Measuring the water absorption capacity of superabsorbent polymers in soils

Yizhang Xu[1], *Mai* Sawada[1], *Stefano* Muraro[2], and *Hirokatsu* Fujita[3]

[1] Department of Civil and Environmental Engineering, Institute of Science Tokyo, Meguro, Tokyo, Japan
[2] Department of Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands
[3] Technica Goudou Co., Ltd, Kobe, Hyogo, Japan

Abstract. Superabsorbent polymers (SAPs) are used to remove excess water from liquid excavated soils and dredged soils. They are also used to improve soil water retention for agricultural purposes. The pore water of SAP-treated soils exists in two forms: absorbed and free water. Measuring the amount of absorbed water is crucial for assessing the hydro-mechanical behaviour of SAP-treated soils, as only free water contributes to suction-induced interparticle forces and water paths; however, methods for separating these two forms of water have not been established. This study presents an experimental methodology to estimate the water absorption capacity of SAP in soils. A centrifugal force smaller than the SAP absorption force was used to extract free water from the SAP-treated soil. Sandy soil treated with various SAP dosages and water contents was tested. The amount of absorbed water increased with higher dosage at a constant initial water content until it reached the maximum value. Based on the experimental results, a three-dimensional equation has been established to describe the relationship among the absorbed water content, SAP dosage, and initial water content. Regression analysis showed that the proposed equation effectively fitted the experimental data and provided a reliable prediction of absorbed water content for the tested material. The proposed experimental methodology and prediction method are useful for evaluating the mechanical and hydraulic properties of SAP-treated soil and for determining the optimal SAP dosage for soil with various initial water contents.

1 Introduction

Rapid and expanding urbanisation generates a huge amount of liquid excavated and dredged soils (e.g., river and marine sediments). Natural disasters, including floods, landslides, and tsunamis, also produce liquid soils to be disposed of. Disposal sites for these soils must be selected and managed with consideration for geotechnical risks (e.g., slope failure and settlement), as their capacity is limited. Reducing and recycling waste soil is important for sustainable development. Superabsorbent polymers (SAPs) can be used to remove excess water from liquid excavated and dredged soils for efficient transportation and sieving; however, as of today, guidelines for reusing waste soils treated with SAPs have not been established.

SAPs consist of cross-linked hydrophilic networks capable of absorbing and retaining large amounts of water, typically hundreds of times their own weight [2]. Instead of consuming water through chemical hydration reactions, SAPs function through a physical mechanism driven by osmotic pressure and the affinity of hydrophilic functional groups for water molecules [3]. In agriculture, SAPs are mixed with soil to improve soil water retention, especially under deficit irrigation, and benefit the physiological growth of crops [4]. Previous studies have investigated the hydraulic and mechanical behaviour of soils treated with superabsorbent polymers. Experimental results generally show that soil volume increases as SAPs absorb water and swell. This expansion reduces bulk density and, in some cases, increases permeability [5]. However, SEM observations by Zhao et al. (2019) [6] suggest that swollen SAP particles may clog soil pores, thereby limiting water infiltration. The swelling process can generate a modest swelling pressure and surface heave. Nevertheless, this effect is found to diminish with repeated wetting–drying cycles due to ionic interactions that reduce the swelling capacity of SAPs [7].

In cement-treated soils, SAPs have been shown to enhance compressive strength due to continuous hydration ensured by water stored within the polymer structure [8, 9]. Mercury Intrusion Porosimetry (MIP) results further indicate that SAP particles occupy pore space and reduce inter-aggregate voids [10]. Recent studies of potential applications of SAPs include the water-retention capacity of SAP-treated soils and desiccation cracks mitigation [11].

Temperature effects have also been examined, particularly under cyclic freeze–thaw conditions. The results indicate that interaction between water molecules and the polymer network can lower the freezing temperature and increase unfrozen water content, thereby improving freeze–thaw resistance [12].

Despite the previous experimental studies, significant knowledge gaps remain in developing a conceptual framework which describes the hydro-mechanical response of SAP-treated soils. The fundamental distinction lies in the physical state of soil water, as the absorption by SAPs transforms porewater morphology and interparticle forces due to surface tension. In this case, the pore water in SAP-treated soils is partitioned into two distinct phases as schematically shown in Fig. 1: (1) absorbed water, which is encapsulated within the SAP hydrophilic network, and (2) free water, which remains in the voids between soil particles. The water absorption by the SAP makes the water paths discontinuous, and the swollen SAP can block them. The remaining free water forms water paths, and surface tension forces acting on the air-water interface bond particles. Consequently, quantifying the actual amount of absorbed water in soil is crucial for evaluating the hydro-mechanical properties of SAP-treated soils; however, methods for distinguishing between absorbed and free water have not been established.

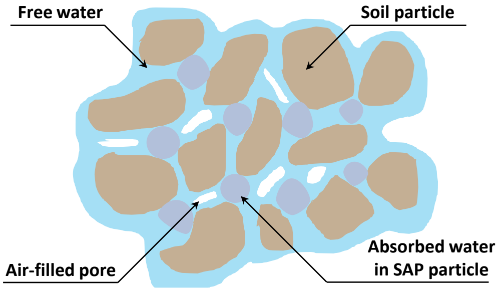

Fig. 1. Components of SAP-treated soil.

To bridge this gap, this study proposed a novel experimental method to separate the absorbed and free water using centrifugal force. Furthermore, the relationship between SAP dosages, initial water content, and absorption capacities was quantified. Based on the experimental results, a three-dimensional semi-empirical equation was derived by regression analysis to predict the water absorption capacity. These proposed methods are useful for evaluating the hydro-mechanical properties of SAP-treated soils and optimising dosages.

2 Materials

Sandy soil with an optimum water content of 15% and a maximum dry density of 1.78 g/cm^3 was used. The particle size distribution curve is shown in Fig. 2. The particle density was 2.74 g/cm^3.

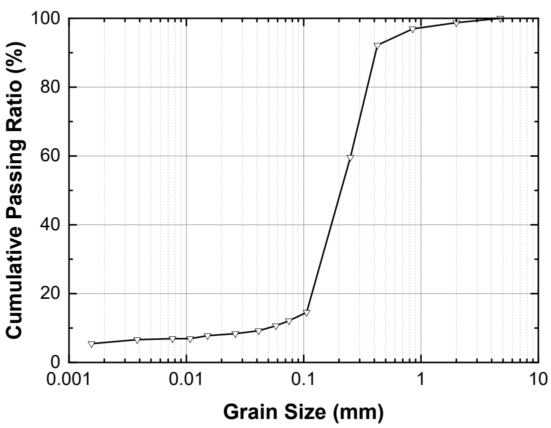

Fig. 2. Particle size distribution of the tested soil.

Fig. 3 shows the drying branch of the primary water retention curves at a dry density of 1.40 g/cm^3. The experimental data were interpolated with the Fredlund-Xing model [13]:

$$S_e = \left[\frac{1}{\ln\left[e + (h/a)^n\right]}\right]^m \quad (1)$$

where e is Euler's number, h is the suction, and the fitted results of three parameters, a, m, and n, are 3.584, 0.505, and 15.864, respectively. The estimated air entry value (AEV) is 3 kPa, while the residual water content is approximately 4.28%.

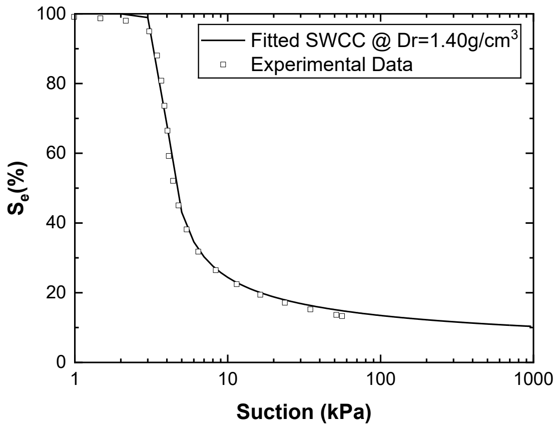

Fig. 3. Soil water characteristic curve for the tested soil.

SAP (Fines Spec, Technica Goudou Co., Ltd.) was used. The particle size is smaller than 149 μm, and the water absorption capacity of 1-gram polymer is approximately 40 g in a 0.9% salt solution with a pH range of 5.5 to 6.5 [14].

For the sample preparation, dry polymers and sand were used to prevent intrinsic soil water from interfering with the SAP water absorption, and to ensure that the total water content reached the target value. Dry sand and SAPs were mixed uniformly, and then distilled water was added, keeping the samples under unsaturated conditions. The curing time was determined as 24 hours for sufficient absorption of SAPs.

3 Methodology

3.1 Mechanisms and apparatuses

The free water in the SAP-treated soil can be extracted, while maintaining the saturation of the absorbed water by applying centrifugal force-induced suction that is smaller than the SAP internal capsule force, defined as the ability to retain the water; for the tested SAP, the capsule force measured in similar studies is approximately 1500 kPa [15], thus ensuring that the separated water is mainly from the pore water, while the water remains absorbed in the SAPs.

The suction at equilibrium with centrifugal force can be expressed as [16]:

$$\Phi = \frac{\rho\omega^2}{2g}(r_1^2 - r_2^2) \quad (2)$$

where Φ is the suction in the soil specimen, ρ is the density of the pore fluid, ω is the angular velocity, g is the gravity acceleration, r_1 is the radial distance to the midpoint of the soil specimen, and r_2 is the radial distance to the free water surface. Considering the soil type, sandy soil, used in this experimental study, it is reasonable to assume that the SAPs mainly absorb free water present in the soil pores rather than bonded water. [17].

The sample container (Fig. 4) was designed referring to the method by Thibault and Sheppard [18]. The outer tube had a capacity of 15 mL, with a diameter of 1.47 cm and a length of 10 cm. The dimensions of the inner one were slightly smaller than those of the outer one, with a diameter of 1.13 cm and a length of 8.82 cm, ensuring it can be nested within the outer one. A pipe spacer was settled at the bottom of the outer tube to support the inner one and store the drained water. At the bottom of the inner tube, a piece of filter paper was placed on polypropylene twine fibres as a cushioning layer. The strength of all components can withstand the large centrifugal forces involved.

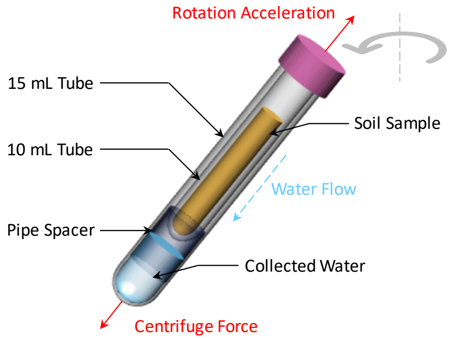

Fig. 4. The specimen container used for centrifuge tests.

The Beckman Avanti J-26S XP centrifuge (Fig. 5) was used to determine the water content at a rotation speed of 10,000 RPM, corresponding to a suction of 432 kPa. The suction value was calculated using Eq.1. The aluminium rotor with six 250 mL containers at a 25-degree angle to the rotation axis was used. Two adopters that can hold eight polypropylene conical tubes of 15 mL were set in the containers.

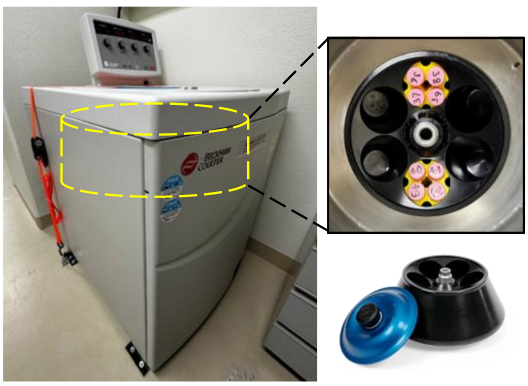

Fig. 5. Beckman Avanti J-26S XP and rotor.

The specimens were prepared using polymer dosages (d) ranging from 0.0% to 1.6% at 0.2% increments and the total water content (w_0) ranging from 12% to 30% (with 2% increments). Two specimens are prepared for each case. Each specimen is maintained at approximately 20 g with an accuracy of 0.01 g and an error not exceeding 0.03 g, in case of damage to the centrifuge caused by imbalance.

This method is inspired by blood centrifugation, which forces denser substances and particles to move outward in the radial direction. The movement of soil particles can be readily constrained, whereas liquids can pass through granular samples with low fine-fraction contents. However, this separation method may be less suitable for clayey soils, as fines restrict the movement of liquids within the sample.

3.2 Experimental procedures

The centrifugation time span was determined to record the steady-state water content at the generated suction. The specimens with d = 0% and w_0 = 20% were tested for 60 minutes, and the water contents at 1, 2, 3, 6, 10, 20, 40, and 60 minutes were recorded.

The separated water content, denoted as w_{sep}, which varies with time, is shown in Fig. 6. It was found that the maximum occurred at 10 minutes, after which the amount appeared to decrease. The average value was taken to minimise the experimental errors, i.e. 13.27%. The water content remaining in the sample, w_{rmn}, was 6.73%, in close agreement with the value (6.10%) estimated from the water retention curve at the suction of 432 kPa. These results show that 10-minute loading at 10,000 RPM enabled drying the sample to the residual state and extracting free water. In the following experiments, 10-minute loading at 10,000 RPM was used.

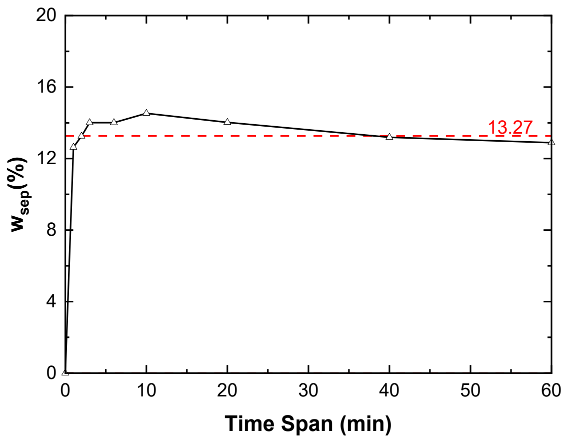

Fig. 6. Time effect on separated water content for the sample with d=0%.

Two specimens were prepared for each combination of d and w_0, and the mean value of the measured extracted free water masses was analysed. The post-test specimens were oven-dried to determine their exact initial water content.

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4 Results and discussions

4.1 Water separation

Fig. 7 illustrates the relationship between the separated water content (w_{sep}), defined as the ratio between the extracted water mass and soil particle mass, and initial water content (w_0) for different SAP dosages.

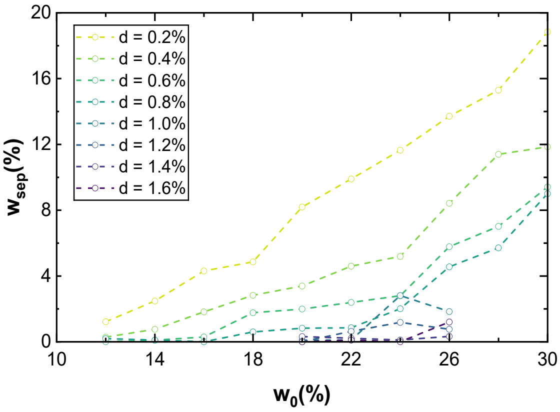

Fig. 7. Separated water content with initial water content.

Taking the curve at 0.6% SAP dosage as an instance, it can be seen that no water separation occurs for an initial water content lower than 14%. This suggests that within this range, the water is completely retained within the sample. This range extends with a greater SAP dosage. Meanwhile, the amount of separated water increases with the addition of w_0 because excess free water is supplied for absorption.

Fig. 8 shows the amount of separated water as a function of the SAP dosage at a given initial water content. The separated water gradually decreases with increasing SAP dosage. This tendency indicates that a greater amount of water is absorbed as more SAP is added, while the separable water becomes less. Equally, for a given dosage, the separated water decreases with lower initial water content. For example, with reference to w_0 = 12%, no separation is found when the SAP dosage approached 0.4%, indicating that the whole water is retained within the polymers and voids. These results indicate that, under the tested conditions, a specific dosage can sufficiently retain water in the soil to prevent drainage.

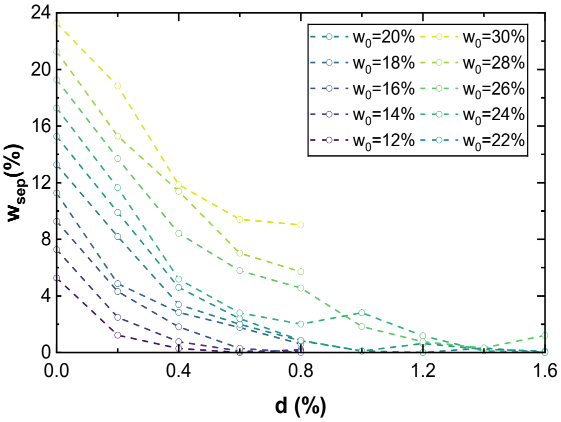

Fig. 8. Separated water content with SAP dosage.

4.2 Water absorption

Within the scope of centrifugation, water is present in the formation as separated water, absorbed water, and remaining water, collectively constituting the initial water content. This relationship can be expressed with Eq. 3:

$$w_0 = w_{abs} + w_{sep} + w_{rmn} \quad (3)$$

where w_0 is the total water content, w_{abs} is the absorbed water content, w_{sep} is the separated water content, and w_{rmn} = 6.73% is the remaining water content, consistent with the value reported in Section 3.2. Given the initial water content, w_0, the absorbed water content can be calculated.

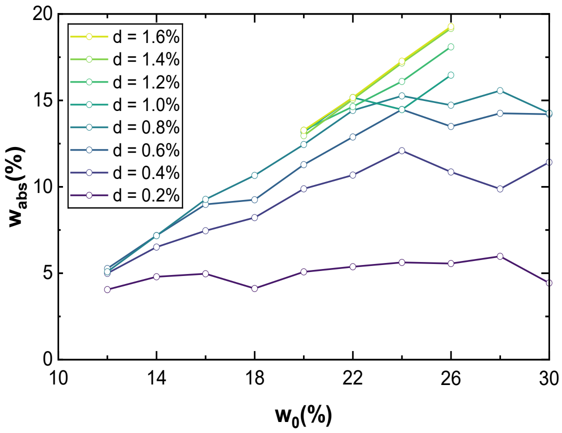

Fig. 9. Absorbed water content with initial water content.

Accordingly, Fig. 7 can be converted into a relationship between absorbed and initial water content, as shown in Fig. 9. As expected, the absorbed water increases with increasing initial water content. However, it is noteworthy that the curves exhibit a plateau at higher water contents. For example, at a dosage of 0.2%, the trend begins to level off once the initial water content reaches approximately 16%. Similarly, for a dosage of 0.4%, the plateau occurs when w_0 reaches about 22%. Furthermore, the plateau value increases consistently with increasing SAP dosage.

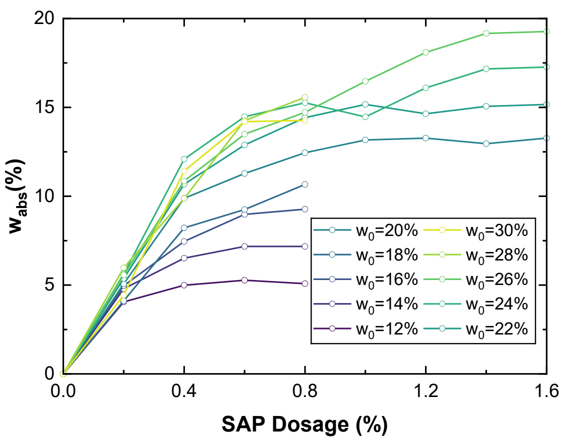

Fig. 10. Absorbed water content with SAP dosage.

Similarly, Fig. 10 depicts the variation in w_{abs} with increasing SAP dosage. It is observed that the amount of absorbed water rises gradually; on the contrary, the slope of the curves decreases, reaching a maximum imposed by the limited water available for absorption. A critical threshold value of SAP dosage can be identified, beyond which w_{abs} remains constant, which conforms with the observations in the previous section based on Fig. 8. Moreover, for all cases considered, the curves exhibit a similar pattern.

4.3 Non-linear regression model

The experimental results presented in the previous section are here explored to derive a regression model linking absorbed water content, w_{abs}, and SAP dosage. The proposed expression is reported in Eq. 4:

$$w_{abs} = w_{abs}^{max}\left(1 - e^{-\frac{d}{D}}\right) \tag{4}$$

where e is Euler's number, w_{abs}^{max} is the maximum absorbed water content for a given SAP dosage, d, and D is a fitting parameter. The regression curves at 14% and 20% are plotted in Fig. 11 as examples.

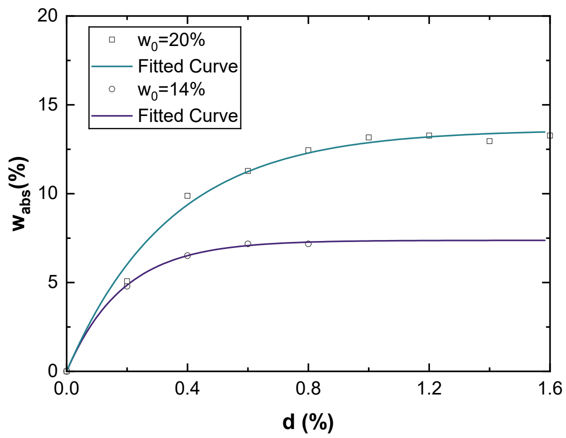

Fig. 11. Regression curve at w_0=14% and w_0=20%.

The fitted results and matched residual standard error (RSE) at each w_0 are listed in Table 1, revealing a good match between the experimental data and the fitted trends. It is found that the values of w_{abs}^{max} and D are positively correlated with higher w_0, which also implies that the specific dosage will subsequently increase.

4.4 3D regression surface

The results in Table 1 indicate that, as a first approximation, w_{abs}^{max} and D increase linearly with the initial water content. As a result, the previous regression model is here expanded as a surface by introducing a linear relationship for w_{abs}^{max} and D as a function of water content. The resulting model links the absorbed water to "design" inputs, such as the initial water content and dosage. The relationship can thereby be expressed as Eq. 5:

$$w_{abs} = (aw_0 + b)\left(1 - e^{-\frac{d}{cw_0 + f}}\right) \tag{5}$$

where e is Euler's number, d is the dosage of SAP, w_0 is the initial water content, and a, b, c, and f are fitting parameters. The domain zone of Eq. 5 needs to be constrained, as w_{abs} and $aw_0 + b$ should be larger than zero.

Table 1. Regression results of all cases.

w_0 (%)	w_{abs}^{max} (%)	D	RSE
12	5.212	0.132	0.096
14	7.374	0.188	0.085
16	10.040	0.290	0.148
18	13.759	0.522	0.368
20	13.606	0.346	0.459
22	15.889	0.401	0.911
24	17.188	0.383	0.934
26	20.698	0.591	0.454
28	22.349	0.645	0.525
30	19.418	0.526	1.400

Fig. 12 shows the regression results for a = 1.034, b = -7.083, c = 0.0201, and f = -0.083, with an R^2 of 0.98, indicating a high level of fitting confidence and requiring w_0 to be strictly greater than 6.85%. This threshold coincides with the value. w_{rmn} acquired from Fig. 3, as well as from Fig. 6, in line with the finding proposed by Wu et al. [17], linking the water absorption of SAP particles to the free pore water.

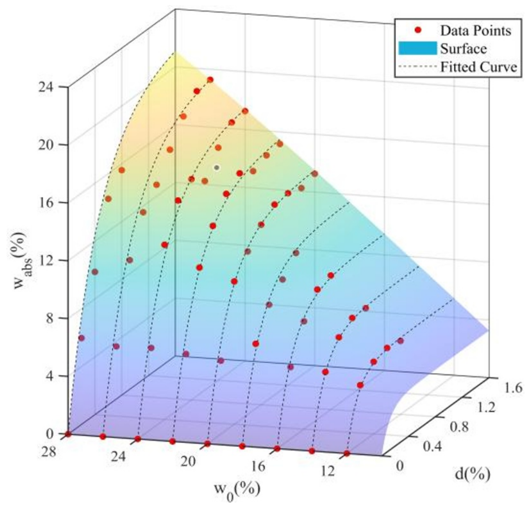

Fig. 12. 3D regression surface of the proposed model.

5 Conclusions

This study aimed to quantify the water absorption capacity of superabsorbent polymers (SAPs) in order to evaluate their performance in soil. Centrifugation was employed to generate controlled suction levels, driving the sand to a residual state and enabling the separation of free water from the SAP-treated soil matrix. Based on the experimental results, the following conclusions can be drawn:

1. Centrifugation provides a reliable means of generating a wide range of suction values, enabling effective extraction of free water from SAP-treated soils. The measurements obtained through this method show good consistency and validation.
2. The proposed model successfully captures the interrelationship between initial water content, SAP dosage, and water absorption. Water absorption increases with both initial water content and SAP dosage, but is ultimately constrained by the availability of free water and the absorption capacity of the SAP.
3. Within the tested soil range, the model demonstrates good predictive capabilities and can be used to estimate water absorption. This provides a practical framework for identifying optimal SAP dosages for soils with varying initial water contents.

Further research is required to generalise the methodology and refine its applicability.

1. The underlying principles of the proposed approach are based on centrifugation and soil suction—fundamental physical concepts applicable to most geomaterials. This suggests broad applicability; however, validation across different soil types is necessary to confirm robustness.
2. The water absorption capacity and rate of SAPs are influenced by the coupling effect of pH and dissolved ions in the liquid. In turn, the volume of water affects the osmotic pressure. As soil matrices contain different soluble salts, the interaction of water absorption and solution should be further investigated.

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References

1. H. Zhao, C.J. Zhao, X. Zheng and C. Liu, Physicochemical characterization of cement stabilized highly expansive soil. Proc. Geo-Congress 2013: Stab. Perform. Slopes Embankments III, 231, 2084–2093 (2013). https://doi:10.1061/9780784412787.211
2. X. Ma and G. Wen, Development history and synthesis of super-absorbent polymers: a review. J. Polym. Res., **27**, 136 (2020). https://doi.org/10.1007/s10965-020-02097-2.
3. M.J.A.D. Zohuriaan-Mehr and K. Kabiri, and Kourosh Kabiri, Superabsorbent polymer materials: a review. Iran. Polym. J., **17**, 451-477 (2008).
4. M.R. Islam, Y. Hu, S. Mao, P. J. Mao, A.E. Eneji and X. Xue, Effectiveness of a water-saving super-absorbent polymer in soil water conservation for corn (Zea mays L.) based on eco-physiological parameters. J. Sci. Food Agric., **91**, 1998-2005 (2011). https://doi.org/10.1002/jsfa.4408
5. Y.G. Han, P.L. Yang, Y.P. Luo, S.M. Ren, L.X. Zhang and L. Xu, Porosity change model for watered super absorbent polymer-treated soil. Environ. Earth Sci., **61**, 1197-1205 (2010). https://doi.org/10.1007/s12665-009-0443-4
6. W. Zhao, J. Hu, Z. Cui, P. Dou and Y. Fan, Effects of superabsorbent polymers on the vertical infiltration of soil water with sand mulching. Environ. Earth Sci., **78**, 648 (2019). https://doi.org/10.1007/s12665-019-8665-6
7. H.X.D. Lee, H.S. Wong and N.R. Buenfeld, Effect of alkalinity and calcium concentration of pore solution on the swelling and ionic exchange of superabsorbent polymers in cement paste. Cem. Concr. Compos., **88**, 150-164 (2018). https://doi.org/10.1016/j.cemconcomp.2018.02.005
8. X. Bian, Z.F. Wang and G.Q. Ding, Y.P. Cao, Compressibility of cemented dredged clay at high water content with super-absorbent polymer. Eng. Geol., **208**, 198-205 (2016). https://doi.org/10.1016/j.enggeo.2016.04.036
9. C.A. Ahmad, J. Liu and X.M. Huang, Geotechnical properties of superabsorbent polymer solidified slurry. Proc. 70th Can. Geotech. Conf. (GeoOttawa 2017), Ottawa, Canada (2017).
10. X. Bian, W. Zhang, X. Li, X. Shi, Y. Deng and J. Peng, Changes in strength, hydraulic conductivity and microstructure of superabsorbent polymer stabilized soil subjected to wetting–drying cycles. Acta Geotech., **17**, 5043-5057 (2022). https://doi.org/10.1007/s11440-022-01573-x
11. L. Joaquín and S. Muraro, Drying of silty soil treated with superabsorbent hydrogels: Retention behaviour and cracking. Eng. Geol., **331,** 107433 (2024). https://doi.org/10.1016/j.enggeo.2024.107433.
12. X. Cui, Y. Du, X. Zhang, J. Hao, Z, Bao, Q. Jin and X. Li, Characterizing the dynamic resilient modulus of subgrade soil treated by BT-SAP subjected to freeze-thaw cycles. Cold Reg. Sci. Technol., **220**, 104153 (2024). https://doi.org/10.1016/j.coldregions.2024.104153
13. D. G. Fredlund and A. Xing, Equations for the soil-water characteristic curve. Can. Geotech. J., **31**(4), 521-532 (1994). https://doi.org/10.1139/t94-061
14. Technica Goudou Co., Ltd. Super Absorbent Polymer (SAP) Specifications. (2024). https://www.technica-goudou.co.jp/products/function/674.html
15. A. Saha,, S. Sekharan and U. Manna. Superabsorbent hydrogel (SAH) as a soil amendment for drought management: A review. Soil Till. Res., **204**, 104736 (2020). https://doi.org/10.1016/j.still.2020.104736
16. R. Gardner, A method of measuring the capillary tension of soil moisture over a wide moisture range. Soil Sci., **43**, 277-284 (1937). https://doi.org/10.1097/00010694-193704000-00004
17. H. Wu, Z. Li, W. Song and S. Bai, Effects of superabsorbent polymers on moisture migration and accumulation behaviors in soil. J. Clean. Prod., **279**, 123841 (2021). https://doi.org/10.1016/j.jclepro.2020.123841
18. D.H. Thibault and M.I. Sheppard, A disposable system for soil pore-water extraction by centrifugation. Commun. Soil Sci. Plant Anal., **23**, 1629-1641 (1992). https://doi.org/10.1080/00103629209368692