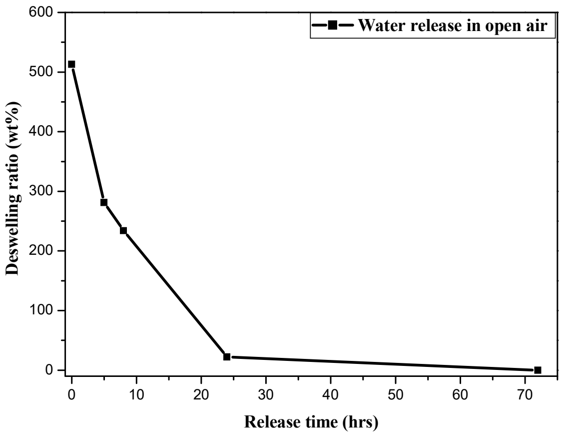

Figure 5. Water desorption kinetics of the PAM-coated sand at different temperatures.

4. Conclusion

The facile preparation of super-hydrophilic sand by coating the sand particles with cross-linked PAM hydrogels for enhanced water absorption and extended water release is reported. 4 wt% of PAM solution is mixed with organic cross-linkers in a 1:1 weight ratio and KCl solution. A specific amount of the PAM hydrogel solution is added to the sand particles, well mixed, and subsequently cured at 150 ℃ for 8 h. The prepared super-hydrophilic sand was characterized by FT-IR for chemical composition and XRD for successful polymer coating onto the sand. The FT-IR and XRD results revealed the successful coating of the PAM with sand. The water storage for the samples was studied by absorption kinetics at various temperature conditions, and extended water release was studied by water desorption kinetics. The water swelling ratio for the super-hydrophilic sand has reached a maximum of 900% (9 times its weight) at 80 ℃ within 1 h. Water absorption is found to be higher at higher temperatures. The desorption kinetics of the samples showed that the water can be stored for up to a maximum of three days. Therefore, super-hydrophilic sand particles were successfully prepared by coating them with PAM hydrogels, which have great potential to be used in sustainable desert agriculture.

Data availability statement

The data will be available based on a request from the corresponding authors.

Author contributions

MRK contributed to experimental studies, data analyses, and writing the original manuscript, and EHA supervised the project.

Acknowledgments

The authors gratefully acknowledge the continued support from Alfaisal University and its Office of Research.

Conflict of interest

The authors declare no competing financial interests.

Abbreviations

SAPs = Superabsorbent polymers
PAM = Polyacrylamide
HQ = Hydroquinone
HMT = Hexamethylenetetramine
KCl = Potassium chloride
FT-IR = Fourier-transform infrared spectroscopy
ATR = Attenuated reflectance
XRD = X-ray diffraction

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