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Desert Water Saving and Transportation for Enhanced Oil Recovery: Bridging the Gap for Sustainable Oil Recovery

O. Toktarbaiuly[1], A. Kurbanova[1], G. Imekova[2,3], M. Abutalip[1,2], Zh. Toktarbay[2]*

[1]Renewable Energy Systems and Material Science Laboratory, National Laboratory Astana, Nazarbayev University, 53, Kabanbay Batyr St., Astana, Kazakhstan
[2]Laboratory of Engineering Profile, Satbayev University, 22a, Satbayev St., Almaty, Kazakhstan.
[3]L.N. Gumilyov Eurasian National University, 2, Satbayev St., Astana, Kazakhstan

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Abstract

With concerns about water scarcity in arid regions, innovative solutions are imperative to meet the increasing water demand for Enhanced Oil Recovery (EOR) processes. This article presents a study on the preparation of superhydrophobic sand for water-saving and storage, with a focus on potential applications in EOR. The results of the research indicate that the maximum water contact angle after sand hydrophobization was 158°. The water storage capacity of the sand was assessed by growing plants in soil layered with superhydrophobic sand. When superhydrophobic sand was used both above and below the soil, the soil remained moist for more than 10 days. In contrast, without the use of superhydrophobic sand, soil moisture lasted for only 3 days. This research demonstrates the potential of superhydrophobic sand in prolonging soil moisture, making it a valuable asset for water-saving applications in EOR and arid regions.

1. Introduction

In recent years, superhydrophobic sand has gained attention for its applications in desert water conservation and agriculture. This innovative technology, which enables efficient water harvesting and storage in arid regions, has the potential to offer indirect benefits to industries such as Enhanced Oil Recovery (EOR). In EOR operations, the availability of water for injection processes is crucial. Superhydrophobic sand's ability to capture, store, and release water in a controlled manner could enhance water management practices in EOR, ultimately contributing to improved oil recovery rates while simultaneously addressing water scarcity concerns in water-stressed regions [1–3]. The unique water-harvesting capabilities of superhydrophobic sand offer an exciting avenue for enhancing water supply in EOR operations, potentially transforming the way we approach oil recovery processes in water-stressed regions [4, 5]. Also, recently scientific attraction has focused on desert water savings and transportation for the purpose of EOR [6]. However, most superhydrophobic coatings are considered not environmentally friendly and not suitable for large-scale production, or prohibitively expensive to become standard manufacturing practice. Obtaining environmentally friendly "green" materials for superhydrophobic coating plays a significant role and contributes to the improvement of the level and quality of life of the population [7–10]. Superhydrophobic sand on vicinal surfaces is an intriguing and innovative area of study that merges the principles of materials science and surface chemistry [11–14].

For a very long time, deserts are considered as lifeless and dryland for water shortage and sand storm. Recent decades, many countries are interested in desert greening for farming purpose [15–16].

*Corresponding author.
E-mail address: zhexenbek.toktarbay@gmail.com

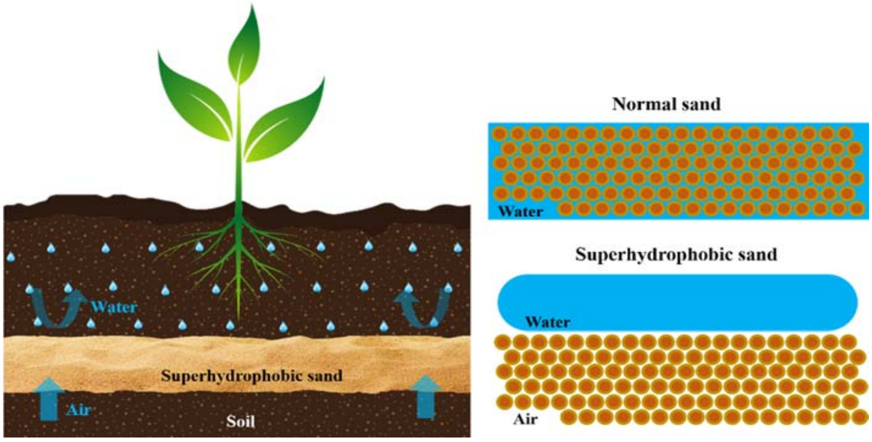

Fig. 1. An illustration for superhydrophobic sand applications for desert water saving and farming.

However, this type of project requires a sufficient amount of water. Water can be quickly absorbed by sand due to the strong hydrophilicity of sand itself, which greatly impedes desert greening. The fresh water is a limited resource on Earth. Sand is a natural granular substance of finely divided rock and mineral particles. The conception of "superhydrophobic sand" can be an opportunity to realize the storage and transportation of surface water [17–18]. Figure 1 is an illustration of superhydrophobic sand applications for desert water saving and farming.

Superhydrophobic sand applications for water saving and farming play an important role in the agriculture sector of Kazakhstan. Most parts of the land of Kazakhstan are dry, semi-dry and desert climates. Steppes – 63%, deserts and semi-deserts – 25%, and mountains 10%. In the north of the republic, forest-steppes prevail (2%). 23% of the country's territory is suitable for agriculture (forest-steppe and cold steppe) [19]. However, the northern part of Kazakhstan is located in a harsh continental climate zone and this causes limitations of the agriculture industry. Applications of superhydrophobic sand for farming and agriculture can be helpful for the greening of semi-dry and desert parts of Kazakhstan. Figure 2 shows the geography of Kazakhstan and Google Earth image. The geographical setting of the western part of Kazakhstan, characterized by a harsh desert climate, presents a formidable challenge due to the scarcity of water resources. As depicted in Fig. 2, the geographical scope of Kazakhstan illustrates the vast expanse of arid and semi-arid areas, making water conservation an imperative undertaking.

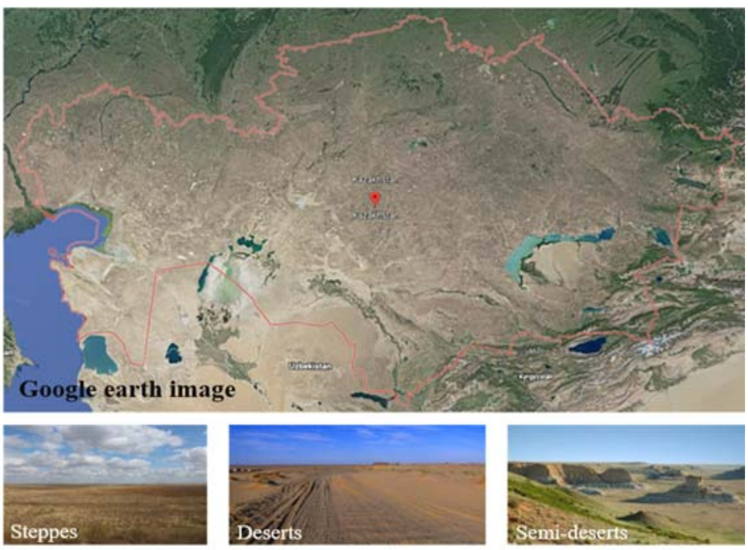

Fig. 2. The geography of Kazakhstan and Google earth image. Steppes – 63%, deserts and semi-deserts – 25% and mountains 10%. In the north of the republic, forest-steppes prevail (2%).

The practical applications of the synthesized superhydrophobic sand are central to the significance of this research. Notably, it has the potential to save substantial volumes of water for EOR applications, a domain where water plays a crucial role. By enhancing water retention and reducing the rate of evaporation, superhydrophobic sand contributes to water efficiency and conservation. This is a particularly valuable attribute, considering the demands of EOR in water-scarce environments. Beyond EOR, the applications of superhydrophobic sand extend to various sectors, including agriculture and environmental sustainability. The synthesized superhydrophobic sand holds the potential to make a significant impact, fostering sustainable practices in water management and contributing to the greening of arid regions. This research serves as a valuable source of insight into the efficient utilization and conservation of water resources, offering a sustainable solution to water-related challenges in the western part of Kazakhstan. The work aims to study and highlight the potential applications of superhydrophobic sand, especially in the context of water conservation in the arid regions of Kazakhstan. The study aims to address water scarcity and contribute to various sectors, including enhanced oil recovery (EOR) and agriculture.

2. Materials and methods

2.1. Chemicals

High purity titanium (IV) oxide nanoparticles (TiO_2, 99.5%, size 21 nm), Polydimethylsiloxane (PDMS) from Silicone Sealant, anhydrous hexane (95%), borosilicate cover glasses were purchased from Sigma Aldrich. Mixed carbonate-silicate sand from the north region of Kazakhstan with a grain size of 0.1 to 800 µm was used as raw material.

2.2. Preparation of superhydrophobic solution

Firstly, 1g PDMS was dissolved in 10 ml of hexane by magnetic stirring for 3 h, then placed into an ultrasound bath for 1 h under a hermetically covered cap. Further, 50 mg TiO_2 was added to the mixture and ultra-sonicated for another 2 h. The as-prepared superhydrophobic solution was coated with quartz sand. Finally, quartz sand mixed with superhydrophobic coatings was left at room temperature for drying overnight (Fig. 3).

2.3. Material Characterization

Contact angles (OCA) of water droplets on the as-prepared sand surfaces were investigated by a goniometer (Dataphysics OCA 15Pro, Filderstadt, Germany). Scanning electron microscopy (SEM) (Zeiss Auriga Crossbeam 540, Carl Zeiss, Germany) was applied to measure the morphology of superhydrophobic sand materials.

3. Result and discussion

Figure 3 is a visual representation of the process and structure involved in the formation of superhydrophobic quartz sand. Its purpose is to provide a clear and informative description of the stages and structural modifications that lead to the desired superhydrophobic properties.

The wettability of superhydrophobic sands was investigated with optical contact angle measuring and contour analysis system. To measure the contact angle, sand particles were uniformly distributed on the surface of conductive double sided carbon tape and thereafter placed in the sample stage. An amount of 2 µl water droplet was applied to all samples. Figure 4 shows contact angle measurements of quartz sand after processing with superhydrophobic coatings, the maximum contact angle with water was 158.1° (Fig. 4b).

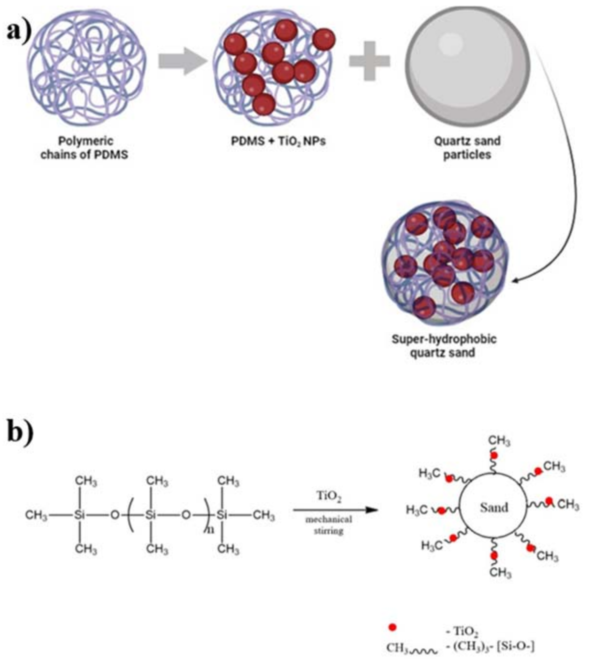

Fig. 3. Process of formation of superhydrophobic quartz sand graphic (a) and structural (b) illustration.

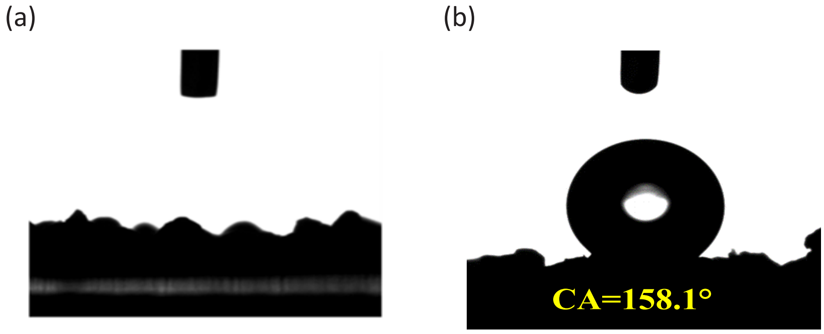

Fig. 4. Contact angle measurements of quartz sands before (a) and after coating with PDMS/TiO_2 (b).

Photographic images of water droplets on quarts sands before and after coating with superhydrophobic materials were presented in Fig. 5. It can be seen that the bare sand instantly absorbs water drops in Fig. 5a and this means that the sands have hydrophilic properties. The quarts sands coated with PDMS/TiO_2 demonstrate superhydrophobic properties because spherical water droplets levitate on the surface of the sands (see Fig. 5b and 5c).

The microstructure and surface morphology of uncoated and coated with superhydrophobic materials have been studied using SEM (Fig. 6). Upon applying the PDMS/TiO_2 coating to the sand, a notable transformation in surface roughness was observed. In essence, the coated sand exhibited an increased degree of roughness, a key characteristic contributing to its newfound superhydrophobicity. It is crucial to recognize that surface roughness is a pivotal factor in rendering surfaces hydrophobic, a phenomenon substantiated by numerous studies in the field.

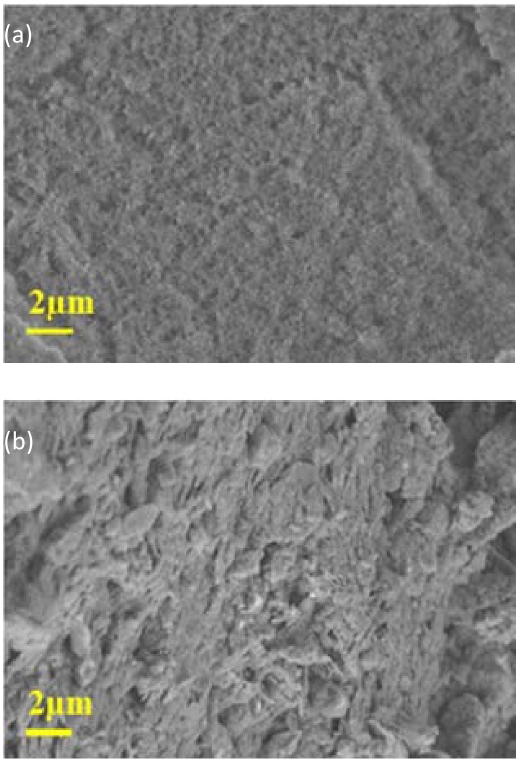

Fig. 6. SEM images of quarts sand before (a) and after coating PDMS/TiO_2 (b).

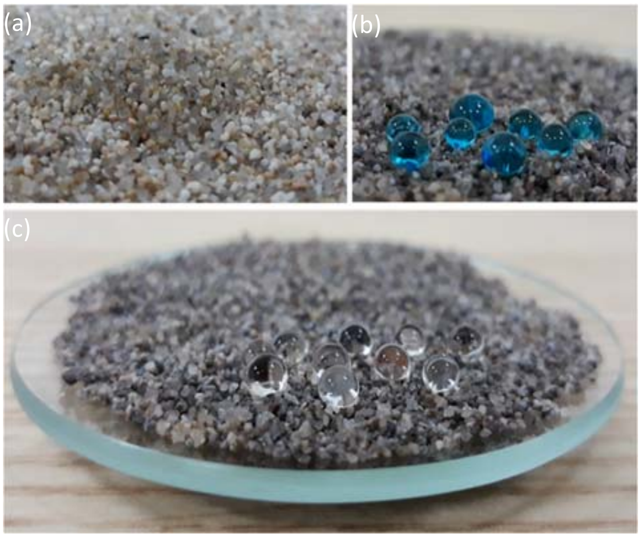

Fig. 5. Digital photography of water droplets on quartz sands: a) water droplets adsorbed on bare quartz sand; b) dye water droplets; c) normal water droplets on superhydrophobic sand.

The alteration in surface roughness induced by the PDMS/TiO_2 coating is a significant achievement in achieving superhydrophobic properties. This enhanced roughness introduces unique surface features that facilitate the repulsion of water, leading to superhydrophobic behavior. As established by prior research, the correlation between surface roughness and hydrophobicity underscores the importance of this characteristic in designing effective superhydrophobic surfaces [20–21].

We carried out experiments on the wettability of superhydrophobic sand under soil conditions and a biological object – strawberry roots. For this experi-

Fig. 7. Specially designed transparent polystyrene pot for growing plants (a), fertile soil (b) and 4 in 1 soil survey instrument (c).

ment, the following materials were used: hydrophobic sand with a fraction of up to 800 µm, commercially available mineral water, silica soil, PH300 soil hygrometer, and polystyrene pot with 8 holes at the bottom.

Superhydrophobic sand has been used for plant growing experiments. Figure 7 shows specially designed transparent polystyrene plant pots, a soil moisture sensor meter tester – a device for studying fertile soil and a digital meter.

At the bottom of the polystyrene pot, 8 round holes were made to pass air to the roots of the plant. Fully transparent pots were used for real-time monitoring and assessment of plant growth. Holes in the bottom of the pots served as air inlets to prevent root rot.

In order to test superhydrophobic sand to save water in agriculture, three experimental lines were carried out (shown in Fig. 8): planting strawberries in a pot with fertile soil (Fig. 8a), strawberries planted in a pot with fertile soil (Fig. 8b) with superhydrophobic sand under the strawberry root and strawberry planting with superhydrophobic sand placed under the plant root and above the soil (Fig. 8c).

Fig. 8. Schematic and digital representations of the use of superhydrophobic sand to save water in agriculture: a) strawberries planted in a pot with soil; b) strawberries planted in a pot with soil and superhydrophobic sand placed under the root of the plant; c) strawberries planted in a pot with soil and superhydrophobic sand placed above the soil and under the root of the plant.

In the third experiment, superhydrophobic sand was placed both above and below the soil in order to conserve as much irrigation water as possible. In this experiment, a small channel was made from a plastic tube to water the plant. All three experiments were started simultaneously and all three soil pots were tested under the same environmental conditions. 150 ml of mineral water was poured into each of the three pots.

The digital image is shown below after watering the strawberries (Fig. 9). As expected, the water did not pass through the superhydrophobic sand, thereby retaining soil moisture. Air can pass through the sand to the root of the plant, which accordingly prevents root rot of the plant.

The results of our research, which assessed the growth and external condition of strawberries under varying soil conditions, provide valuable insights into the role of superhydrophobic sand in water conservation and plant health. This discussion focuses on the observed outcomes and their significance:

– the first pot, containing strawberries planted in fertile soil, exhibited rapid water loss, with the plants drying out within just 2 days when exposed to ambient conditions. This outcome underscores the challenge of retaining soil moisture and preventing rapid dehydration, particularly in arid or sunny environments. Such conditions can significantly impact plant health and growth, as indicated by the drooping leaves observed.

– in the second experiment, where efforts were made to maintain soil moisture, a notable improvement was observed, with the soil retaining adequate moisture for almost 5 days. While this demonstrated a more favorable environment for plant growth, there remained considerable potential for further enhancement in water conservation.

The most striking results emerged from the third experiment, where superhydrophobic sand was employed both above and below the soil. In this scenario, the soil retained water and moisture for an impressive duration of almost 10 days. This finding is particularly significant, as it highlights the remarkable water-conserving properties of superhydrophobic sand.

The ability of superhydrophobic sand to create a barrier that prevents rapid water loss due to sunlight exposure is a key takeaway from this research. By effectively blocking water molecules from drying out in the presence of sunlight, superhydrophobic sand offers a practical and innovative solution to the challenge of soil moisture retention. This technology has the potential to revolutionize water-saving practices in agriculture, horticulture, and environmental sustainability [22, 23].

Furthermore, the observed results underline the value of applying superhydrophobic sand in a dual-layer configuration, both above and below the soil. This approach yielded excellent outcomes, further emphasizing the potential for this technology in addressing water scarcity and promoting the healthy growth of plants. Our research demonstrates the promising role of superhydrophobic sand in prolonging soil moisture, thereby contributing to water conservation and healthier plant growth. These findings open the door to a range of practical applications, from agriculture to landscaping and environmental management, where efficient water management is essential.

The soil moisture and mean temperature of the current environment and soil were determined us-

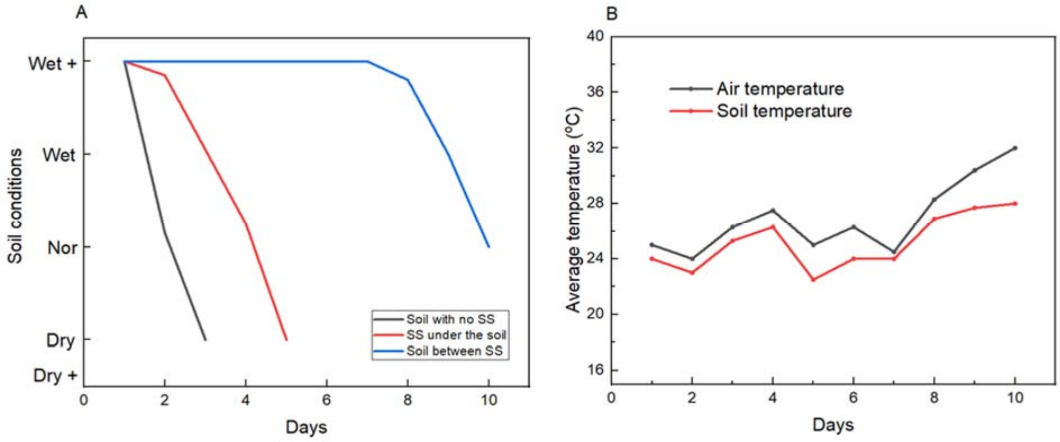

Fig. 10. Digital image after 3 days of watering 150 ml of mineral water: a) soil moisture; b) average temperature of the current environment and soil.

ing a digital soil hygrometer (see Fig. 10) after a 10-day irrigation period.

The results presented in Figure 10 provide compelling evidence of the remarkable potential of superhydrophobic sand in water conservation and its relevance to applications such as Enhanced Oil Recovery (EOR) in arid regions. This discussion emphasizes the significance of the findings:

Figure 10 shows a critical experiment in which strawberries were irrigated with 150 ml mineral water and the soil moisture, current environment and soil temperature were monitored over a period of 10 days. The outcomes of this experiment are striking and carry substantial implications.

The introduction of superhydrophobic sand into the soil led to a dramatic fivefold increase in water savings compared to scenarios without its use. This is a pivotal revelation, as it underlines the transformative potential of superhydrophobic sand in addressing water scarcity in regions where water resources are limited [24, 25].

Importantly, the implications of these findings extend beyond traditional agricultural and horticultural applications. The concept of "superhydrophobic sand" emerges as a novel and efficient approach to water storage [26, 27–29]. It is particularly pertinent to EOR in arid regions, where water scarcity is a pressing challenge. By conserving and efficiently managing water resources, superhydrophobic sand offers a practical solution to the demand for water in EOR operations.

The value of this research is evident, as it not only demonstrates the ability to conserve water necessary for plant growth but also highlights the broader potential for water storage. This innovative approach aligns with the critical need for sustainable water management in water-stressed areas and its applicability to EOR, where access to water is a pivotal factor in the success of oil recovery processes. This technology represents an opportunity to address water scarcity challenges, offering a sustainable solution for water storage in regions where water resources are limited. Superhydrophobic sand has the capacity to revolutionize water-saving practices, providing a significant contribution to EOR and various other applications where water conservation is paramount.

4. Conclusion

In conclusion, the research presented in this study underscores the critical importance of innovative solutions to address water scarcity concerns in arid regions, especially in the context of Enhanced Oil Recovery (EOR) processes. The development of superhydrophobic sand has proven to be a promising advancement, with remarkable results. The achieved maximum water contact angle of 158° exemplifies its exceptional water-repellent properties, rendering it a valuable tool for water management.

The practical applications of superhydrophobic sand in water harvesting, storage, and conservation are particularly noteworthy. The prolonged moisture retention observed in soil layers when superhydrophobic sand was utilized, with soil remaining moist for over 10 days, stands in stark contrast to the mere 3 days of moisture retention in the absence of this technology. This not only has implications for water-saving practices in EOR but also highlights the potential for mitigating water scarcity in arid regions.

Moreover, the findings from soil temperature checks indicate a beneficial effect on soil temperature, which further contributes to its potential for applications in agriculture and environmental sustainability.

In summary, superhydrophobic sand offers a multifaceted solution to the pressing challenges of water conservation and management in arid regions, with significant implications for both EOR processes and broader water-saving initiatives. This research presents a compelling case for the integration of superhydrophobic sand technology into strategies aimed at addressing water scarcity and promoting sustainable water use.

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