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Experimental investigation of hydrophobic bentonite effects on reducing evaporation from water surfaces

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Abstract: In recent years, due to the occurrence of water shortage and drought problems, particularly in arid and semi-arid regions of the world, new methods to reduce evaporation from the surface of dam reservoirs, lakes, and other water-free surfaces are investigated. This study aimed to use hydrophobic bentonite to reduce water evaporation from water surfaces, on a laboratory scale, and field conditions for the first time. Bentonite initially became hydrophobic by stearic acid (SA). Under such conditions, hydrophobic bentonite floats on the surface of water and forms a thin coating layer. The produced hydrophobic bentonite had a contact angle of 150°, indicating its superhydrophobicity. Evaporation reduction was measured under laboratory and field conditions and it was compared to hexadecanol as the reference material. The results demonstrated that the hydrophobic bentonite efficiency under laboratory conditions was similar to that of hexadecanol and prevented water evaporation by 36%. However, under field conditions, hydrophobic bentonite and hexadecanol efficiencies were 40% and 23% to reduce evaporation for 30 days, respectively. In terms of stability, hexadecanol needed to be re-injected after three days, while hydrophobic bentonite was stable and remained on the surface for more than 100 days under laboratory conditions and for more than 15 days under field conditions without needing re-injection. This coverage with method can be used to reduce evaporation from lakes, tanks, and reservoirs of small dams.

Keywords: Water evaporation; Water surface; Hydrophobic bentonite; Hexadecanol monolayer.

1 INTRODUCTION

One of the most effective processes causing water loss is evaporation of natural waters, such as lakes and artificial water sources like dam reservoirs, tanks, and other water-free surfaces. This is even more considerate in arid and semi-arid regions of the Earth. Although significant effort, time, and money are invested in water storage in these reservoirs, there is often a high amount of evaporation. Therefore, various studies have been conducted to provide a useful and effective method to reduce water evaporation water-free surfaces. Accordingly, both chemical and physical methods are used to reduce evaporation. In physical methods, the use of floating bodies and suspended covers reduces the evaporation of water-free surfaces (Barnes, 2008). Suspended covers are horizontal structures suspended on the surface of water and supported by steel cables and external backups (Benzaghta and Mohamad, 2009). These covers reduce the amount of evaporation by blocking solar radiation on the water surface (Yao et al., 2010). For example, Aminzadeh et al. (2018) placed floating rings on the water surface of a reservoir for a specified period and observed that the water evaporation was reduced by 80%. In another work, using 100 cm^2 plates on the surface of dam reservoirs and creating holes with a diameter of 0.44 cm on these plates, Zipper et al. (2014) investigated the amount of evaporated water and concluded that at 299.73 K, 22% efficiency was achieved. Han et al. (2019) also achieved 26% efficiency by placing plastic spheres on the water surface.

In chemical methods, formation of monolayers on water is used to reduce the amount of evaporation. These materials are often alcohols, fatty acids, or surface agents, such as detergents and phospholipids forming molecular layers on the water surface (Barnes, 2008). Molecular layers are films that are one molecule thick, and they are formed at the water/air interface (Dawood, 2013). First, Langmuir (1917) studied the effect of molecular layers like hexadecanol on water evaporation and concluded that these molecular layers delivered acceptable efficiency to reduce evaporation of the water stored in dam reservoirs. Using hexadecanol monolayers in addition to the temperature effect, Saggaï and Bachi (2018) considered the wind effect and concluded that if the material is spread over the water surface in the absence of wind, at an average temperature of 300 K, evaporation is reduced by 34%. However, this method does not work if there is wind. Herzig et al. (2011) simultaneously used hexadecanol and octadecanol molecular layers and added them to the water specimen in tanks. Their results indicated that addition of these layers at the same time would be more effective than using only one layer. Verlee and Zetland (2015) examined powder monolayers, such as hexadecanol and octadecanol on the surface of Lake Arrowhead in United States, and achieved a water evaporation reduction of 15%. Panjabi et al. (2016) spread the hybrid monolayer of Cetyl and Stearyl alcohol on the water surface and concluded that the utilized monolayer could prevent water evaporation by 19%.

According to the literature, two available chemical and physical methods exist to reduce the evaporation of water-free surfaces. The physical method has good efficiency; however, it is not cost-effective. Chemical methods are less expensive than physical methods, while they have lower efficiency. The concerns about environmental issues might be caused by the surfactants in the structure of some monolayers. Moreover, the materials used in this method are relatively expensive and re-

quire re-injection. However, owing to their low longevity and difficult separation of monolayers during consumption, they are problematic (Huang et al., 2015). Therefore, the study of a new method appears to be necessary with the features of reasonable cost, stable coverage, adequate efficiency, and low contamination. According to the issues mentioned above, in this study, a new physio-chemical method was utilized to reduce the evaporation from water-free surfaces.

In a recently published study (Jajin et al., 2021), a hydrophobic silver-doped titanium dioxide nanoparticles coating was used to reduce the water evaporation from the dam reservoirs. This method reduced water evaporation by 39 and 30% in the laboratory and field conditions, respectively. Furthermore, the quality of stored water in the reservoirs was improved owing to its antibacterial and photocatalytic properties leading to less water pollution in bacterial and organic materials. Therefore, the high performance of these materials was demonstrated by all achieved results of mentioned nanoparticles. However, two points seem to be necessarily considered in this case. First, in the new science of nanotechnology, the effects of nanoparticles on human health and other organisms are not fully known. On the other hand, nanoparticles are relatively expensive, which increases the cost of the coating.

To overcome these limitations, hydrophobic bentonite was used for the first time in this research. Due to its low cost, high surface area, high porosity, and ion exchangeability, Bentonite is widely used in various applications (Aminzadeh et al., 2018; Isalou and Ghorbanpour, 2019; Shayegh and Ghorbanpour, 2020; Wu et al., 2020). The layered structure of bentonite is made of aluminosilicate, which has a strong tendency to absorb water. By adding this substance to water, the water absorbance and swell of its interlayer space were observed. Conversely, its porosity of substance is refilled with water, and as a result, the density is increased. Hence, the floating of bentonite on the water surface is needed to reduce its tendency to absorb water, namely its hydrophobic property. It can be stated that the porosity of bentonite must be air-trapped and sealed, so that the bentonite density would not be increased in the case of water entrance. All of these strategies lead to the bentonite floating on the water. Hydrophobic bentonite floating on the water surface inhibits the escape of water molecules and consequently reduces the amount of evaporated water. Additionally, incoming shortwave radiation is better reflected, and lower solar energy is available for water molecules to be evaporated.

Thus far, various methods have been utilized to make the hydrophobicity of bentonite, such as cetyltrimethylammonium bromide (CTAB), polymers (for example, polyethylene), octadecyl dimethyl phenylmethyl ammonium chloride (ODPAC), silanes, and stearic acid (SA) (Hong et al., 2020; Huang et al., 2015; Johansson and Clegg, 2014; Ogunlaja and Pal, 2020; Saki et al., 2020).

Among the above-mentioned methods for hydrophobicity, the use of SA has several advantages, such as ease of synthesis of hydrophobic materials in the shortest time, requirement of the least laboratory facilities, and acceptable hydrophobicity.

The present study, for the first time, aimed to use hydrophobic bentonite as a coating on the water-free surface to reduce water evaporation from water surface. Initially, the efficiency of hydrophobic bentonite is measured in reducing the evaporation of the samples prepared under laboratory conditions, and then its contamination is investigated by TOC as well as its stability compared to hexadecanol. The pans of type A were used for a more detailed study of the efficiency of this method in the field conditions.

2 MATERIALS AND METHODS

2.1 Materials

In this experiment, bentonite was supplied by Kanysazejam (Rasht, Iran). Stearic acid, cetyl alcohol, and sodium dodecyl sulfate were purchased from Merck Co. (Germany).

2.2 Preparation of hydrophobic bentonite

Bentonite (mesh 100) was first washed several times with distilled water to remove contaminants that may interfere with the results. The washed bentonite was then filtered using filter papers and dried for 24 hours at 85 °C. To make it hydrophobic, first, the distilled water was heated to 60 °C, and then stearic acid was added. Then, stirring was continued for 15 minutes.

Subsequently, bentonite was added to the prepared solution (the weight ratio of bentonite to stearic acid was 1:1), and stirring continued for 24 hours. Finally, the filtered solution was dried at 60 °C for 24 hours and milled.

2.3 Preparation of hexadecanol solution

To prepare hexadecanol solvent, first, 4 mg of hexadecanol was added to 15 mg water at 50 °C under stirring. Then, sodium dodecyl sulfate was added to the solution, and stirring was continued for 20 minutes. The results of evaporation reduction from the surface with hexadecanol coating were employed as a reference method, and the results of evaporation reduction from the surface with hydrophobic bentonite coating were compared to it.

2.4 Physicochemical characterization of hydrophobic bentonite

The prepared samples were characterized by Fourier-Transform Infrared Spectroscopy (FT-IR) (Spectrum RXI-USA), Scanning Electron Microscopy (SEM) (LEO 1430VP - Germany) and Brunauer Emmett Teller, BET, (Mini Belsorp2 Japan) methods.

The contact angle is essential to detect hydrophobicity. Accordingly, 3 grams of parent and prepared hydrophobic bentonite were dispersed on the adhesive tape, and then the adhesive tape was applied on a slide. Afterward, a drop of distilled water (5 microliters) was added on the surface by a syringe from 1 cm distance, and the image was taken after approximately ten seconds.

To compare the amount of water absorbed before and after hydrophobicity, 3 grams of samples were put in 200 ml of water for 24 hours, and after that the materials were filtered and immediately weighed.

2.5 TOC analysis

To measure the amount of organic carbon release from dispersed material, hydrophobic bentonite and hexadecanol solution were separately dispersed on a container containing distilled water. After 100 days, the TOC values of filtered water were analysed (AQUALYTIC Spectrophotometer Spectro, Germany).

2.6 Evaporation rate

2.6.1 Laboratory conditions

Synthesized hydrophobic materials were dispersed on the plates (10 cm radius) containing a certain amount of water to

cover the entire surface. A standard solution (hexadecanol) and a control solution (uncoated water) were used for comparison. The containers were placed in an isolation chamber with relative humidity (65%) at 25 °C, and the evaporated water was weighed within specified periods for 24 hours. All experiments were replicated at least three times on a small-scale model, and then the mean values of the evaporation rate were reported.

2.6.2 Field conditions

To evaluate the performance of hydrophobic bentonite in reducing evaporation, outdoor experiments were conducted in evaporation pans. To this end, to estimate the amount of the water evaporated from the surface with and without coating, three galvanized Class A evaporation pans were used. This pan had a height of 0.25 and a radius of 1.21 meters. To reduce the heat transfer from the ground to the pans, wooden bases with a height of 0.15 m were used. These bases also provided better air circulation under the pans. In addition, a Lambrecht anemometer made in Germany with an accuracy of ±1 % FS (Full scale) was used to measure the wind speed on the surface of the pans. Furthermore, the maximum and minimum water temperatures were calculated with an Amarell thermometer made in Germany. This thermometer, which was placed on the surface of the water, had an accuracy of 0.5 °C. Moreover, to measure temperature and humidity, the Chinese produced HTC2 model was used, which had an accuracy of ± 1 degree for temperature and ± 5% for humidity. Vernier, which measures the evaporation rate with an accuracy of ± 0.1 liters, was used to measure the amount of evaporated water. Mli7 was also used to measure the daily rainfall. This device was made by Nivar Company in Iran and had an accuracy of 0.1 mm.

2.7 Stability

The stability of hydrophobic bentonite was evaluated at a constant temperature under laboratory conditions for 100 days after being spread on the water surface. During the 100-day test period, images were taken from the surface of samples with hydrophobic bentonite and hexadecanol to observe changes in the coating surface and stability. Furthermore, the stability of hydrophobic bentonite was investigated under field conditions and by addressing the rate of evaporation during the 30-day period of the experiment.

2.8 Calculation of evaporation flux

Using the laboratory data obtained from the previous section for evaporation, the amount of evaporation flux was calculated by Eq. (1) (Shah, 2018)

$$N_A = \frac{1}{A} \times \frac{\mathrm{d}m}{\mathrm{d}t} \tag{1}$$

where A, m and t are the evaporation surface (m^2), evaporated mass (g) and time (s), respectively. The diameter of the container used in this experiment was 0.1 m. Fick's law (Eq. 2) was used to find the water evaporation flux of the surface, and the parameters in the Fick relationship were defined as follows:

$$N_A = \frac{D_{AB} \times P_t}{R \times T \times Z \times P_{B.M}} (P_A - P_B) \tag{2}$$

$$P_{B.M} = \frac{P_{B_2} - P_{B_1}}{\ln\left(P_{B_2} / P_{B_1}\right)} \tag{3}$$

$$P_{B_1} = P_t - P_A \tag{4}$$

$$P_{B_2} = P_t - P_B \tag{5}$$

In these relations: D_{AB} indicates the diffusion coefficient of water vapor into air (m^2/s), P_t indicates the amount of atmospheric pressure (N/m^2), P_A denotes the partial pressure of water vapor at the lowest point of the hydrophobic layer (N/m^2), P_B shows the partial pressure of water vapor in the atmosphere (N/m^2), the R is related to gas constant and the value is 8314 (N·m/kmol·K). T shows the temperature in degrees Kelvin, and Z represents the distance traveled by water vapor, which is assumed to be 0.001 m.

2.9 Economic profitability

To evaluate the economic profitability of using this coating, the economic profitability coefficient (BP) according to Eq. (6) was used:

$$BP = \frac{Cp}{Wp} \tag{6}$$

where C_p is the price of coverage (¥/m^2) and W_p represents the price of non-evaporated water (¥/m^2).

The coefficient BP can have different values. If this coefficient is less than one, the used coverage is economically justified.

3 RESULTS AND DISCUSSION

3.1 Physicochemical characterization of hydrophobic bentonite

Figure 1 shows the parent and hydrophobic bentonite morphology and contact angle. A comparison of Figs. 1a and 1b show that the parent bentonite lamellar structure acid has become spherical after introducing the stearic acid. Furthermore, stearic acid covers the outer surface of bentonite well and clogs its pores. As a result, water cannot easily enter the pores of bentonite.

Figures 1 c and d show the comparison of the contact angle of parent and hydrophobic bentonites. They also show that the contact angle of parent bentonite is approximately zero, indicating its hydrophobicity. Hydrophobic bentonite has a contact angle of approximately 150°, demonstrating its superhydrophobicity.

Figure 2 shows the FT-IR spectra for parent bentonite, stearic acid, and hydrophobic bentonite. In the spectra of parent bentonite, the peak at around 1050 cm^{-1} is related to Si-O and at around 456 cm^{-1}, and 798 cm^{-1} is related to Si-O-Si. Stearic acid has characteristic peaks at around 1698 cm^{-1}, 1382 cm^{-1}, 2842 cm^{-1}, and 2900 cm^{-1}, which are attributed to C=O, -OH, $-CH_2$, and $-CH_3$ bonds, respectively. According to hydrophobic bentonite spectra (Fig. 2c), there are characteristic peaks of both bentonite and stearic acid. This indicates that stearic acid enters the bentonite structure. Furthermore, the new peaks in the hydrophobic bentonite spectra, such as the peak in the wavenumber 1739 cm^{-1}, indicate the esterification reaction between the carboxylic groups of stearic acid and OH in the bentonite (Huang et al., 2015).

Table 1 shows the specific surface area, the pore volume and water absorption analysis of parent and hydrophobic bentonite. As Table 1 shows, the specific surface area and the pore volume of parent bentonite were decreased from 120.83 cm^2/g and 0.134 cm^3/g to 0.19 cm^2/g and 0.022 cm^3/g for hydrophobic bentonite, respectively. This is due to filling bentonite pores by stearic acid.

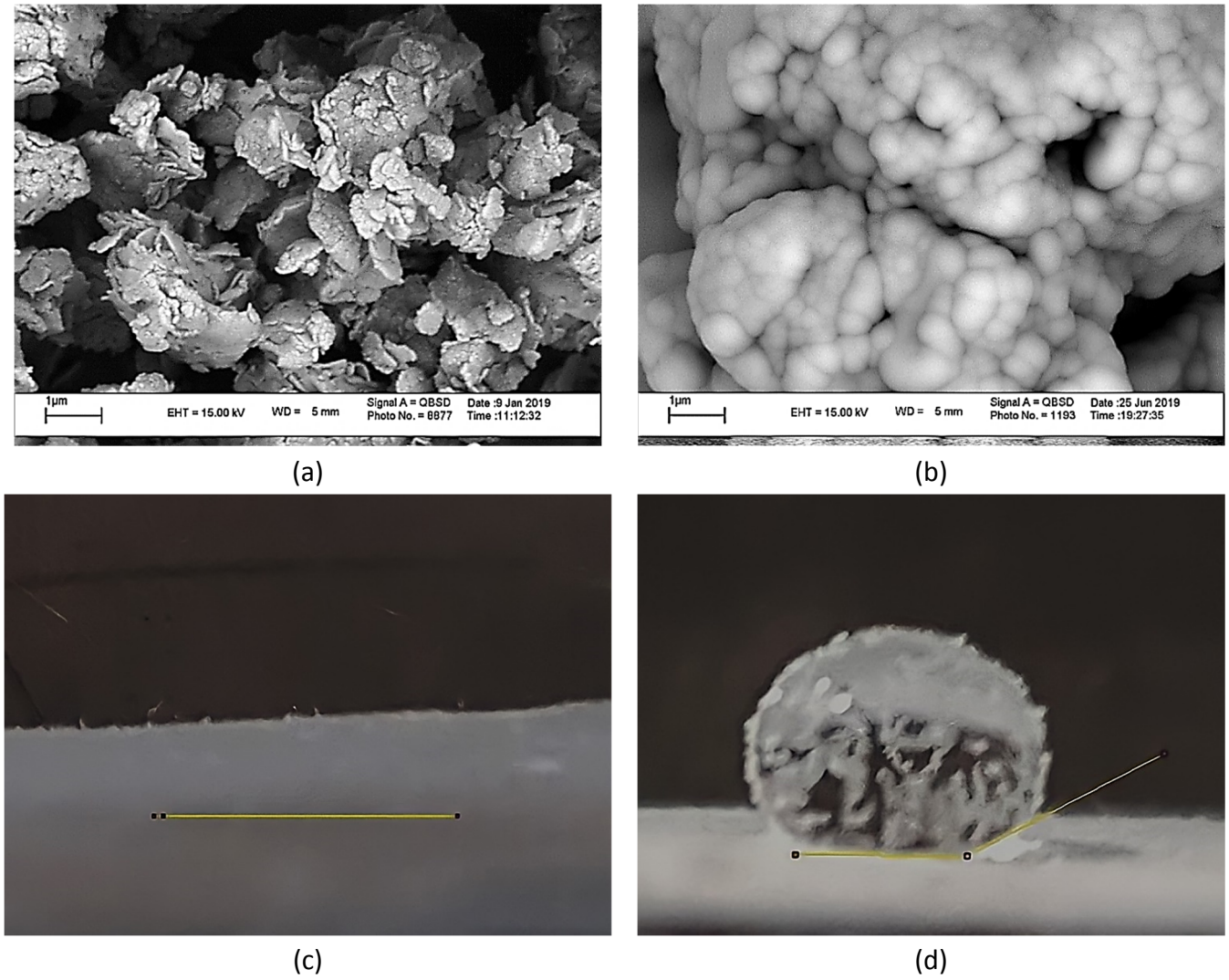


Fig. 1. Morphology of (**a**) parent, and (**b**) hydrophobic bentonite; Contact angle of (**c**) parent, and (**d**) hydrophobic bentonite.

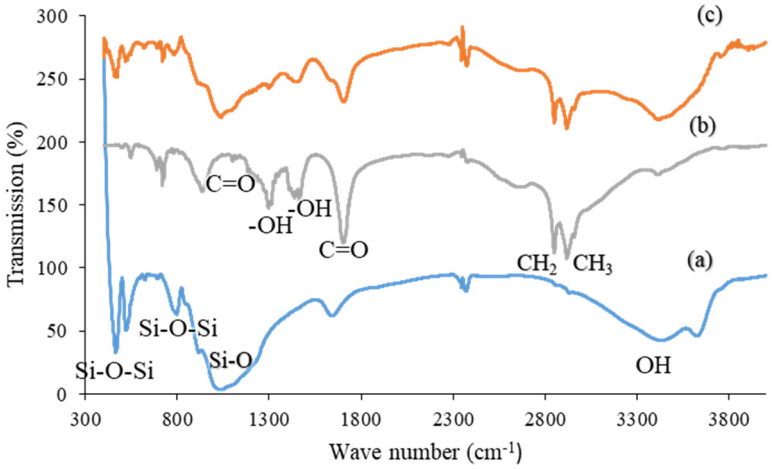


Fig. 2. FT-IR spectra of (**a**) parent bentonite, (**b**) stearic acid, and (**c**) hydrophobic bentonite.

Table 1. Specific surface area, the pore volume, and water absorption analysis of parent and hydrophobic bentonite.

Sample	Specific surface area (cm^2/g)	Pore volume (cm^3/g)	Water absorption (%)
Parent bentonite	120.83	0.134	106
Hydrophobic bentonite	0.19	0.022	16

Moreover, based on the results, it is concluded that parent bentonite can adsorb water up to its weight owing to its hydrophobic nature and porous structure. However, hydrophobic bentonite with a capsular and spherical shape has fewer pores and absorbs less water (16%). According to SEM and BET results, most of bentonite pores have been closed. According to the results, stearic acid coated bentonite surface, penetrated into its pores and subsequently, reduced its water adsorption.

3.2 TOC analysis

At the beginning of the experiments, the TOC amount of the distilled water was extremely small. According to the analysis, the TOC content of the water coated with hydrophobic bentonite (3 mg/L) is lower than that of hexadecanol (6 mg/L) due to the strong bonding force between stearic acid and bentonite, thereby preventing the leaching of stearic acid from bentonite and its entry into the water.

However, hexadecanol solution was opaque. This was due to formation of micelles in the presence of sodium dodecyl sulfate surfactant. Sodium dodecyl sulfate surfactant was used to prevent the hexadecanol from solidification and better dispersion. These materials pollute water, and their separations are difficult. In contrast, hydrophobic bentonite poses fewer risks to aquatic animals and even humans.

3.3 Analysis of the reduced evaporation rate

3.3.1 Under laboratory conditions

Figure 3 displays water evaporation at a temperature of approximately 25 °C and 65% relative humidity for uncoated, hydrophobic bentonite, and hexadecanol coated water. The results show that the rate of water evaporation from the surface that has no coating has more significant values than the surface covered with hexadecanol or hydrophobic bentonite. This is due to the easier movement of water molecules at the water/air interface due to absence of any inhibitors. However, in the presence of the mentioned coating with a hydrophobic nature, the movement of water molecules from the interface is reduced, and evaporation is decreased. Furthermore, hydrophobic bentonite and hexadecanol have a relatively similar performance and prevent water evaporation by approximately 36%. The reported results are inconsistent in the previous investigations. Piri et al. (2009) used fatty alcohols, such as octadecanol and hexadecanol, to reduce evaporation water in Type A pans and achieved 24% efficiency over four weeks. In another study, Gugliotti et al. (2005) prevented evaporation by 19.5% under optimal conditions using hexadecanol and octadecanol and coating water with them at room temperature for 72 hours. Therefore, compared to these studies, the hydrophobic bentonite used in the present study exhibited an acceptable performance.

3.3.2 Considering field conditions

At the beginning of the experiment, hydrophobic bentonite and hexadecanol solution (water, hexadecanol, and sodium lauryl sulfate) were spread as a monolayer on the surface of the pan water, and the effective parameters on evaporation were measured every day for a 30-day period. The wind speed in 30 days ranged from 3 to 4 meters per second, and the mean relative humidity and air temperature during the test were 54.33% and 22.86 °C, respectively (minimum and maximum air temperature during the test were 5 and 40 °C).

Figure 4a demonstrates the rate of cumulative evaporation during the experiment (thirty days). The results show that the rate of evaporation during this period for the surface with hexadecanol and hydrophobic bentonite coat was 237.3 and 180.67 mm, respectively. This evaporated water height was obtained on an uncoated surface of 292.3 mm. Hydrophobic bentonite and hexadecanol reduced the evaporation rate by 40% and 23%, respectively, demonstrating the proper performance of hydrophobic bentonite under both laboratory and field conditions. Grundy (1957) used hexadecanol monolayers over a 4-week period and concluded that approximately 24% reduction in water evaporation could be obtained in the presence of the hexadecanol coating. Harbeck and Koberg (1959) used hexadecanol as a monolayer and examined its effectiveness in reducing evaporation for 21 days. The results demonstrated that this monolayer had an efficiency of 18% in reducing evaporation during the experiment.

Figure 4b shows the temperature changes of the pan water in three modes of uncoated water, water with hydrophobic bentonite coating, and water with hexadecanol coating over 30 days. Accordingly, the temperature of the water inside the pan when using the hexadecanol coating as a monolayer is almost the same as the surface without coating. However, hydrophobic bentonite coating can significantly reduce the water temperature. Moreover, since the water temperature is one of the most important reasons for evaporation, hydrophobic bentonite has a better performance than hexadecanol in the reduction of water evaporation. Generally, hydrophobic bentonite coating, due to its white color, can reflect heat from the sun to some extent. Although, the surface without coating or surface with hexadecanol coating is transparent, it absorbs most of the solar radiation, and increases the temperature of the water inside the pan.

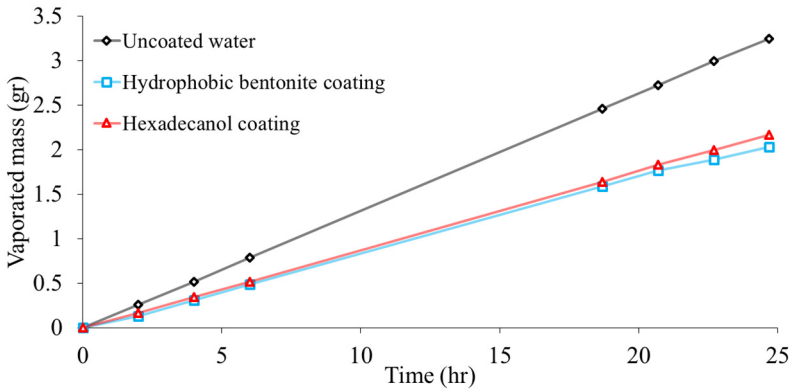


Fig. 3. Reduction of water evaporation under laboratory conditions.

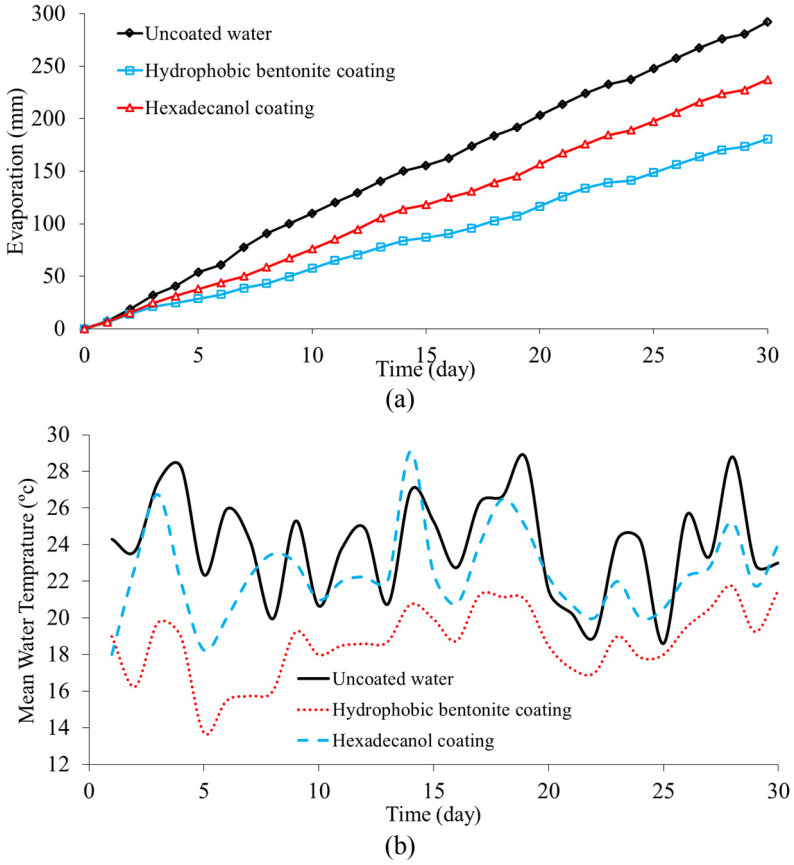


Fig. 4. (**a**) Cumulative values of the evaporation amount, and (**b**) the mean water temperature under field conditions.

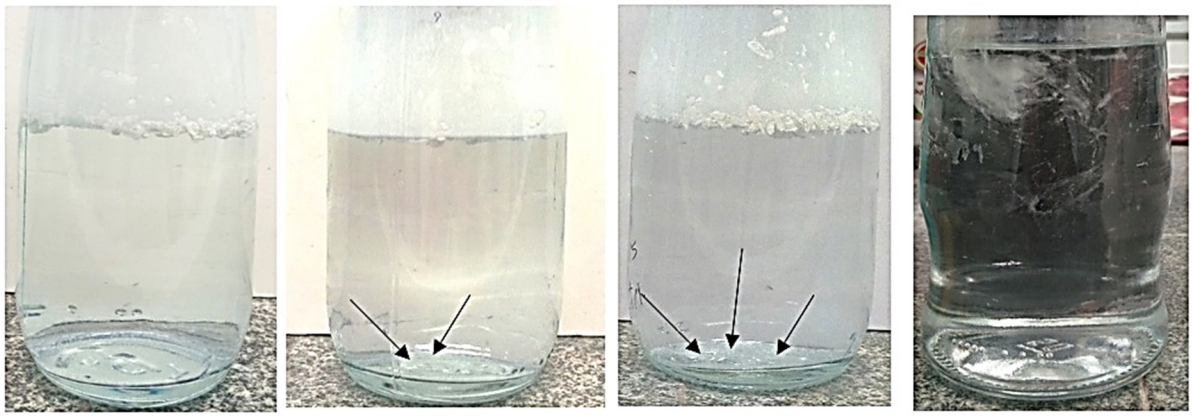


Fig. 5. Stability evaluation of (**a**) first day, (**b**) day 30, (**c**) day 100 for hydrophobic bentonite, and (**d**) day 100 for hexadecanol.

3.4 Stability

3.4.1 Under laboratory conditions

This test aimed to evaluate the stability of hydrophobic bentonite to stay floating on water. Figure 5 depicts the stability of hydrophobic bentonite particles and hexadecanol coated water. Accordingly, there were small sedimentation masses, and the bentonite floating was stable. In the first 30 days, there was a low amount of precipitated bentonite. Afterward, it was occasionally increased; however, sedimentation remained almost constant even after 100 days. Based on the results of FTIR, a stable esterification reaction was performed between bentonite and SA. These bonds are not easily broken at room temperature. Consequently, the prepared hydrophobic bentonite has acceptable stability for more than 100 days.

3.4.2 Considering field conditions

Figure 6 shows the stability and buoyancy of hydrophobic bentonite on the first day and 15 days after injection, respectively. As observed, after this period, hydrophobic bentonite loses its integrity, and it becomes fragmented gradually; however, it can reduce evaporation. However, hexadecanol coating must be injected every 3 days, and due to continuous use, it causes turbidity and contamination by producing micelle in water. The results show that when the air temperature is above 33 °C and the sunlight is intense, the injection time of hexadecanol will decrease to every 2 days. Also, on days with heavy rainfall, hexadecanol should be re-injected to prevent reduced yields after it stops raining.



(a) (b)

Fig. 6. Stability of hydrophobic bentonite (**a**) First day, (**b**) Day 15.

Table 2. The diffusion coefficient and evaporation flux under laboratory and field conditions.

	Hexadecanol		Hydrophobic Bentonite				
Conditions	D_{AB} (m^2/s)	N_A ($kmol/s{\cdot}m^2$)	D_{AB} (m^2/s)	N_A ($kmol/s{\cdot}m^2$)	$P_{B,M}$ (N/m^2)	P_A (N/m^2)	RH (%)
Laboratory	$0.02*10^{-5}$	$1.72*10^{-7}$	$0.02*10^{-5}$	$1.64*10^{-7}$	101285.04	2059.85	65
Field	$0.01*10^{-5}$	$0.63*10^{-7}$	$0.01*10^{-5}$	$0.38*10^{-7}$	100395.45	1987.83	67.5

3.5 Calculation of evaporation flux

Table 2 presents the comparison of the calculated diffusion coefficient and evaporation flux of hydrophobic bentonite and hexadecanol under laboratory and field conditions at approximately 24.7 °C and 67.5% relative humidity. The evaporation flux for hydrophobic bentonite under laboratory and field conditions is 1.64×10^{-7} and 0.38×10^{-7} $kmol/s{\cdot}m^2$, respectively. Furthermore, the evaporation flux for hexadecanol under laboratory and field conditions is 1.72×10^{-7} and 0.63×10^{-7} $kmol/s{\cdot}m^2$, respectively. The comparison of the evaporation flux of hydrophobic bentonite and hexadecanol indicates that hydrophobic bentonite has lower evaporation flux than hexadecanol.

3.6 Economic analysis

According to Equation (6), the BP coefficient for hydrophobic bentonite and hexadecanol was calculated. The net price for the synthesis of hydrophobic bentonite coverage, including the cost of pure bentonite and SA, is approximately €0.772 per square meter. The net price of hexadecanol coverage, includes the cost of hexadecanol and sodium lauryl sulfate, is appraised at approximately €4.07 per square meter. This cost variance is payable to the higher price of pure hexadecanol compared to bentonite. Since hydrophobic bentonite needs to be re-injected every 15 days and hexadecaneol every 3 days, ultimately the cost of hydrophobic bentonite and hexadecaneol coating per square meter per month is € 1.54 and € 40.7, respectively. In addition, the local water price is around €2.5 and over €0.5 for industrial centers and agricultural centers, respectively.

According to the mentioned values, the BF values of hydrophobic bentonite and hexadecaneol for industrial and agricultural centers by Equation (6) are calculated 0.616 ($BF = 1.54/2.5 = 0.616$) and 16.28 ($BF = 40.7/2.5 = 16.28$), as well as 3.08 ($BF = 1.54/0.5 = 3.08$) and 81.4 ($BF = 40.7/0.5 = 81.4$), respectively. The results indicated that the BP coefficient for the hydrophobic bentonite coating in industrial centers was less than one and offered better economic justification than agricultural centers did.

4 CONCLUSION

The aim of this paper was to evaluate the efficiency of hydrophobic bentonite and hexadecanol in evaporation reduction from dam reservoirs and other water-free surfaces on a laboratory scale and under field conditions. It is concluded that hydrophobic bentonite and hexadecanol has a similar performance in the reduction of water evaporation by approximately 36% under laboratory conditions; however, hydrophobic bentonite has higher efficiency (40%) than hexadecanol (23%) under field conditions. Therefore, hydrophobic bentonite can be a more suitable and practical option than hexadecanol owing to its high stability and low contamination of hexadecanol. The results of the analysis also show that bentonite is well hydrophobized by stearic acid, and it has a wider contact angle and lower water absorption compared to plain bentonite. All of the above cases demonstrate the possibility of using hydrophobic bentonite instead of the conventional hexadecanol monolayer method.

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REFERENCES

Aminzadeh, M., Lehmann, P., Or, D., 2018. Evaporation suppression and energy balance of water reservoirs covered with self-assembling floating elements. Hydrology and Earth System Sciences, 22, 7, 4015–4032. http://doi.org/10.5194/hess-22-4015-2018

Barnes, G.T., 2008. The potential for monolayers to reduce the evaporation of water from large water storages. Agricultural Water Management, 95, 4, 339–353. http://doi.org/10.1016/j.agwat.2007.12.003

Benzaghta, M.A., Mohamad, T.A., 2009. Evaporation from reservoir and reduction methods: An overview and assessment study. International Engineering Convention. Domascus, Syria and Medinah, Kingdom of Saudi Arabia, 11, 18.

Dawood, K.A., 2013. Reduce evaporation losses from water reservoirs. IOSR Journal of Applied Physics, 4, 13–16. http://doi.org/10.9790/4861-0461316

Grundy, F., 1957. Reduction of evaporation from reservoirs. In: Proceedings of the 2nd International Congress of Surface Activity, London.

Gugliotti, M., Baptista, M.S., Politi, M.J., 2005. Reduction of evaporation of natural water samples by monomolecular films. Journal of the Brazilian Chemical Society, 16, 6a, 1186–1190. http://doi.org/10.1590/s0103-50532005000700015

Han, K.-W., Shi, K.-B., Yan, X.-J., Cheng Y.-Y., 2019. Water savings efficiency of counterweighted spheres covering a plain reservoir in an arid area. Water Resources Management, 33, 5, 1867–1880. http://doi.org/10.1007/s11269-019-02214-x

Harbeck, G.E., Koberg, G.E., 1959. A method of evaluating the effect of a monomolecular film in suppressing reservoir evaporation. Journal of Geophysical Research, 64, 1, 89–93. http://doi.org/10.1029/jz064i001p00089

Herzig, M.A., Barnes, G.T., Gentle, I.R., 2011. Improved spreading rates for monolayers applied as emulsions to reduce water evaporation. Journal of Colloid and Interface Science 357, 1, 239–242. http://doi.org/10.1016/j.jcis.2011.01.071

Hong, Y., Yan, W., Du, J., Li, W., Xu, T., Ye, W.-B., 2020. Thermal performances of stearic acid/sepiolite composite form-stable phase change materials with improved thermal conductivity for thermal energy storage. Journal of Thermal Analysis and Calorimetry, 143, 5, 3317–3329. http://doi.org/10.1007/s10973-020-09299-2

Huang, W., Wang, Y., Qiu, Z., Leong, Y.-K., Cui, M., Zhong, H., 2015. Synthesis and characterisation of strong hydrophobic bentonite. Materials Research Innovations, 19, 6, 428–434. http://doi.org/10.1179/1433075x15y.0000000066

Isalou, S.K., Ghorbanpour, M., 2019. Catalytic activity of Fe-modified bentonite in heterogeneous photo-Fenton process. Desalination and Water Treatment, 162, 376–382. http://doi.org/10.5004/dwt.2019.24272

Jajin, R.G., Feizi, A., Ghorbanpour, M., 2021. Reduction of water evaporation from dam reservoirs using hydrophobic silver doped titanium dioxide nanoparticles coating. Water Resources Research, 57, e2020WR029231. https://doi.org/10.1029/2020WR02923

Johansson, C., Clegg, F., 2014. Hydrophobically modified poly(vinyl alcohol) and bentonite nanocomposites thereof: Barrier, mechanical, and aesthetic properties. Journal of Applied Polymer Science, 132, 13. http://doi.org/10.1002/app.41737

Langmuir, I., 1917. The constitution and fundamental properties of solids and liquids. Journal of the American Chemical Society, 39, 9, 1848–1906. https://doi.org/10.1021/ja02254a006

Ogunlaja, S.B., Pal, R., 2020. Effects of bentonite nanoclay and cetyltrimethyl ammonium bromide modified bentonite nanoclay on phase inversion of water-in-oil emulsions. Colloids and Interfaces, 4, 1, 2. http://doi.org/10.3390/colloids4010002

Panjabi, K., Rudra, R., Goel, P., 2016. Evaporation Retardation by Monomolecular Layers: An Experimental Study at the Aji Reservoir (India). Open Journal of Civil Engineering, 6, 3, 346–357. http://doi.org/10.4236/ojce.2016.63029

Piri, J., Amin, S., Moghaddamnia, A., Keshavarz, A., Han, D., Remesan, R., 2009. Daily pan evaporation modeling in a hot and dry climate. Journal of Hydrologic Engineering, 14, 8, 803–811. http://doi.org/10.1061/(asce)he.1943-5584.0000056

Saggaï, S., Bachi, O.E.K., 2018. Evaporation reduction from water reservoirs in arid lands using monolayers: Algerian experience. Water Resources, 45, 2, 280–288. http://doi.org/10.1134/s009780781802015x

Saki, S., Senol-Arslan, D., Uzal, N., 2020. Fabrication and characterization of silane-functionalized Na-bentonite polysulfone/polyethylenimine nanocomposite membranes for dye removal. Journal of Applied Polymer Science, 137, 36, 49057. http://dx.doi.org/10.1002/app.49057

Shah, D.O., 2018. Reducing water evaporation and enhancing plant growth using a hydrophobic capillary layer formed with hydrophobic soil. Google Patents.

Shayegh, R., Ghorbanpour, M., 2020. A new approach for preparation of iron oxide-pillared bentonite as adsorbent of dye. Desalination and Water Treatment, 183, 404–412. http://doi.org/10.5004/dwt.2020.25322

Verlee, D., Zetland, D., 2015. Extending water supply by reducing reservoir evaporation: a case study from Wichita Falls, Texas. In: Proceedings of Mine Water Solutions in Extreme Environments, Vancouver, Canada.

Wu, L.M., Liu, Q.X., Wang, X.L., Cao, S.Y., Tang, N., Wang, Q., Lv, G.C., Liao, L.B., 2020. Preparation of two-dimensional nano montmorillonite/stearic acid energy storage composites with excellent stability and heat storage property. Applied Clay Science, 191, 105614. https://doi.org/10.1016/j.clay.2020.105614

Yao, X., Zhang, H., Lemckert, C., Brook, A., Schouten, P., 2010. Evaporation reduction by suspended and floating covers: overview, modelling and efficiency. Urban Water Security Research Alliance Technical Report.

Zipper, L.E, Aristide, X., Bishop, D.P, Joshi, I., Kharzeev, J., Patel, K.B., Santiago, B.M., Joshi, K., Dorsinvil, K., Sweet, R.M., 2014. A simple technique to reduce evaporation of crystallization droplets by using plate lids with apertures for adding liquids. Acta Crystallographica Section F: Structural Biology Communications, 70, 1707–1713. http://doi.org/10.1107/s2053230x14025126

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