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A water retention model considering biopolymer-soil interactions

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Abstract

Biopolymer treatment has been considered as one of the most sustainable methods of soil improvement for controlling subsurface water flow. It is able to alter pore structure and hence water retention behaviour of soil, as demonstrated by extensive experimental results in the literature. To predict the biopolymer treatment on the surface and subsurface water flow, it is important to develop a proper water retention model for biopolymer-amended unsaturated soil. The existing models do not consider the complex biopolymer-soil interactions, such as soil expansion induced by the biopolymer swelling. In this study, a new soil water retention model is developed with a consideration of various mechanisms of biopolymer-soil interactions, including (1) biopolymer occupies some pore space and therefore changes the pore size distribution of soil; (2) biopolymer itself is able to hold water; (3) the swelling of biopolymer may induce soil volume change; (4) the swelling of biopolymer is partially constrained by soil particles. To verify the new model, it is applied to simulate the measured water retention curves of seven soils. Measured and calculated results are well matched. It is convincingly demonstrated that the new model is able to well capture the water retention behaviour of various soils amended by different biopolymers.

Keywords: water retention; soil; suction; biopolymer;

Key points:

1. A water retention model is developed for unsaturated soil containing biopolymer.

2. The complex biopolymer-soil interactions are considered in the new model.

3. The model capability is well verified using extensive experimental data.

1. Introduction

With the growing demand for environmentally friendly and sustainable methods of soil improvement, biological approaches such as biopolymer treatment have been actively investigated in recent years. The biopolymer treatment is able to alter the hydraulic behaviour of soils (Chang et al., 2016; Klepikova et al., 2018; Xia et al., 2016). For example, Klepikova et al. (2018) used biopolymer as a temporary grout in borehole to investigate how to remediate the natural groundwater flow. Biopolymer has been also used to reduced soil permeability and hence to control the direction of oil flow in the petroleum industry. When biopolymer is applied in the vadose zone, a very important issue is the soil water retention curve (SWRC), which is defined as the relationship between suction and soil moisture condition. The soil moisture condition is generally described using gravimetric water content, volumetric water content and degree of saturation. This curve is one of the most important hydrological parameters for seepage analysis used in the agricultural, environmental, hydrological and geotechnical areas related to the vadose zone (Lamorski et al., 2017; Ng and Pang, 2000; Sakai et al., 2015; Tan et al., 2016; Walczak et al., 2006).

The water retention behaviour of soil-biopolymer mixture is very complicated, since the application of biopolymer would alter the microstructure of soil. To investigate biopolymer effects on the SWRC, Rosenzweig et al. (2012) measured the SWRC of a sand amended by xanthan gum. It was found that the equilibrium water content at a given suction increased greatly by biopolymer treatment. By adding 1% biopolymer in weight, the saturated water content increased by about 25%. This implies that the biopolymer induced a swelling of soil and increased the average void ratio. At suctions ranging from 10 to 100 kPa, increase in the soil water content due to the biopolymer was up to two times. One of the reasons is that pure xanthan gum is able to hold water about twenty and five times in weight (i.e., $f_{w(p)}$ = 1000% and 500%) at suctions of 10 and 100 kPa, respectively. Similarly, some other researchers have observed that the water retention ability of a sand increased significantly by adding biopolymer (Jung et al., 2017; Tran et al., 2017). The observed biopolymer effects are most probably attributed to the interactions between soil and biopolymers. Biopolymer itself is able to adsorb some water to form hydrogel. During the hydration process, the biopolymer swells and tends to induce an expansion of soil. More importantly, the biopolymer occupies some pore space in the soil and therefore alters the pore size distribution.

To investigate the SWRC of biopolymer-amended soil, some theoretical studies have been carried out by previous researchers. Rosenzweig et al. (2012) reported a SWRC model based on linear superposition of the SWRCs of pure biopolymer and biopolymer-free soil. The model was applied to simulate the water retention behaviour of a xanthan gum-amended sand. The calculated and measured results were reasonably well matched at suctions higher than 10 kPa. However, the model over-predicted the equilibrium water content at suctions below 10 kPa. The discrepancy is likely because the swelling of biopolymer is larger at lower suctions, inducing stronger physical biopolymer-soil interactions. The swelling biopolymer in soil is also partially mechanically constrained by soil particle, but this mechanism was not taken into account in the model. Another simplification of this model is that it did not model the effects of biopolymer on the volume and pore space of biopolymer-amended soil. Hence, the model can be used to calculate the gravimetric water content only, but not the volumetric water content and degree of saturation which are important in the prediction of water flow volume. Recently, Carles Brangari et al. (2017) developed an advanced water retention model for biopolymer-amended soil. Different from the work of Rosenzweig et al., it considered suction-induced volume changes of biopolymer and their effects on the pore size distribution of soil. The new model, however, assumed a rigid soil and did not consider soil expansion induced by the swelling of biopolymer. The influence of soil void ratio, which strongly affects the SWRC, was not incorporated.

In this study, a new SWRC model is developed for biopolymer-amended soil. Different from existing models, the new model considers various mechanisms of biopolymer-soil interactions: (1) biopolymer itself is able to hold water; (2) biopolymer occupies some pore space and therefore changes pore size distribution of soil; (3) the swelling of biopolymer may induce soil volume change; (4) the swelling of biopolymer is partially constrained by soil particles. In the following sections, the derivation of the new model is presented. Then, model calibration and verification are discussed in detail.

2. Theoretical Development

2.1. A new SWRC model for biopolymer-amended soil

The new SWRC model is developed and based on the phase diagram shown in Figure 1. It can be seen that soil system consists of soil particle, biopolymer, pore air and pore water. Moreover, the pore water is presented in two forms. The first form of water is held by biopolymer to form hydrogel (i.e., inside biopolymer), while the second form of water is distributed in the pores between soil particles and hydrogels (i.e., outside biopolymer). The following three variables (f_p, $f_{w(s)}$ and $f_{w(p)}$) are used to define the mass ratio of different phases:

$$f_p = M_p / M_s \tag{1}$$

$$f_{w(p)} = M_{w(p)} / M_p \tag{2}$$

$$f_{w(s)} = M_{w(s)} / M_s \tag{3}$$

where M_s is the total mass of all soil particles; M_p is the dry mass of biopolymer; $M_{w(p)}$ and $M_{w(s)}$ are the mass of pore water in the first and second forms, respectively.

Similarly, four variables (e_p, $e_{w(p)}$, $e_{w(s)}$ and e_a) are used to define the volume ratio of different phases:

$$e_p = V_p / V_s \tag{4}$$

$$e_{w(p)} = V_{w(p)} / V_s \tag{5}$$

$$e_{w(s)} = V_{w(s)} / V_s \tag{6}$$

$$e_a = V_a / V_s \tag{7}$$

where V_s is the total volume of all soil particles; V_p is the total volume of all biopolymers; $V_{w(p)}$ and $V_{w(s)}$ are the volume of pore water in the first and second forms, respectively; V_a is the volume of pore air.

The gravimetric water content (w) of biopolymer-amended soil, which is defined as the ratio of pore water mass and the total mass of solid components (including all soil particles and biopolymers), is therefore equal to

$$w = \frac{f_{w(s)} + f_p \, f_{w(p)}}{1 + f_p} \tag{8}$$

When soil suction (s) changes, the value of $f_{w(s)}$, $f_{w(p)}$ and hence w varies. In the following sections, the $f_{w(s)}$-s and $f_{w(p)}$-s relations are derived individually. These two relations are then substituted into equation (8) to determine the relationship between w and s (i.e., SWRC).

2.2. Water storage in the biopolymer at different suctions

To determine $f_{w(p)}$ value in equation (8), one of key issues is to model the water retention ability of biopolymer, with and without the mechanical constraint from soil particles. Figure 2 shows the water retention behaviour of four different pure biopolymers, which have different polymer-soil interactions and were tested by Bhardwaj et al. (2007). The water content of each biopolymer reduces with an increase in suction, similar to the water retention behaviour of pure soil. To describe the relationship between $f_{w(p)}$ and suction (unit: kPa), the following semi-empirical equation is proposed:

$$f_{w(p)} = \frac{a}{1+s^b} \tag{9}$$

where a and b are soil parameters, controlling the saturated water content and desorption rate, respectively. It should be noted that equation (9) is proposed by modifying the equation of Rosenzweig et al. (2012): $f_{w(p)} = a/s^b$. By introducing the modification, the new equation does not predict an infinite $f_{w(p)}$ value when the suction approaches zero. Equation (9) is used to fit the water retention curves of the four biopolymers. The calculated results are shown Figure 2 for comparisons. It can be seen that equation (9) is able to well capture the water retention behaviour of these four types of biopolymers from 0 to 5 kPa suction. Furthermore, equation (9) is applied to simulate the water retention curve of biopolymer reported by Rosenzweig et al. (2012). They determined the water retention curve of xanthan gum in a wide suction range of 1 to 1000 kPa. The measured and calculated water retention curves are shown in Figure 3. They are clearly well matched. The value of parameters a and b for all biopolymers are summarized in Table 1.

On the other hand, Chenu and Roberson (1996) found that in a wide suction range of 3 to 1000 kPa, the air content in xanthan gum was almost zero. Based on their observation, it is assumed here that biopolymer in the soil remains saturated upon suction change. Hence, $e_{w(p)}$ is equal to

$$e_{w(p)} = f_p \ f_{w(p)} G_s \tag{10}$$

where G_s is the specific gravity of soil particles, which is defined as the ratio of soil particle density and water density.

Equations (9) and (10) can be used to calculate the mass and volume of biopolymer in soil. Both of them are derived without considering the interactions between biopolymer and soil particles. When biopolymer is distributed in soil pores, its swelling is likely to be constrained by surrounding soil particles. The constraint would be more obvious when the pore space in soil is small. As illustrated by equations (4) through (7), the pore space in soil is divided into four parts: e_p, $e_{w(s)}$, $e_{w(p)}$ and e_a. The value of $e_{w(p)}$ is zero prior to the swelling of biopolymer. Among the other three components, only the pores associated with $e_{w(s)}$ and e_a can be occupied by swelled biopolymer. The sum of these two void ratios is defined as effective void ratio (e_{eff}):

$$e_{eff} = e_a + e_{w(s)} \tag{11}$$

Following this definition, e_{eff} describe the total volume of pore spaces between soil particles. The initial value of e_{eff} prior to biopolymer swelling is denoted as e_0, and the $e_{w(p)}$ calculated using equation (10) is denoted as e^*. Using these variables (e_0 and e^*), the following equation is proposed to simulate the influence of biopolymer-soil interactions on biopolymer swelling:

$$e_{w(p)} = \frac{e^*}{1 + c\left(e^*/e_0\right)} \tag{12}$$

where c is a soil parameter. A larger c means stronger interactions between biopolymer and soil particles, and consequently the difference between $e_{w(p)}$ and e^* is larger. Although equation (12) is very simple, it has very clear physical meaning. When the ratio e^*/e_0 is higher, the constraint of soil particles on biopolymer swelling is larger. The ratio of $e_{w(p)}/e^*$ is hence smaller. Moreover, for a given e_0, the value of $e_{w(p)}$ increases consistently with e^*, but at a decreasing rate.

According to equation (12), equation (9) is modified as follow:

$$f_{w(p)} = \frac{a}{1+s^b}\frac{1}{1+c\left(e^*/e_0\right)} \tag{13}$$

Equation (13) describe the water retention behaviour of biopolymer in biopolymer-amended soil. The influence of soil particles is incorporated on the swelling and water retention behaviour of biopolymer. This is one of the key features of equation (13). It is used to calculate $f_{w(p)}$ in equation (8).

2.3. Water retention in soil pores

Many semi-empirical models for the water retention behaviour of biopolymer-free soil have been reported in the literature. The following equation of Van Genuchten (1980) is widely used:

$$f_{w(s)} = \left(1+(\frac{s}{d})^{m_2}\right)^{-m_1}\frac{e}{G_s} \tag{14}$$

where d, m_1 and m_2 are soil parameters. Among these parameters, d is closely related to the air-entry value (AEV) of soil. It is well recognized that the AEV increases with a reduction of void ratio (e). For obtaining the relationship between d and e, Gallipoli et al. (2003) proposed the following semi-empirical equation:

$$d = m_3 e^{-m_4} \tag{15}$$

where m_3 and m_4 are soil parameters. So far, equations (14) and (15) have been well verified using extensive experimental data (Gallipoli et al., 2003; Zhou and Ng, 2014). When they are applied to calculate $f_{w(s)}$ of biopolymer-amended soil, e_{eff} rather than total void ratio should be used. Furthermore, the value of e_{eff} would be affected by the presence of biopolymer. Firstly, the swelling of biopolymer induces clogging effects and hence reduce e_{eff} value. Secondly, the swelling of biopolymer induces an expansion of soil (i.e., an increase in e_{eff} value). By considering these two mechanisms, e_{eff} is equal to

$$e_{eff} = e_0 - e_{w(p)} + \Delta e \tag{16}$$

where Δe is the incremental void ratio induced by the swelling of soil. $e_{\mathrm{w(p)}}$ is calculated using equation (12), while a new formulation is proposed for Δe:

$$\Delta e = \frac{{e_{w(p)}}^2}{e_{w(p)} + e_0} \tag{17}$$

Note that equation (17) is semi-empirical, and it is used here because it is able to consider several important features of soil-biopolymer-water interactions. First of all, when the ratio $e_{\mathrm{w(p)}}/e_0$ is very small, the swelling of biopolymer does not induce an obvious expansion of soil. This is because the biopolymer-soil interactions are very weak. Secondly, with an increase in $e_{\mathrm{w(p)}}/e_0$, the volume of soil become more significantly affected by biopolymer due to stronger biopolymer-soil interactions. Furthermore, according to equations (16) and (17), the formulation $e_0+\Delta e > e_{\mathrm{w(p)}}$ is always valid. This ensures that the total volume of water in biopolymer never exceeds the total volume of pores.

To verify equation (17), it is used to model the volumetric strains of a sand induced by the swelling of xanthan gum. Three different mass concentrations of biopolymer were considered: 0.25%, 0.5% and 1%. The experimental results (Rosenzweig et al., 2012) and theoretical predictions are all shown in Figure 4, and they are well matched. It should be noted that to calculate the volumetric strain of soil, only three parameters (i.e., *a*, *b* and *c* in equation (13)) are required. Parameters *a* and *b* are calibrated using the results in Figure 3 (see Table 1). Hence, only parameter *c* is needed when equation (17) is applied. For the results shown in Figure 4, *c* value is estimated to be 1. At a biopolymer concentration of 0.25%, the volumetric strain of soil is very small (below 3%) when the suction is above 5 kPa. This is because at the early stage of wetting, the swelling of biopolymer is relatively less constrained. With a further reduction of suction below 5 kPa, the swelling of soil is much more significantly. This is attributed to the fact that when the volume of swelled biopolymer is larger, the interactions between biopolymer and soil are more significant. In addition, it can be seen from the figure that with an increase in the biopolymer concentration, the volumetric strain of soil is larger. When the biopolymer concentration is 0.25%, 0.5% and 1%, the accumulated volumetric strains at zero suction at about 10%, 15% and 20%, respectively. On the other hand, previous experimental results reveal that a volumetric strain above 10% is able to alter the water retention behaviour of unsaturated soil significantly (Ng and Pang, 2000). It is therefore very important to consider the biopolymer-soil interactions in developing a water retention model.

By combining equations (14) through (17), the following equation is derived for determining $f_{w(s)}$ in equation (8):

$$f_{w(s)} = \left(1 + \left(\frac{s\left(e_0^{\,2} / \left(e_{w(p)} + e_0\right)\right)^{m_4}}{m_3} \right)^{m_2} \right)^{-m_1} \frac{e_0^{\,2}}{\left(e_{w(p)} + e_0\right) G_s} \tag{18}$$

Equation (18) describe the water retention behaviour of unsaturated soil with a consideration of biopolymer-soil interactions. The effects of biopolymer on the inter-particle pore space and on the volume change of soil are taken into account. This equation is used to calculate $f_{w(s)}$ in equation (8).

2.4. Water retention of biopolymer-amended soil

Based on equations (8), (13) and (18), it is obtained that

$$
w = \frac{\left(1 + \left(\frac{s\left(e_0^{\ 2} / \left(e_{w(p)} + e_0\right)\right)^{m_4}}{m_3}\right)^{m_2}\right)^{-m_1} \frac{e_0^{\ 2}}{\left(e_{w(p)} + e_0\right)G_s} + f_p \frac{a}{1+s^b} \frac{1}{1+c\left(e^* / e_0\right)}}{1 + f_p} \tag{19}
$$

Equation (19) is the final formulation for modelling SWRC of biopolymer-amended soil. It can be used to calculate the gravimetric water content at any suction. Based on the mass-volume relationship of unsaturated soil, the volumetric water content (θ) and degree of saturation (S_r) can be calculated using the following equations:

$$
\theta = \frac{w\left(1 + f_p\right)G_s}{\left(1 + e_p\right) + \left(e_0 + \Delta e\right)} \tag{20}
$$

$$
S_r = \frac{w\left(1 + f_p\right)G_s}{e_0 + \Delta e} \tag{21}
$$

In each of the three equations above, there are seven model parameters: m_1, m_2, m_3, m_4, a, b and c. Parameters m_1, m_2, m_3, and m_4 can be calibrated using one SWRC of biopolymer-free soil (see equations (14) and (15)), in a similar approach as some previous studies (e.g., Gallipoli et al. (2012); Zhou & Ng (2014)). Parameters a and b can be calibrated based on one water retention behavior of pure biopolymer (see equation (9)). The last parameter c can be determined by fitting one SWRC of biopolymer-amended soil using equations (19) through (21).

3. Experimental verification of the proposed water retention model

To evaluate the capability of the new model, it is applied to model the water retention curves of seven soils containing biopolymer. The water retention curves of these several biopolymer-soil mixtures are available in the literature. All of them and the corresponding value of soil parameters are summarized in Table 2.

Bhardwaj et al. (2007) measured the water retention ability of a mixture of cross-linked polymeric substance and a sandy soil. Four different biopolymer concentrations were considered in their study, including 0, 0.25%, 0.5% and 1%. All specimens of biopolymer-soil mixture were saturated and then subjected to a drying process using the hanging column method. The experimental results, which shows the relationship between gravimetric water content and suction, are presented in Figure 5. The calculated results using the new model are also included in the figure for comparisons. It is clear that the model is able to well capture the water retention ability of PAM-soil mixture at various biopolymer concentrations. Without polymeric substance, the saturated gravimetric water content is about 0.2. The water content maintains almost constant at suctions below 3 kPa, suggesting an AEV of 3 kPa. When the PAM concentration increases to 1%, the gravimetric water content at the saturated state increases from about 0.2 to 0.5. This suggests that the addition of 1% PAM increased the total volume of saturated soil by 2.5 times. This observation is well captured by the new model, mainly because equation (17) is able to predict the volume change of soil induced by biopolymer. It should be pointed out the model of Carles Brangari et al. (2017) assumed a rigid soil, so it is not able to predict a change of saturated water content. Moreover, the water content starts to decrease at a suction of about 0.5 kPa when the PAM concentration is 1%. This AEV is only about 17% of that at the condition of zero biopolymer concentration. The reduction of AEV by adding PAM is most likely because the soil swelled significantly, as illustrated above, leading to a much larger void ratio. In addition, it is revealed in Figure 5 that with an increase in suction, the differences associated with biopolymer concentration become smaller. This is attributed to the fact that at a higher suction, the volume of biopolymer is smaller (see equation (12)) and the biopolymer-soil interactions are less significant.

Rosenzweig et al. (2012) measured the water retention curve of soils containing xanthan gum. Two soils were adopted in their studies, including Caesarea sand and Hamra soil (a Chromic Luvisol). The Caesarea sand is characterized by a narrow range of particle size distribution. Over 90% of the particles have a diameter in the range of 0.21 and 0.35 mm. The Hamra soil is characterized by a wider range of particle sizes, with 7% particles smaller than 0.11 mm and 15% particles larger than 0.5 mm. Four values, including 0, 0.25%, 0.5 and 1%, were used for the mass ratio between xanthan and soil. The water retention tests were carried out using the hanging column method in the suction range of 0 to 20 kPa and using the pressure plate method in the suction range of 20 to 500 kPa. Each test started from the saturated condition, followed by a cycle of drying and wetting. Figure 6 shows the measured relationship between volumetric water content and suction for the mixture of Caesarea sand and xanthan. It can be seen that the water retention ability of Caesarea sand increases significantly with increasing biopolymer concentration. For instance, when the concentration increases from 0 to 1%, the saturated water content increases from about 0.4 to 0.6, confirming that the addition of biopolymer induces a swelling of soil. The AEV increases from about 1 kPa to 5 kPa, suggesting that biopolymer is able to reduce the pore sizes of soil significantly. All of these features are well captured by the proposed model, as shown in this figure. It should be pointed out the existing model of Rosenzweig et al. (2012) is not able to predict the volumetric water content, as discussed in the section of Introduction. The current model has solved this problem by considering the influence of biopolymer swelling on the volume change of soil.

The measured and calculated water retention curves of the mixture of Hamra soil and xanthan are presented in Figure 7. It is clear that the measured and calculated results are well matched. With an increase in biopolymer concentration, there are obvious increase in the saturated water content and AEV. It should be noted that with increasing biopolymer concentration, the AEV reduces for cases in Figure 5, while it increases for cases in Figures 6 and 7. The different treads can be well explained using the new model. The AEV of soil is altered by biopolymer due to at least two mechanisms: (1) biopolymer reduces the effective void ratio (see equation (16)) by clogging effects and hence increase the AEV of soil; (2) the swelling of biopolymer induces an expansion of soil (see equation (17)), which would lead to a reduction of the AEV. The above results suggest that the first mechanism is dominant for the cases in Figures 6 and 7, while the second mechanism is more important for the case shown in Figure 5.

Narjary et al. (2012) measured the water retention curves of two biopolymer-amended soils, including a sandy soil from Rajasthan and an alluvial sandy loam soil from New Delhi. Pusa Hydrogel, which is a biopolymer based superabsorbent hydrogel, was used with three different concentrations: 0%, 0.5% and 0.7%. In each test, the biopolymer-soil mixture was compacted and saturated in a one-dimensional column. Then, the soil was subjected to drying with measurements of pore water pressure and water content at various locations. Figure 8 shows the measured and calculated water retention curves for the sandy soil. The experimental results can be well captured by the new model. Similar to the results above, the addition of biopolymer is able to greatly enhance the water retention ability of soil. At a quantitative level, the equilibrium water content at a given suction increases up to 100% as biopolymer increases from 0 to 0.5%. When the biopolymer concentration further increases from 0.5% to 0.7%, the increase in equilibrium water content at a given suction is less than 10%. It is clear that the increase rate of equilibrium water content with increasing biopolymer concentration is much larger, when the concentration is relatively lower. The different increase rates are attributed to the complex interactions between biopolymer and soil. As illustrated by equations (12) and (13), the biopolymer is able to swell more freely during the hydration process when the concentration is relatively lower. Hydrogel is therefore able to reduce pore size and improve the water retention ability of soil. When the biopolymer concentration is relatively higher, however, the swelling of hydrogel is more significantly constrained by soil particles. As a consequence, a further increase in the biopolymer concentration does not change the soil water retention ability too much.

Figure 9 shows the measured and calculated water retention curves of the alluvial sandy loam soil. The measured and calculated water retention curves are well matched at different conditions of biopolymer concentration. Similar to the water retention behaviour of the sandy soil (see Figure 8), the variation of water retention behaviour is more significant at the range of relatively lower biopolymer concentration. This phenomenon can be well simulated by the new model, mainly because the model is able to well consider the biopolymer-soil interactions, as discussed above.

Jung et al. (2017) determined the water retention curves of an unsaturated sand containing a polymer produced by acrylamide. Four different biopolymer concentrations were considered, including 0, 0.25%, 0.5% and 1%. Each test was started from the saturated condition and soil suction was controlled using the hanging column method. The relationship between degree of saturation and suction was determined and reported in Figure 10. The theoretical water retention curves calculated using the new model are also included in the figure for comparisons. It is clear that the proposed model is able to capture the experimental results. With an increase in biopolymer concentration, the AEV of soil increase significantly. For example, when the concentration increases from 0 to 1%, the AEV increases from about 1 kPa to 20 kPa. This is because the swelling of biopolymer is able to reduce the effective pore volume significantly, as illustrated by equation (16).

Tran et al. (2018) investigated the influence of xanthan gum biopolymer on the water retention behaviour of an unsaturated sand. In each test, the specimen was saturated and then subjected to drying. The suction was controlled using the axis-translation technique. The measured results are summarized in Figure 11, and theoretical results calculated using the new model are also included for comparisons. The measured and calculated results are well matched, confirming the good capability of the new model. When the biopolymer concentration increases from 0 to 0.25%, the saturated volumetric water content increases from about 0.4 to 0.8. This is because the swelling of biopolymer induces the expansion of soil. With a further increase of the biopolymer concentration, the water retention curve of the unsaturated sand only increases slightly. This is likely because a further addition of biopolymer is able to increase the swelling of soil. It should be pointed out that two studies (Tran et al., 2018; Rosenzweig et al., 2012) used xanthan gum. The calibrated values for parameters a, b and c are different between these two studies, likely because of the variation of xanthan gum.

The results shown in Figures 5 through 11 demonstrate that the new model is able to well capture the water retention behaviour of biopolymer-soil mixture. The model capability is closely related to the considerations of biopolymer-soil interactions, such as the expansion of soil and the reduction of effective void ratio by adding biopolymer.

4. Conclusions

In this study, a new soil water retention model is developed for unsaturated soil containing biopolymer. The new model considers various interactions between biopolymer and soil: (1) the biopolymer occupies some pore space of soil and therefore changes the pore size distribution; (2) the biopolymer itself is able to hold a large amount of water; (3) the swelling of biopolymer may induce an expansion of soil; (4) the swelling of biopolymer is partially constrained by soil particles.

This new model is able to well capture the water retention behaviour of seven different soils containing biopolymer, as comparisons with experimental data has convincingly demonstrated.

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References

Bhardwaj, A., Shainberg, I., Goldstein, D., Warrington, D., J Levy, G., 2007. Water retention and hydraulic conductivity of cross-linked polyacrylamides in sandy soils. Soil Science Society of America Journal, 71(2): 406-412.

Carles Brangari, A. et al., 2017. A mechanistic model (BCC‐PSSICO) to predict changes in the hydraulic properties for bio‐amended variably saturated soils. Water Resources Research, 53(1): 93-109.

Chang, I., Im, J., Cho, G.-C., 2016. Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering. Sustainability, 8(3): 251.

Chenu, C., Roberson, E.B., 1996. Diffusion of glucose in microbial extracellular polysaccharide as affected by water potential. Soil Biology and Biochemistry, 28(7): 877-884.

Gallipoli, D., Wheeler, S.J., Karstunen, M., 2003. Modelling the variation of degree of saturation in a deformable unsaturated soil. Géotechnique, 53(1): 105-112. DOI:10.1680/geot.53.1.105.37249

Jung, J., Ku, T., Ahn, J., 2017. Small strain stiffness of unsaturated sands containing a polyacrylamide solution. Materials, 10(4): 401.

Klepikova, M.V., Roques, C., Loew, S., Selker, J., 2018. Improved characterization of groundwater flow in heterogeneous aquifers using granular polyacrylamide (PAM) gel as temporary grout. Water Resources Research, 54(2): 1410-1419.

Lamorski, K., Šimůnek, J., Sławiński, C., Lamorska, J., 2017. An estimation of the main wetting branch of the soil water retention curve based on its main drying branch using the machine learning method. Water Resources Research, 53(2): 1539-1552.

Narjary, B., Aggarwal, P., Singh, A., Chakraborty, D., Singh, R., 2012. Water availability in different soils in relation to hydrogel application. Geoderma, 187: 94-101.

Ng, C.W.W., Pang, Y.W., 2000. Influence of stress state on soil-water characteristics and slope stability. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 126(2): 157-166.

Rosenzweig, R., Shavit, U., Furman, A., 2012. Water retention curves of biofilm-affected soils using xanthan as an analogue. Soil Science Society of America Journal, 76(1): 61-69.

Sakai, M., Van Genuchten, M.T., Alazba, A., Setiawan, B.I., Minasny, B., 2015. A complete soil hydraulic model accounting for capillary and adsorptive water retention, capillary and film conductivity, and hysteresis. Water Resources Research, 51(11): 8757-8772.

Tan, F., Zhou, W.-H., Yuen, K.-V., 2016. Modeling the soil water retention properties of same-textured soils with different initial void ratios. Journal of Hydrology, 542: 731-743.

Tran, T.P.A., Cho, G.-C., Chang, I., Lee, S., 2018. Effect of xanthan gum biopolymer on the water retention characteristics of unsaturated sand. International Conference on Unsaturated Soil, International Society for Soil Mechanics and Geotechnical Engineering.

Tran, T.P.A., Im, J., Cho, G.C., Chang, I., 2017. Soil–water characteristics of xanthan gum biopolymer containing soils, Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017.

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America journal, 44(5): 892-898.

Walczak, R., Moreno, F., Sławiński, C., Fernandez, E., Arrue, J., 2006. Modeling of soil water retention curve using soil solid phase parameters. Journal of Hydrology, 329(3-4): 527-533.

Xia, L. et al., 2016. Effects of bacterial cells and two types of extracellular polymers on bioclogging of sand columns. Journal of Hydrology, 535: 293-300.

Zhou, C., Ng, C.W.W., 2014. A new and simple stress-dependent water retention model for unsaturated soil. Computers and Geotechnics, 62: 216-222. DOI:10.1016/j.compgeo.2014.07.012

Table 1. Summary of input parameters for pure biopolymers

Biopolymer type and reference	*a*	*b*
Alcosorb [*Bhardwaj et al.*, 2007]	500	0.2
Stockosorb 500 Micro [*Bhardwaj et al.*, 2007]	800	0.2
Stockosorb 500 Medium [*Bhardwaj et al.*, 2007]	400	0.1
Stockosorb HCMG [*Bhardwaj et al.*, 2007]	600	0.15
Xanthan gum [*Rosenzweig et al.*, 2012]	90	0.51

Table 2. Summary of input parameters for various soils

Reference	Soil type	Biopolymer type	Testing method	m_1	m_2	m_3	m_4	a	b	c
Bhardwaj et al. (2007)	Sand	Polyacrylamide (PAM)	Hanging column method	3	3	6	0.2	100	1.5	0.4
Rosenzweig et al. (2012)	Chromic Luvisol	Xanthan gum	Hanging column method and pressure plate method	3.5	3	3	1	90	0.51	0.3
Rosenzweig et al. (2012	Caesarea sand	Xanthan gum	Hanging column method and pressure plate method	2	1.5	8	0.5	90	0.51	0.6
Narjary et al. (2012)	Sand	Pusa Hydrogel	One-dimensional column	0.5	1	2	1	400	0.5	0.4
Narjary et al. (2012)	Sandy loam	Pusa Hydrogel	One-dimensional column	0.4	1	8	1	300	0.4	0.6
Jung et al. (2017)	Sand	Polyacrylamide (Acros Organics)	Hanging column method	1.2	4	1	5.2	100	0.5	0.1
Tran et al. (2018)	Sand	Xanthan gum	Axis-translation method	0.5	1	2	1	6000	0.3	0.55

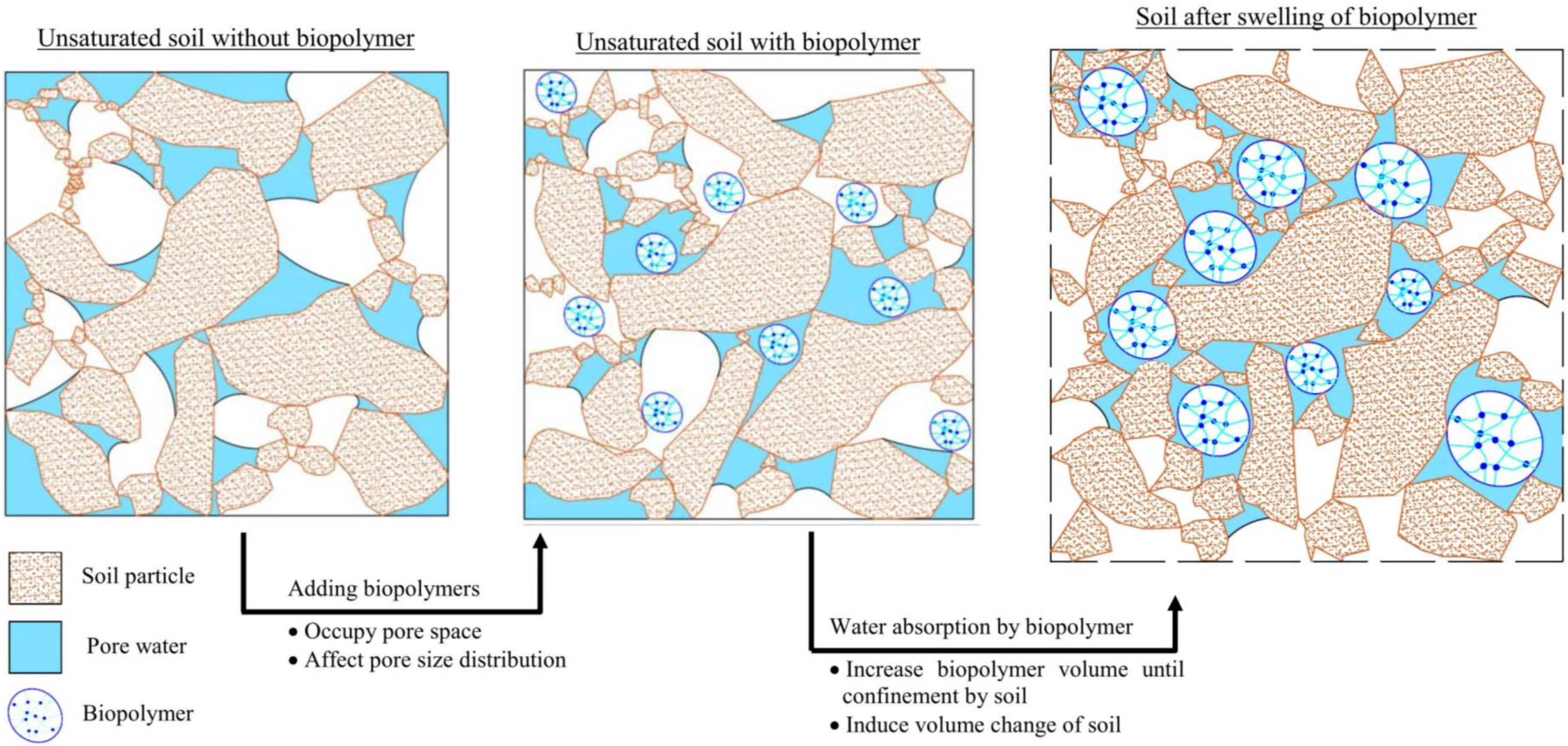

Figure 1. Schematic diagram illustrating biopolymer-soil interactions and the four assumptions made in this study

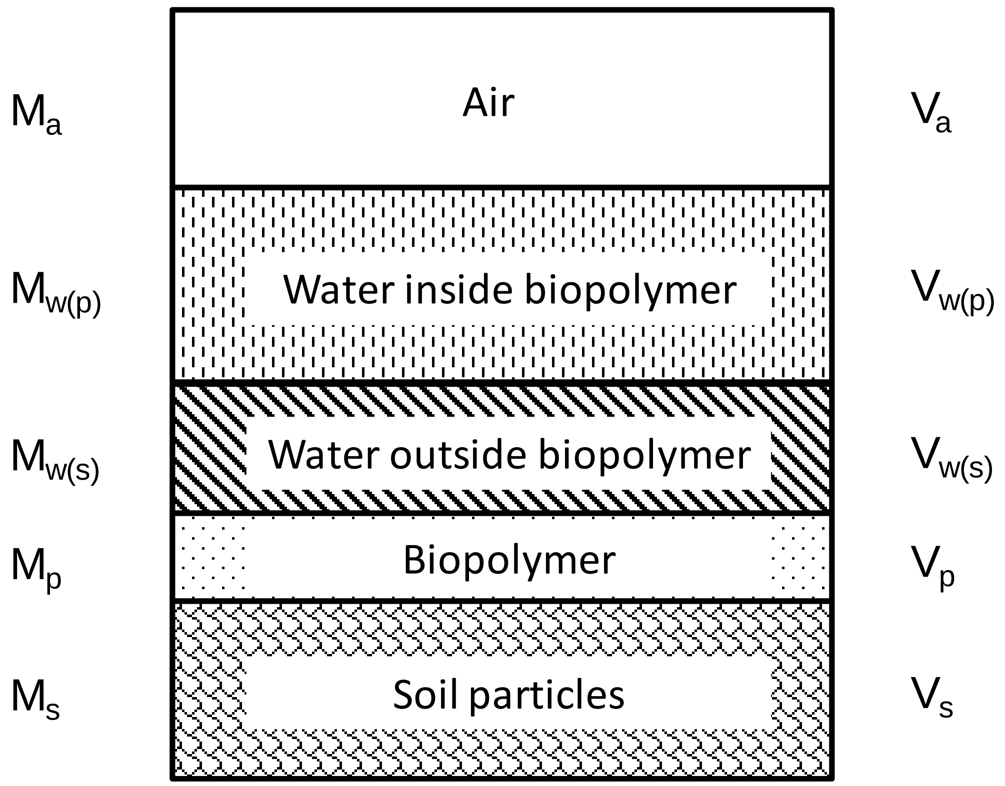

Figure 2. Phase diagram of a soil containing biopolymer

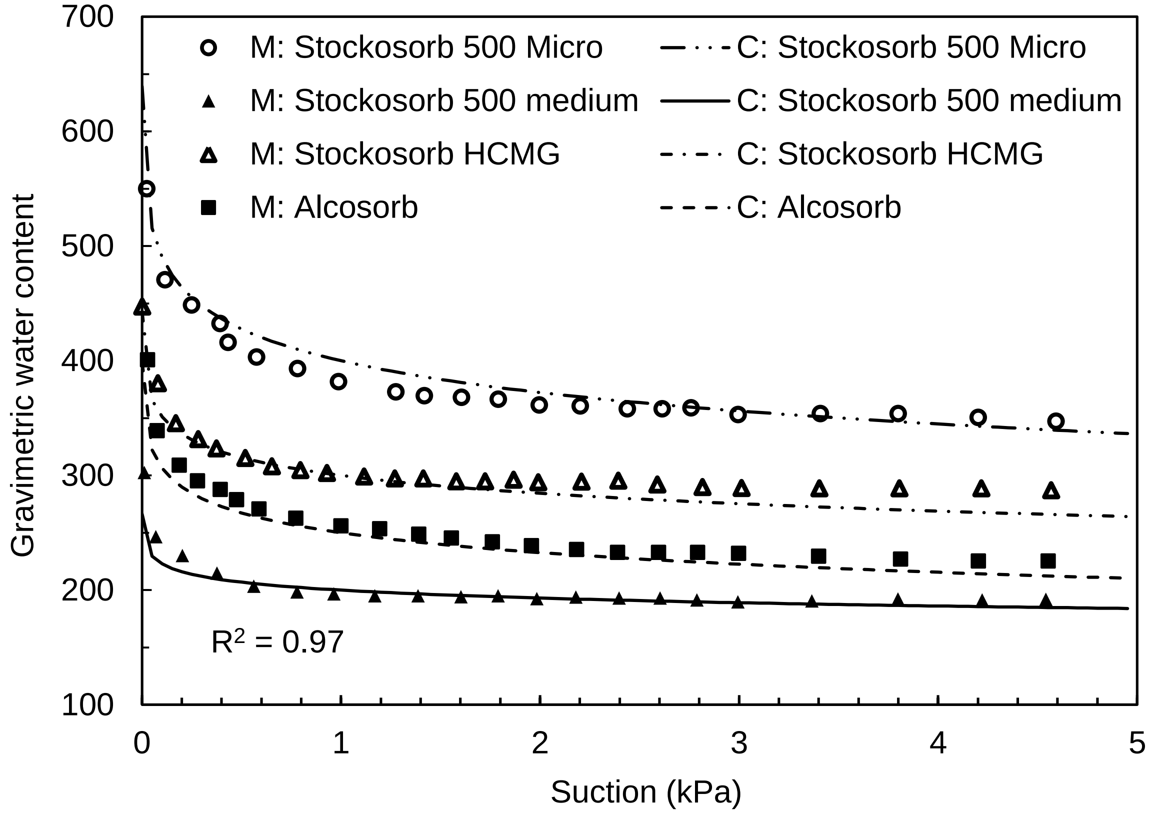

Figure 3. The relationship between gravimetric water content and suction for various pure biopolymers (M and C denote measured and calculated results, respectively; the test data was reported by Bhardwaj et al., 2007)

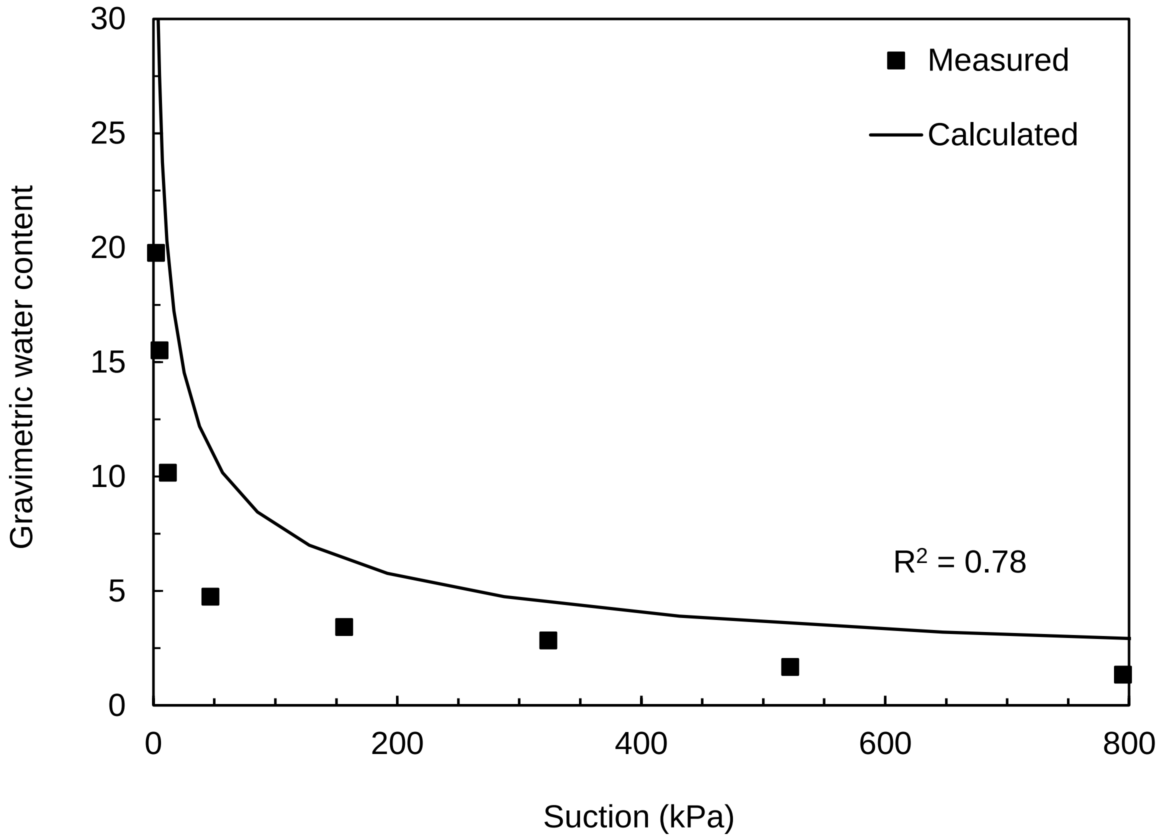

Figure 4. The relationship between gravimetric water content and suction for pure xanthan gum in a wide suction range (the test data was reported by Rosenzweig et al., (2012))

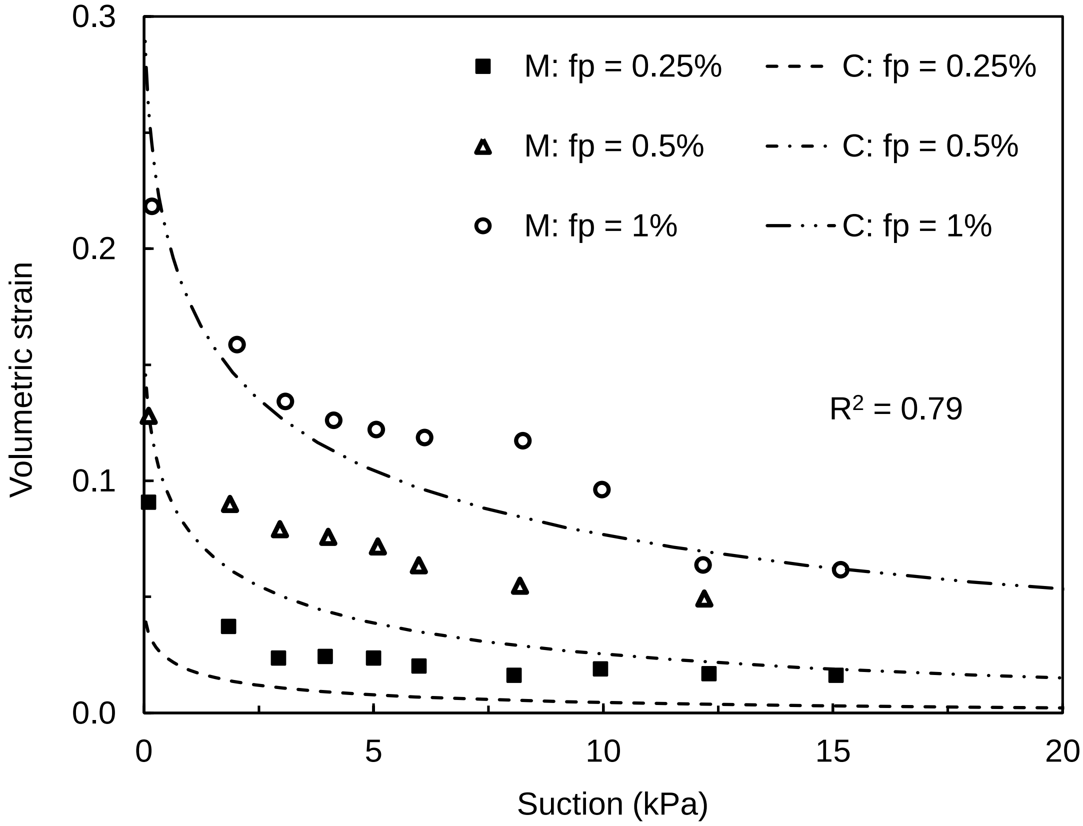

Figure 5. Measured (M) (Rosenzweig et al., 2012) and calculated (C) volumetric strains of a sand induced by the swelling of biopolymer

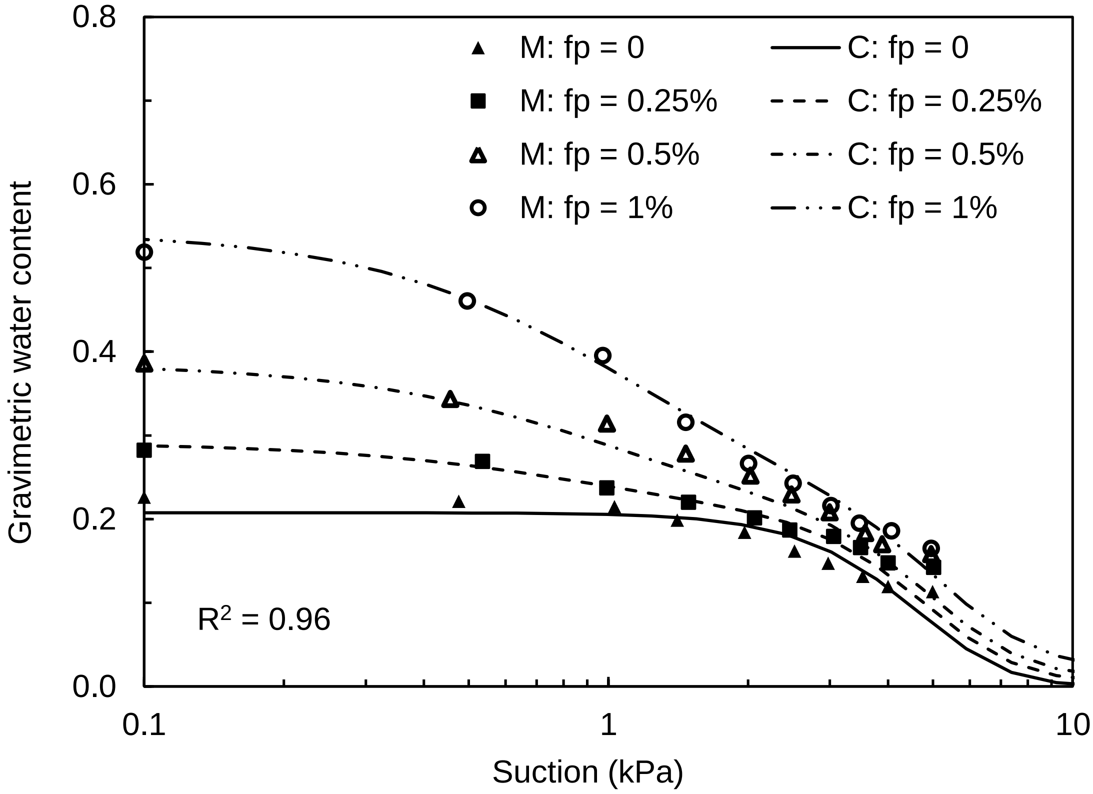

Figure 6. Measured (M) (Bhardwaj et al., 2007) and calculated (C) water retention curves of a sand containing polyacrylamide (PAM)

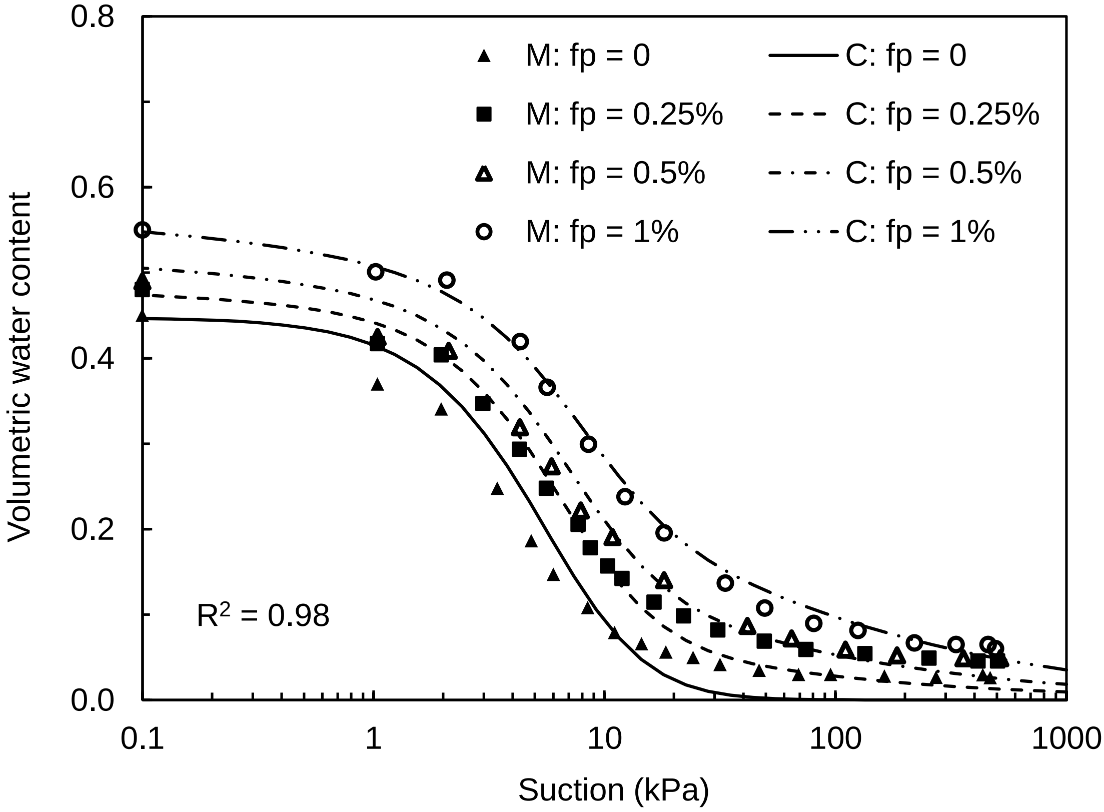

Figure 7. Measured (M) (Rosenzweig et al., 2012) and calculated (C) water retention curves of Caesarea sand containing xanthan gum

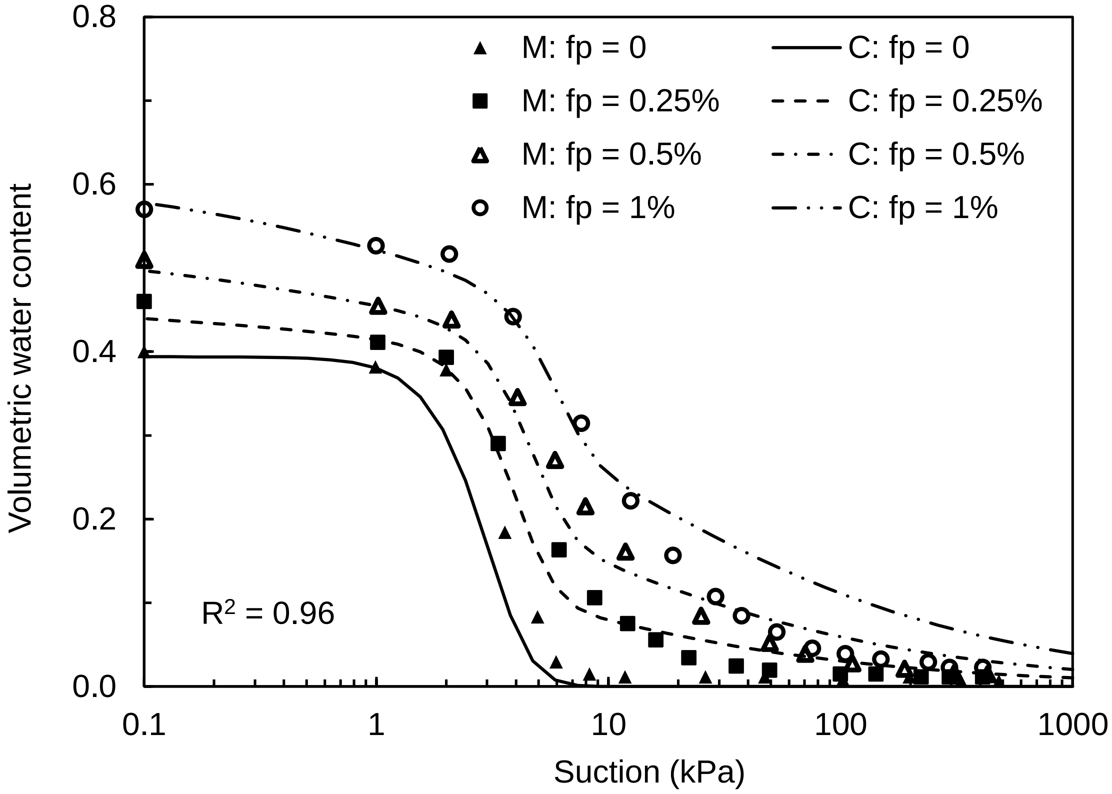

Figure 8. Measured (M) (Rosenzweig et al., 2012) and calculated (C) water retention curves of a Chromic Luvisol containing xanthan gum

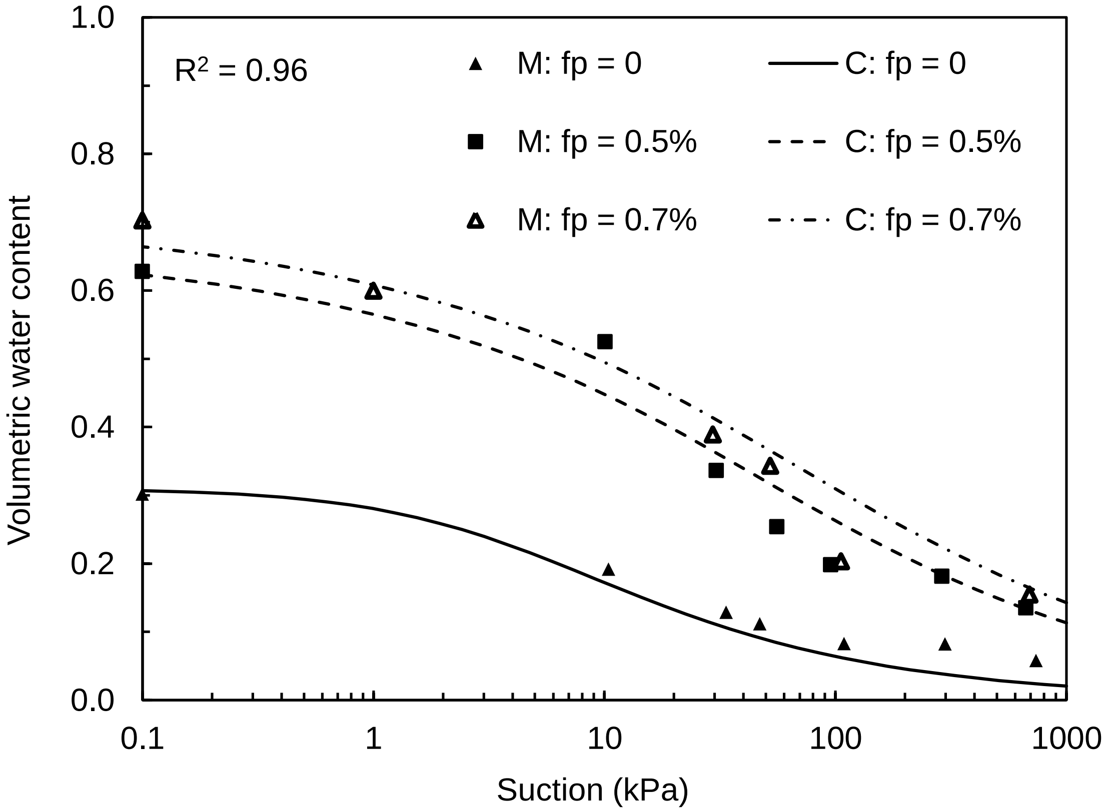

Figure 9. Measured (M) (Narjary et al., 2012) and calculated (C) water retention curves of a sand containing biopolymer-based Pusa hydrogel

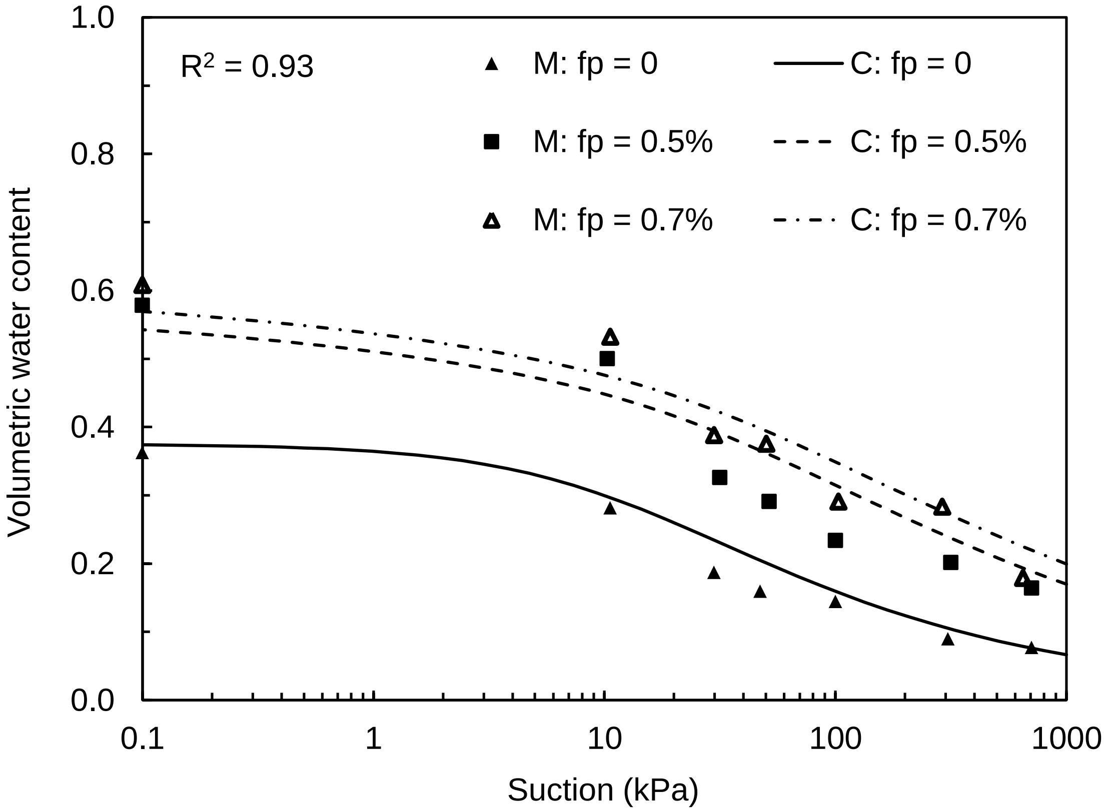

Figure 10. Measured (M) (Narjary et al., 2012) and calculated (C) water retention curves of a sandy loam soil containing biopolymer-based Pusa hydrogel

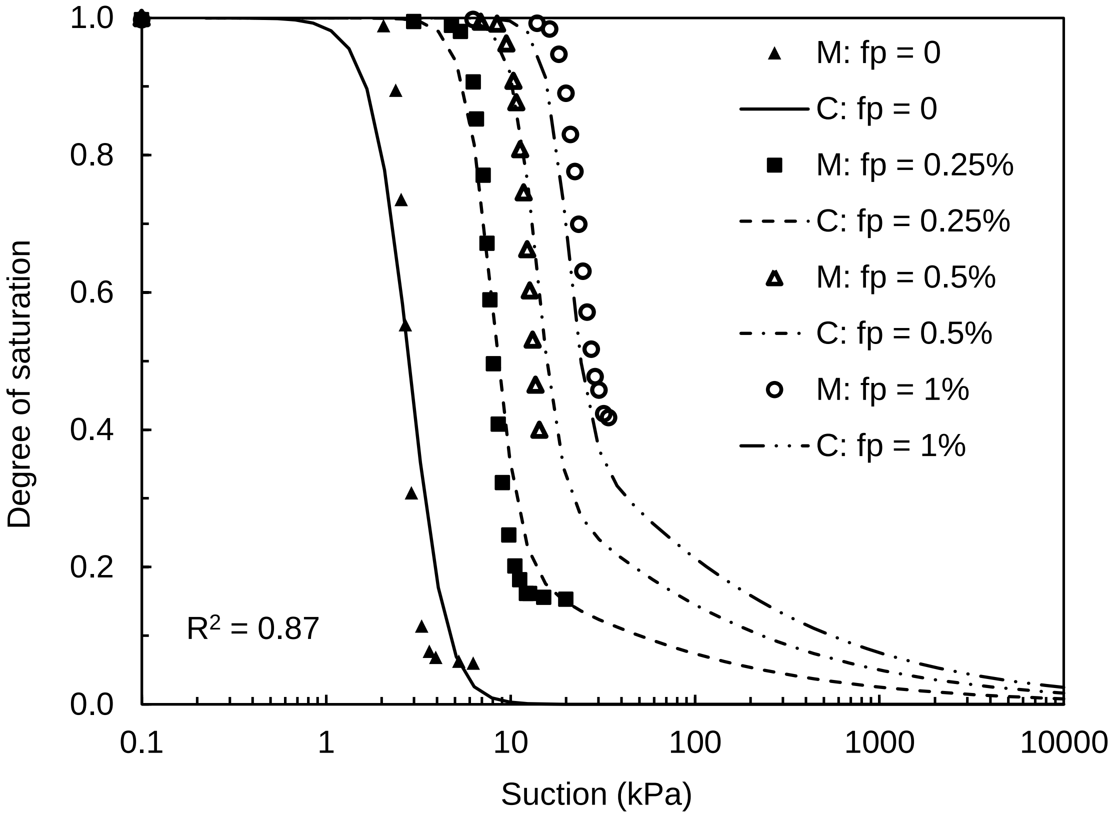

Figure 11. Measured (M) (Jung et al., 2017) and calculated (C) water retention curves of a sand containing polymer produced by acrylamide

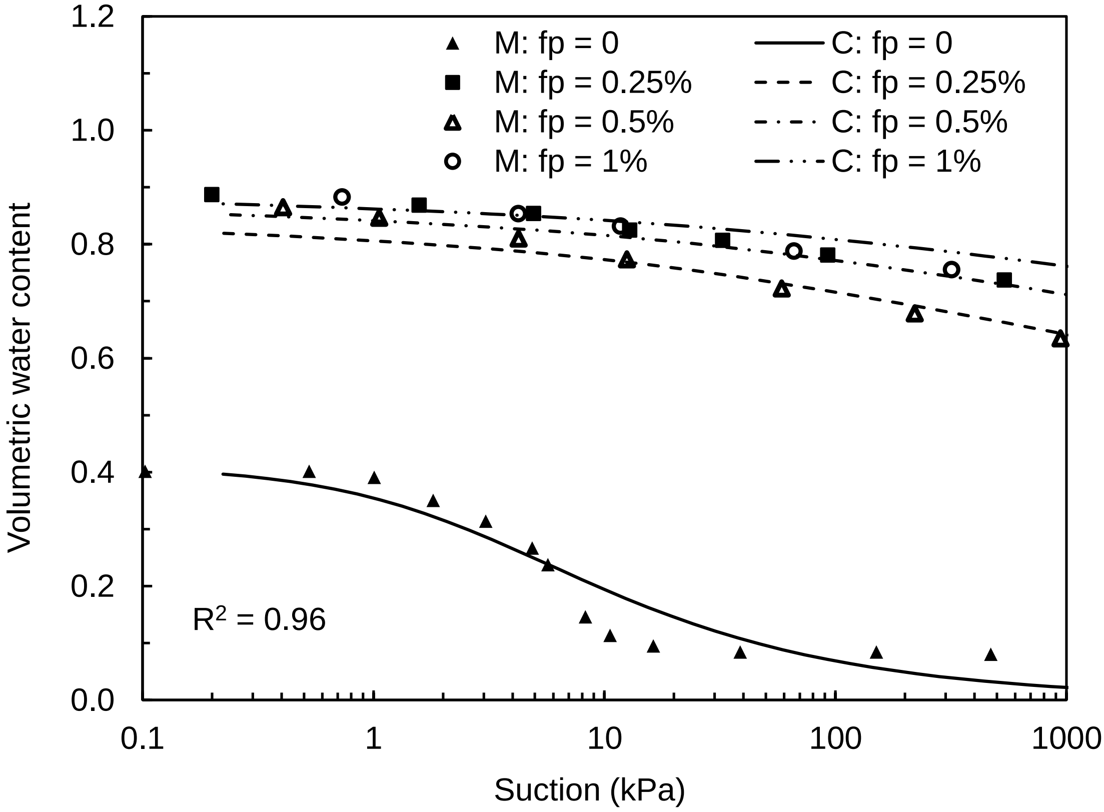

Figure 12. Measured (M) (Tran et al., 2018) and calculated (C) water retention curves of a sand containing xanthan gum