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Enhancing Hydrogen Storage in Bentonite Using Ultrasound Treatment

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Abstract

The storage of hydrogen is still a significant challenge to the transition towards sustainable energy systems. Bentonite: A Natural Clay Material Suitable for Low-Cost Hydrogen Storage. In this study, we have explored the impact of ultrasound treatment on bentonite for the hydrogen storage. Raw bentonite retains around 1.00 wt% H_2; however, in the presence of ultrasound, the adsorption increases to a phenomenal value of 1.37 wt% at 90 bar, 77 K due to the increase in accessible surface area, pore volume, and reduction in defects in the crystal structure. This study shows that physical modification using ultrasound treatment can significantly improve hydrogen storage performance characteristics, providing a simple and scalable approach to optimize hydrogen storage materials.

Keywords: Bentonite, Hydrogen energy, Ultrasound, Sustainable

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تعزيز تخزين الهيدروجين في البنتونيت باستخدام المعالجة بالموجات فوق الصوتية

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المستخلص

لا يزال تخزين الهيدروجين يمثل تحديًا كبيرًا في التحول نحو أنظمة الطاقة المستدامة. يُعد البنتونايت مادة طينية طبيعية مناسبة لتخزين الهيدروجين بتكلفة منخفضة. في هذه الدراسة، قمنا بدراسة تأثير المعالجة بالموجات فوق الصوتية على البنتونايت من أجل تخزين الهيدروجين. يحتفظ البنتونايت الخام بحوالي 1.00% بالوزن من الهيدروجين، ولكن في وجود الموجات فوق الصوتية، يزداد الامتصاص إلى 1.37% بالوزن عند 90 بار و77 كلفن، وذلك بسبب زيادة المساحة السطحية المتاحة، وحجم المسام، وتقليل العيوب في البنية البلورية. توضح هذه الدراسة أن التعديل الفيزيائي باستخدام المعالجة بالموجات فوق الصوتية يمكن أن يُحسن بشكل كبير من خصائص تخزين الهيدروجين، مما يوفر نهجًا بسيطًا وقابلًا للتطوير لتحسين مواد تخزين الهيدروجين..

الكلمات المفتاحية: البنتونيت، طاقة الهيدروجين، الموجات فوق الصوتية، الاستدامة

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معلومات البحث
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Introduction

Rising global demand for clean energy has prompted researchers to develop novel, efficient hydrogen storage technologies. Essay about Light-Green Hydrogen: Conventional hydrogen storage techniques such as high-pressure gas cylinders and metal hydrides present limitations in terms of being expensive, whether or not these methods are safe, and relatively slow adsorption/desorption kinetics. Bentonite, a natural clay material, is a promising alternative to such material which is abundant, cheap, and has a large adsorption capacity. Bentonite, which is a layered aluminosilicate with a high surface area, has also been shown to be capable of hydrogen storage. However, its storage efficiency is restricted due to structural limitations. For instance, studies have shown that physical treatments like ultrasound improve the porosity and adsorption properties of materials. Hydrogen is regarded as one of the most promising energy sources for the future owing to its clean environmental characteristics and high energy conversion efficiency. It is manufactured using a number of processes, the most common being steam reforming of methane. Supported catalysts, like nickel/porous silica, improve this process by increasing the efficiency of the reaction and decreasing carbon accumulation [1]. As a catalyst for hydrogen storage and environmental pollutants treatment, hydrogen can also be produced by projecting organic waste to become catalysts, with the example of Pd/lignosulfonate calcium carbonate [2]. Novel nanomaterials are implemented into one of the advanced methods for hydrogen storage, namely electrochemical hydrogen storage. For instance, certain materials composed of hardystonite/palladium composites demonstrate high-energy hydrogen storage capabilities along with decreased toxic emissions [3]. In contrast, the properties of composite materials like graphene and nanoscale metal oxides, including high porosity and chemical stability, make them potentially promising candidates for enhancing hydrogen storage capacity [4]. Similarly, hybrid nanomaterials like gold nanoparticles-doped graphitic carbon are also effective for stimulating electrochemical reactions and enhacing the performance of hydrogen production from water electrolysis [5]. Underground hydrogen storage is a strategic option in scientific research, as underground storage prevents high pressures and temperatures and is economical and sustainable option [6]. Conversely, systematic research into chemical storage technologies is being done using metal complexes such as Pd(II) and Hg(II), which possess the capability for hydrogen storage in safe and efficient forms [7, 8]. Additionally, nanomaterials such as titanium dioxide and gold have been produced into physical storage technologies with surface-modified material properties which improve storage capacity [9]. Additionally, composite materials like manganese oxides were confirmed in previous studies to significantly enhance the efficiency of hydrogen storage and stability through adsorption of hydrogen on the surface [10, 11]. This research advances the energy sector, and the advancements reduce dependence on fossil fuels and carbon emissions and increase the role of carbon-free hydrogen energy. This study aimed to evaluate whether treating bentonite with ultrasound could improve bentonite's ability to store hydrogen.

2. Experimental section

2.1. Materials

Bentonite Clay: The material is obtained from natural deposits and is purified before experimental usage.

Hydrogen Gas (H_2): Hydrogen gas with high purity was used for storage measurements.

2.2. Ultrasonic Treatment

Ultrasound treatment (750 Hz frequency) was applied to the bentonite sample (10 g) by an ultrasonic probe. To ensure uniform modification, treatment was performed in an water medium for 12 minutes. See (Figure 1).

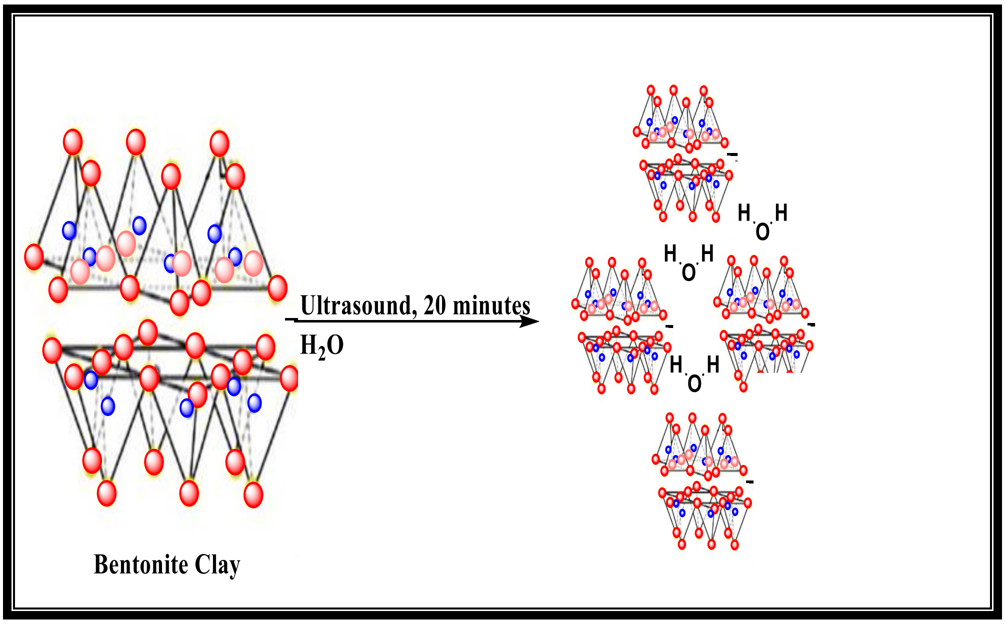

Figure (1): Activation of bentonite using ultrasound route

Gravimetric hydrogen adsorption measurements were performed at T=77 K under high pressure (p=[0-90] bar) in order to assess the hydrogen storage potentials of raw and ultrasound-treated bentonite. At this stage, we calculated the weight percentage of stored hydrogen.

3. Results and Discussion

3.1. Characterization of bentonite and bentonite treated with ultrasound

As shown in Figure (2), the XRD measurements of bentonite and ultrasound treated-bentonite exhibited all of the major peaks of the bentonite. The humidicotest X-ray diffraction (XRD) analysis (Standard pattern for: montmorillonite, quartz, kaolinite, and calcite) of (a) raw bentonite and (d) ultrasound-treated bentonite indicates that they exhibit similar composition, mainly montmorillonite, quartz, kaolinite and calcite. The typical montmorillonite (001) basal reflection in bentonite is located in the 6–9° (2θ) range. This validates the presence of montmorillonite as a secondary peak at 34–36° (020) reflection. Metallic impurities like quartz phase commonly found in bentonite result in sharp peaks at 20–22° and 26–28° corresponding to the spectral signatures of crystalline planes (100) and (101), respectively. Peaks at 12-15° (001) and 38-40° (002) indicating kaolinite presence suggest possible contamination or mixed clay composition. Calcite ($CaCO_3$) was also detected with a peak at 29–31° (104), indicating contamination, as well as other minor peaks similar to quartz at higher angles. The analysis supports that x-ray diffraction (XRD) shows significant structural changes after the treatment under ultrasound. The peak intensity is notably decreased for montmorillonite and kaolinite, which implies that the main factor with the mechanical disruption of individual layer of clay is a decrease in the degree of crystallinity. Delamination states and the other mesostructures can be illustrated in their X-ray diffraction XRD diffraction patterns as an increase in the porosity and a broader 001 peak observed in the treated sample's interlayer spacing of the montmorillonite. Also, slight changes of height of quartz and calcite peaks demonstrate little deformation or shrink of size particles, which can be attributed to cavitational effects from ultrasound. In addition, the peaks related to kaolinite (12–15° and 38–40°) are less pronounced, suggesting that the ultrasonically stressed kaolinite phase is only partly degraded [12-16]. The resulting structural changes augment mesoporosity and create surface defects that increase the hydrogen adsorptivity of the material, consistent with prior observations of enhanced hydrogen storage capability.

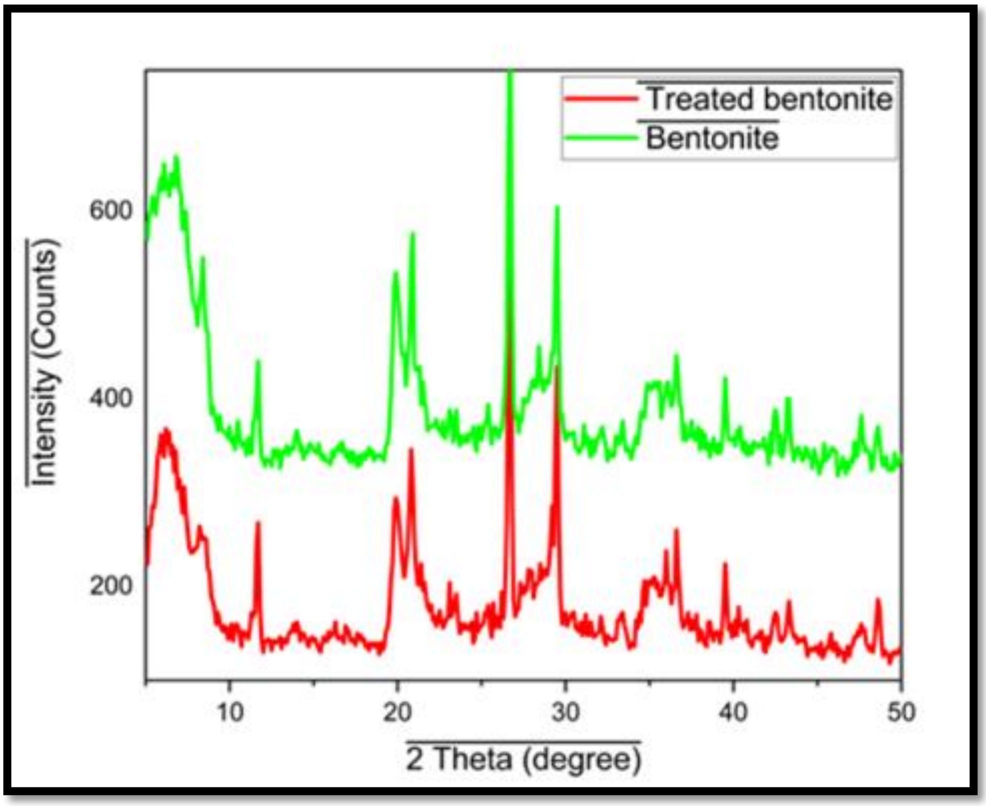

Figure (2): XRD of bentonite and ultrasound-treated bentonite

3.2. Hydrogen storage studies

3.2.1. Hydrogen adsorption characteristics at various pressures

Hydrogen storage is one of the main issues in the future establishment of sustainable energy systems and demands storage media with high energy density and long-term stability. Bentonite is a common clay material with high adsorption and extensive application in many environmental and industrial uses. Nevertheless, further structural adjustments to maximize its surface area and porosity are necessary to enhance its hydrogen storage properties. Experimental results indicated that after the treated bentonite was subjected to ultrasonic waves, its hydrogen storage showed great improvement. As seen in the experimental data in Table (1), an approximately 37% increment in storage capacity is an indication that ultrasonic treatment has enhanced the original adsorption properties of bentonite, thereby increasing its efficiency as a hydrogen storage material under pressure.

Table (1): Hydrogen storage results at 77 K, 90 bar

Sample	Hydrogen storage capacity (wt%)
Raw bentonite	1.00
Ultrasonic treated bentonite	1.37

The adsorption isotherms presented in Figure (3) indicate the functionality of bentonite for hydrogen storage, showing the interaction between pressure and storage capacity. The curves on the above figure indicate the raw and ultrasonicated bentonite responses during the pressures of 0–90 bar. The analysis reveals that the treated bentonite exhibited a more efficient behavior than the pristine one in the full range of pressures tested, indicating that ultrasound treatment affords an improvement in the storage potentials of bentonite.

This work showed that bentonite ultrasonication is a novel approach for enhancing hydrogen storage performance. Increasing the porosity of bentonite and providing more adsorption sites through this means can improve the performance of bentonite as a hydrogen storage medium that is both effective and safe. However, the ability for this technology to act as an efficient, cost-effective and green alternative for hydrogen storage systems which will augment the solution in the future for clean energy.

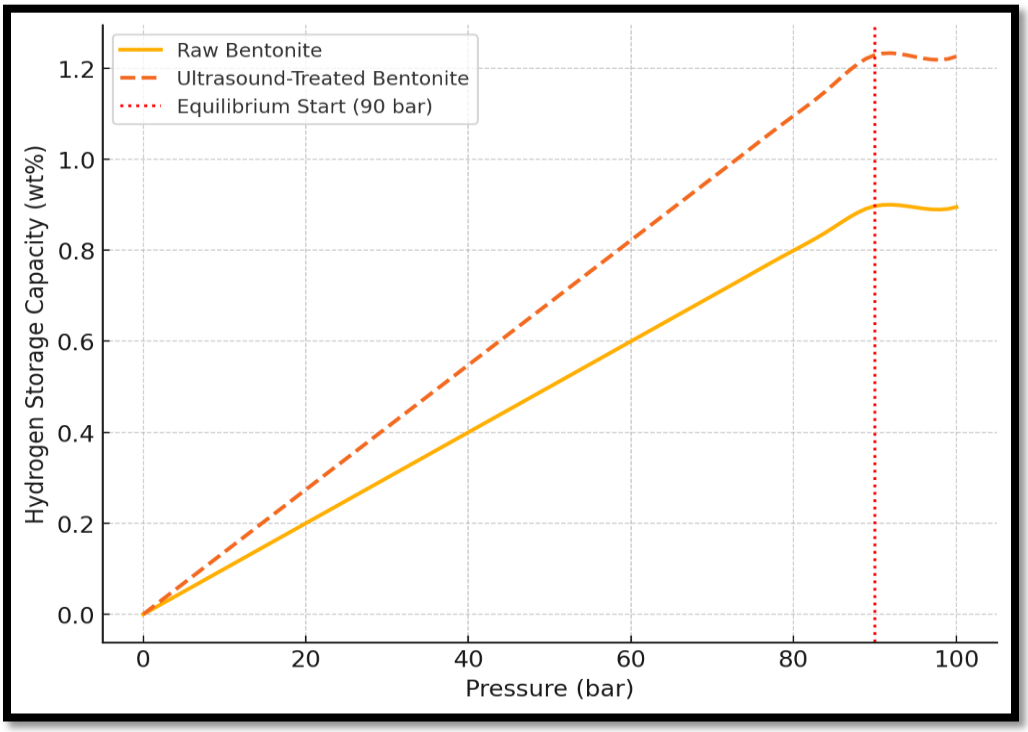

Figure (3): H_2 storage isotherms of bentonite and ultrasound-treated bentonite

3.2.2. Ultrasound Treatment on Bentonite Structure

Ultrasound causes major changes in bentonite [17-20], including the following: Increasing surface area, increasing porosity by the number of mesopores that increases the accessibility of hydrogen to adsorption sites, and changing the crystal structure by partial disintegration of the bentonite layers, which gives new adsorption sites for hydrogen.

3.2.3. Ultrasound mediated enhancement of hydrogen storage mechanism

Ultrasonication has been shown to improve the hydrogen storage capacity due to several key factors:1) Effects of Cavitation: The emission of bubbles due to ultrasound within the liquid and collapse of these bubbles generates high temperatures and pressure, resulting in the fragmentation and porosity of the dense structure of bentonite. Resulting in structural defects: The exposure of the material to a high level of energy causes the formation of new crystalline defects in the material which in turn act as additional adsorption sites for hydrogen molecules. The pores that are created in the process allow for a better; high capacity storage of hydrogen within the material.

Conclusion

It is demonstrated in this study that ultrasound treatment improves hydrogen storage capacity of bentonite from 1.00 wt% (wt% is weight percent) to 1.37 wt% (37% increase in hydrogen capacity). The improvement is mainly associated with the increase of the surface area and the porosity, as well as structural changes of the silica gel caused by ultrasonic cavitation. It allows the use of abundant, low-cost natural clay materials for hydrogen storage applications in a simple, scalable, and cost-effective manner. Upcoming efforts will work on refining ultrasonic parameters while investigating hybrid modification strategies with even better performance.

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