Biomimicry Surface-Coated Proppant with Self-Suspending and Targeted Adsorption Ability

Wenjie Lan, Yingchun Niu, Mao Sheng, Zhaohui Lu, Yong Yuan, Ye Zhang, Yang Zhou, and Quan Xu*

ABSTRACT: Proppant is a key material, which can increase the production of unconventional petroleum and gas. Excellent proppants with a long migration distance are required in the fracture network. Resin-coated proppants have been confirmed as a good choice because of the long migration and the self-suspending ability in fracturing fluids. However, the distribution of the resin-coated proppants in fracture networks is random. The design of proppants with targeted adsorption is urgently needed. In this study, a novel proppant coated with a phenolic resin shell doped with Fe3O4 nanoparticles on ceramic (coated proppant) was designed and investigated. Based on the results, the coated proppant was adsorbed on the magnetic component’s parts of the fracture network surface, which helps in enhancing the uniform distribution of the proppant in the fracture rock cracks. Meanwhile, the self-suspending ability of the coated proppant is five times higher than that of the uncoated proppant and can migrate a longer distance in the fracture network. Moreover, the liquid conductivity of the coated proppant is 30% higher than that of the uncoated ones at a closure pressure of 6.9 MPa. In summary, new insights into the design of functional proppants and further guidelines on the production of unconventional petroleum and gas have been provided in this study.

INTRODUCTION

An energy crisis is expected as finite reserves of fossil fuels are being rapidly depleted. Global remaining recoverable petroleum and gas reserves in 2011 amounted to 2343 × 108 t and 208.4 × 1012 m3,1 which cannot meet the requirements of the current age. Currently, the development of a new energy source is not optimistic and other energy sources are urgently needed to be explored, which aim to alleviate the crisis.2−4 The proportion ratio of global conventional and unconventional petroleum and gas resources is 2:8. It is necessary to point out that the unconventional petroleum reserves are almost equal to the conventional ones and the unconventional gas reserves are more than eight times that of the conventional gas ones. Particularly in China, the unconventional petroleum and gas resource is spectacular, which is about 240 × 108 t and 100 × 1012 m3, respectively. Using proppants in the mining process can effectively improve the production of unconventional petroleum and gas.5,6 However, previously reported coated proppants lost liquid conductivity quickly under higher pressure, leading to the necessity to develop coating proppants with high liquid conductivity to meet the condition of complex and complicated cracks in shale rocks. A previous study indicated that the difficulty of mining is directly related to fracture conductivity of the proppant structure and the size as well as the complexity of the fracture network in unconventional petroleum and gas shale reservoirs.10 In addition, the distribution of proppants is another crucial factor in the efficiency of mining.7−9 Ceramic particles and sand are commonly used as the traditional proppants in the petroleum and gas industry.8,10 The proppant provides a high-porosity conductive channel from the reservoir to the well. In addition, the opened fracture can improve liquid conductivity (petroleum or natural gas). However, the settling rate of the traditional proppant is fast and the liquid conductivity is poor.11−13 The density of proppants coated with resin is lower, which enhances the self-suspending ability.14 Subsequently, the sedimentation time and liquid conductivity capacity are remarkable increased. For example, Xu14 and Wei15 have point out that the self-suspending ability can affect the performance of the proppant. Furthermore, the resin shell can protect the inner brittle materials from crushing and prevent blocking the channel from the liberation of fines.16−19 However, the distribution of the proppants coated with resin in the fracture network could not be controlled.10,11,12,20 Particularly, high stress and magnetic materials in the rock formation can affect the distribution of proppants when
hydraulic fracturing is performed in deep shale petroleum and gas reservoirs. Therefore, designing a self-suspending and directed adsorption proppant is required.

In this work, inspired by a gecko reversible adhesion design, we fabricated a novel target adhesion proppant ceramic coated with Fe₃O₄ nanoparticle-doped phenolic resin shell (coated proppant) successfully. The density of the coated proppant in this paper could reduce because of the presence of the resin shell, leading to a reduction in the settling speed and an increase in the migration distance. The introduction of Fe₃O₄ is expected to greatly increase the yield of unconventional petroleum and gas through adsorbing on the magnetic components of the fractured formation. The coated proppant can be adsorbed on the surface of the magnetic component of the fracture network, which gives control over the distribution of coated proppant in the fracture. The excellent self-suspending ability of the coated proppant is more than five times that of the ceramic. The liquid conductivity of the coated proppant is 30% higher than that of the uncoated proppant at the lower closure pressure of 6.9 MPa.

RESULTS AND DISCUSSION

Discussion of Morphology and Composition. The transmission electron microscopy (TEM) image of Fe₃O₄ is shown in Figure S1. The average size of Fe₃O₄ was 275 nm. The scanning electron microscopy (SEM) photographs of the proppant are shown in Figure 1a–d, which shows the rough and porous nature of the proppant surfaces. Figure 1a–d shows the surface morphology of uncoated and coated proppant obtained using the SEM tests, respectively. The roughness of the surface decreased significantly because of the phenolic resin shell and the sphericity of the coated proppant close to one. Moreover, the surface roughness of the coated proppant is below 2 μm. Figure 1e–h shows the energy-dispersive X-ray spectroscopy (EDX) results of the coated proppant. The aluminum elements (Figure 1e) and silicon elements (Figure 1f) can be observed on the surface, while not obvious. The carbon elements (Figure 1g) and iron elements (Figure 1h) are detected distinctly, which confirms that the phenolic resin and Fe₃O₄ nanoparticles have been successfully coated on the surface of the proppant.

The Fe₃O₄ was decorated with poly (acrylic acid) (PAA), which endowed rich hydrogen bonds. The phenolic resin was adsorbed on the surface of the Fe₃O₄ nanoparticles with a strong hydrogen bond interaction between their phenolic hydroxyl groups as a Lewis base electron donor, and PAA as a polycylic electron acceptor, and the abundant hydrogen-bonds of Fe₃O₄ could also promote the phenolic resin to form a shell on the ceramic. The Fe₃O₄ nanoparticles with rich carboxyl functional groups have a zeta potential of about −23.03 mV at pH = 7, which helps in maintaining a good dispersibility in an alcohol solution. The Fourier transform infrared (FTIR) spectra of the four materials are shown in Figure 2a.

As shown in the spectra of all the four samples, the following significant peaks can be observed in red and blue curves. Two distinct valleys of the characteristic peak of benzene ring skeleton vibration and hydroxyl vibration can be seen in the transmittance spectrum at 1611 and 3228 nm for both coated proppant and phenolic resin but are absent in ceramic, and the characteristic peak at 608 nm is attributed to the Fe₃O₄ nanoparticles. The change in the characteristic peak affirmed the existence of the phenolic resin shell doped with Fe₃O₄ nanoparticles of the coated proppant.

The magnetic hysteresis loop of the coated proppant was further measured in air as shown in Figure 2b. It can be seen that the saturation magnetization (Mₛ) is 1.96 emu·g⁻¹. The low value of Mₛ is ascribed to the low content of Fe₃O₄. As the doping level is relatively low, the density change of the coated proppant could be negligible, but the presence of weak magnetism enables controlled adsorption of the proppant. The XPS element analysis (Table S1) demonstrates that the content of iron, aluminum, silicon, and carbon are 7.6, 4.82, 3.74, and 47.47 wt %, respectively. The higher mass percentage of iron and carbon elements reafirms the presence of the phenolic resin shell doped with Fe₃O₄ nanoparticles since XPS can only detect the elements on the surface layer. The high-resolution XPS spectra of iron are shown in Figure 2c with two peaks at 724.6 and 711.1 eV. The X-ray diffraction (XRD) technology was used to further confirm the composition of the materials, and the results indicate that the coated proppant has all the characteristic peaks of ceramic, phenolic resin, and Fe₃O₄ (Figure 2d). In addition, the characteristic peaks of the coated proppant are attributed to the Al₂O₃ and Fe₃O₄.

Discussion of Liquid Conductivity. An atomic force microscopy (AFM) manipulator system has been used to run the adhesion test. Figure 3a shows the contact time versus adhesion force with the range of contact time from 0.6 to 2.6 s and a load force of 1.5 μN. The adhesion force of the coated proppant and uncoated proppant does not change significantly with the different contact times, and at the same contact time, the values of the coated proppant are higher than that of the uncoated proppant, which indicates that the adhesion force of the coated proppant is enhanced.

The variations of adhesion forces at different load force conditions of the coated proppant and uncoated proppant are shown in Figure 3b with the same contact time-controlled at 0.1 s. The adhesion force increases with increasing load force and both curves show a good linear relationship between load forces and adhesion forces. The adhesion forces of the coated proppant were larger than that of the uncoated proppant at the same load force, which well illustrates that the presence of the phenolic resin doped with the Fe₃O₄ shell will not change the tendency of mechanical property of the proppant.

The typical AFM force curve (Figure 3c) illustrates that the adhesion force is determined by the difference between extended and retracted force values. The higher adhesion force of the coated proppant could be beneficial to improve the liquid conductivity. Figure 3d shows the liquid conductivity of the different proppants under different effective closure stress range from 6.9 to 55.2 MPa with a fixed proppant concentration and flow rate (6 kg/m² and 3 mL/min).
Based on the result, the liquid conductivity of the coated proppant and uncoated proppant decreased with increasing closure stress, and the liquid conductivity of the coated proppant is higher than that of the uncoated proppant at lower closure pressure (6.9–27.6 MPa). The liquid conductivities of the coated proppant are 75.23 and 57.9 D-cm with the closure pressure at 6.9 and 13.8 MPa, respectively, and for the uncoated proppant, it showed 58.23 D-cm at 6.9 MPa, which is 30% lower than that of the coated proppant. At high closure, the pressure ranged from 34.5 to 55.2 MPa and the liquid conductivity of the coated proppant is slightly lower than that of the uncoated proppant.

The components of the rock formation are oxygen, silicon, aluminum, iron, and some other elements,33 which can form van der Waals force with the silicon and aluminum elements of ceramic (Figure 3e).34−38 The carbon elements of phenolic resin have free electron pairs, which can form chemical bonds with the oxygen during the rock formation, including cohesive bonds and hydrogen bonds and the force of the bond's energy will increase significantly with the increasing temperature underground. In addition, a large number of magnetic elements in the rock formation can form attraction with Fe₃O₄, which is beneficial to the directional adsorption in the fracture of the channel. In addition, the gravitational field formed between the coated proppant, could be ascribed to the coulomb force of Fe₃O₄. After entering the channel, the strong gravitational field increases the surface tension of the channel and further enhances the self-suspending performance of the coated proppant. While the coated proppant has a higher contact angle with H₂O, based on Young’s equation, water will stay longer on the hydrophilic surface because of the strong van der Waals force between H₂O and Si−O, while water will move faster on the hydrophilic surface because of the repulse forces between H₂O and the high molecular weight polymer. Thus, the liquid conductivity can be enhanced on the hydrophobic coated proppant. The coated proppant shows enhanced liquid conductivity because of the excellent self-suspending nature, presence of hydrophobic shell, and directional adsorption. This property can be enhanced on coated hydrophobic proppants.

The actual friction coefficient and adhesion determined the friction force offset were the other influencing factors of liquid conductivity, which were dependent on the surface chemistry and structure. The friction coefficient of the pure hydrophobic system is higher than that of the hydrophilic system, but the friction coefficient of the heterogeneous hydrophobic hydrophilic system is the lowest. When the surface of the object is hydrophobic, the friction coefficient will be reduced. It is worth pointing out that the coated shell in this paper was a kind of hydrophobic material. Since the friction forces between water and the hydrophobic surface are smaller than that of water on a hydrophilic surface, thus after the proppant was coated by hydrophobic materials, water would move much faster than that on previously uncoated proppant. This phenomenon was also support by the Esben Thormann group.39

Moreover, the coated proppant surface was smooth and the uncoated proppant was rough (Figure 1a−d). The main composition of ceramic is Al₂O₃ and SiO₂, both of which are hydrophilic substances and will obstruct the flow of liquid. In addition, the rough surface will cause the formation of a vortex when the fluid flows near the uncoated proppant, which will produce greater friction force and hinder the fluid flow. However, the surface of the coated proppant is smooth, which is more conducive to the liquid passage rapidly and avoids the occurrence of vortices, which may cause the better liquid conductivity under the low closure pressure (6.9–27.6 MPa), but slightly lower at high closure pressure (34.5–55.2 MPa because of the breaking and falling off of the phenolic resin shell and the debris could obstruct the flow of liquid.9

Figure 4a,b shows the schematic diagram of the flow and location distribution of proppants in the fractured formation. The uncoated proppant will deposit quickly during the
migration process since the high density of ceramic leads to a short migration distance. A large amount of deposition of the uncoated proppant in the front end of the channels will block the channels and hinder the passage of the liquid; hence, it cannot play the expected role in supporting the fractured formation. The density of the coated proppant could reduce a lot because of the presence of the resin shell, leading to a reduction in the settling speed and an increase in the migration distance.

Videos of the self-suspending experiments of the uncoated and coated proppant are shown in videos S1 and S2. The self-suspending experiments diagram of the coated and uncoated proppant is shown in Figure 5a. Most of the coated proppant could achieve self-suspension in the mixed solution, but ceramic sinks to the bottom instantly after being poured into the mixed solution. The average value was calculated after five groups of tests. Mahoney has designed and prepared a kind of proppant with the self-suspending property. Moreover, the mechanism of the self-suspending property has been pointed out. It is worth pointing out that the proppant prepared in this paper has a good self-suspension than that reported in the literature. In addition, the proppant prepared in this paper can achieve self-suspension without any additive in water. The results of self-suspending experiments of the coated proppant

Figure 3. (a) Adhesion performance of the uncoated and coated proppant surface of different load forces, (b) adhesion performance of the uncoated and coated proppant surface of different contact times, (c) typical AFM force curve in adhesion measurement for a load force of 2μN and a contact time of 0.1 s, (d) liquid conductivity of the uncoated and coated proppant under different closure pressures, and (e) adhesion mechanism diagram of the uncoated and coated proppant.

Figure 4. Schematic diagram of (a) uncoated proppants and (b) coated proppants in shale fractures.
and uncoated proppant are shown in the histogram (Figure 5b), and the self-suspending rates of the coated and uncoated proppant are 67 and 13 wt %, respectively. The pictures of the self-suspending effect of the coated proppant and uncoated proppant at different times are shown in Figure S3, demonstrating a long time excellent self-suspension of the coated proppant. There are two main reasons for the excellent self-suspending performance, including the low-density resin shell and the good hydrophobicity of the phenolic resin shell. The outstanding self-suspension (the self-suspending rate of the coated proppant is more than five times that of the uncoated proppant) endowed the coated proppant good liquid conductivity.

Figure 5d shows the coated proppant speed, and it can be seen that the distance increases by the increasing movement time under the magnetic action. Furthermore, the average speed decreases, keeping at 0.75, 0.56, 0.44, 0.41, 0.37, and 0.33 cm·s⁻¹, respectively. Video S3 shows the trajectory of the coated proppant under magnetic action and the typical position of the coated proppant has been shown in Figure 5c.

In this paper, the proppant exhibited not only a good self-suspending performance but also directional adsorption through a simple coating process. Compared with the commonly used proppants, the proppants designed in this study shows a better liquid conductivity. Moreover, the simpler preparation method is beneficial for industrial production.

Discussion. Since a good self-suspending proppant with high chemical inertness is the key property for petroleum industry applications. Thus, seeking a proppant with low-density, good self-suspension, and excellent liquid conductivity becomes the ultimate goal for petroleum scientists. In a previous study, Wang et al.40 established a proppant migration model that considers both the proppant fluid transport and fracture closure during shut-in. The influence of the properties of the proppant and fluid carriers on proppant distribution was further investigated with numerical simulation and sensitivity analysis. The results show that using a small size and low concentration of proppant for hydraulic fracturing treatment is beneficial to the formation of the fracture network. In addition, the low-density proppant and low-density proppant carrier concentrate the injected proppant in the major fractures. Meng et al.41 simulated the conductivity of a proppant prepared by mixing a proppant and coated proppant according to different proportions using a dl-2000 type conductivity meter. It was found that under the same closing pressure, with the increase of the proportion of the coated proppant, the conductivity decreased, and at the same time, the high proportion of the coated proppant could delay the decline of conductivity. Comparing with their work, the proppant designed in this article is a low-density proppant, which easily migrates to the fractures. In addition, the coated proppant shows an excellent liquid conductivity (6.9−27.6 MPa). Thus, the surface-coated proppant may provide a strategy to fabricate the next-generation coating proppant with low cost and high efficiency.

CONCLUSIONS

A novel coated proppant with excellent self-suspending performance has been designed and fabricated in this article. When introduced into water, the proppant will float on top of water, casing an inhibition of settling, which is beneficial for liquid conductivity.

The self-suspending ability of this coated proppant is five times more than that of the uncoated proppant. In addition, the huge adhesion force of the coated proppant is more promising for the fracture network support, and the liquid conductivity of the coated proppant is 30% higher than that of the uncoated proppant at a lower closure pressure of 6.9 MPa. Moreover, the coated proppant can achieve directional adsorption under a magnetic effect.

Figure 5. (a) Self-suspending effect of the coated proppant (left) and the uncoated proppant (right), (b) self-suspending percentage of the coated and uncoated proppant, (c) typical position of directional movement under magnetic action of the coated proppant, and (d) movement time under different distances of the coated proppant.
The improved self-suspending performance suggests a longer migration distance, resulting in better production, which reduces the total proppant dosage, saving time and cost. Moreover, the coated proppant can be used in the unmodified fluids, reducing the fluid complexity.

**EXPERIMENTAL MATERIALS AND SAMPLE PREPARATION METHODS**

**Experimental Materials.** Ferric chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) was supplied from Aladdin. Anhydrous sodium acetate and phenolic resin were supplied from Perfemiker, and ethylene glycol was purchased from Guangzhou Guanghua Chemical Reagent Co., Ltd. Anhydrous ethanol was supplied by Tianjin Guangfu Fine Chemical Research Institute. PAA (Mr. = 1800) was purchased from Sigma-Aldrich. The improved self-suspending performance suggests a longer migration distance, resulting in better production, which reduces the total proppant dosage, saving time and cost. Moreover, the coated proppant can be used in the unmodified fluids, reducing the fluid complexity.

**Synthesis of PAA-Modified Fe$_3$O$_4$ Nanoclusters.** Fe$_3$O$_4$ nanoclusters modified by PAA (Fe$_3$O$_4$) were synthesized according to the published literature.$^{24}$ First, FeCl$_3 \cdot 6\text{H}_2\text{O}$ (1.08 g), PAA (0.108 g), and anhydrous sodium acetate (9.0 g) were dissolved in ethylene glycol (40 mL). The solution was mixed by magnetic stirring. Subsequently, the mixed solution was sealed in a 50 mL Teflon-lined stainless autoclave. Then, the Teflon-lined stainless autoclave was put into an oven for 12 h at 200 °C. Fe$_3$O$_4$ was obtained after washing with deionized water and absolute ethanol, and the TEM image of Fe$_3$O$_4$ is shown in Figure S1.

**Synthesis of the Coated Proppant.** In the beginning, the phenolic resin was poured into ethanol to obtain a saturated solution with mechanical stirring. Then, a 100 mL mixed solution was measured into the beaker with a volume of 250 mL. Subsequently, 2 g of Fe$_3$O$_4$ was added into the mixed solution and the beaker was kept inside an ultrasonic cleaner for 20 min. Then, 50 g of ceramic is introduced into the mixed solution under mechanical stirring for 15 min at a speed of 300 rpm. Subsequently, the supernatant of the beaker was poured out leaving the sediment on the bottom. Then the sediment was placed in a vacuum with a drying temperature of 60 °C for 5 h. In the end, the coated proppant was collected. Figure S2 shows the synthesis of the coated proppant.

**Self-Suspending Experiment.** First, 1.5 g of guar gum was weighed and poured slowly into 500 mL of deionized water with stirring to obtain a mixed solution. Subsequently, 80 mL of the mixed solution was measured and stirred at 1000 rpm. Then, 1 g of proppant was poured slowly into the stirring mixed solution for 3 min then the magnetic stirring was turned off. Finally, the floated and unflotated proppants were collected and dried, separately, and the mass percentage of the self-suspending rate can be calculated by:

\[
\text{wt}\% = \frac{m_1}{m_1 + m_2}
\]

where $m_1$ is the weight of the floated proppant and $m_2$ is that of the unflotated proppant.

**Directional Migration Experiment.** The proppant was weighed and slowly poured into the simulated channel. The magnet was placed close to the proppant; the distance ($s$), and time ($t$) of the proppant moving under the magnetic field were recorded. The average speed of the proppant was calculated, and the average speed can be calculated using:

\[
V = \frac{S}{t}
\]
REFERENCES

(1) Hu, W.; Bao, J.; Hu, B. Trend and progress in global oil and gas exploration. Adv. Pet. Explor. Dev. 2013, 40, 439–443.
(2) Khanna, A.; Kotousov, A.; Sobery, J.; Weller, P. Conductivity of narrow fractures filled with a proppant monolayer. J. Petol Sci Eng 2012, 100, 9–13.
(3) Khanna, A.; Keshavarz, A.; Mobbs, K.; Davis, M.; Bedrikovetsky, P. Stimulation of the natural fracture system by graded proppant injection. J. Petol Sci Eng 2013, 111, 71–77.
(4) Zhong, Y.; Kimm, E.; Zhang, H.; Kuang, J.; She, J. Effect of Fracturing Fluid/Shale Rock Interaction on the Rock Physical and Mechanical Properties, the Proppant Embodiment Depth and the Fracture Conductivity. Rock Mech Rock Eng 2018, 52, 1011–1022.
(5) Luo, X. R.; Wang, S. Z.; Sun, X.; Ren, X. J. Experimental Research on Proppant Transport Performance of GRF-CO$_2$ Fracturing Fluid. Adv. Mat Res 2013, 807-809, 2583–2588.
(6) Tomac, I.; Gutierrez, M. Micromechanics of proppant agglomeration during settling in hydraulic fractures. J. Pet. Explor. Prod. Technol. 2015, 5, 417–434.
(7) Wen, Q.; Zhang, S.; Wang, L.; Liu, Y.; Li, X. The effect of proppant embodiment upon the long-term conductivity of fractures. J. Petol Sci Eng 2007, SS, 221–227.
(8) Zheng, W.; Silva, S. C.; Tannant, D. D. Crushing characteristics of four different proppants and implications for fracture conductivity. J Nat Gas Sci Eng 2018, 53, 125–138.
(9) Xu, Q.; Zhang, R.; Sheng, M.; Tian, S. C.; Li, W. G. Nanoscale Mechanical Property of Marine and Continental Organic Kerogen in Shale. Chin. Chem. Lett. 2020, 31, 509–512.
(10) Shiozawa, S.; McClare, M. Simulation of proppant transport with gravitational settling and fracture closure in a three-dimensional hydraulic fracturing simulator. J. Petol Sci Eng 2016, 138, 298–314.
(11) Zou, C.; Dong, D.; Wang, S.; Li, J.; Li, X.; Wang, Y.; Li, D.; Cheng, K. Geological characteristics and resource potential of shale gas in China. Adv. Pet. Explor. Dev. 2010, 37, 641–653.
(12) Zhang, J.; Ouyang, L.; Zhu, D.; Hill, A. D. Experimental and numerical studies of reduced fracture conductivity due to proppant embedment in the shale reservoir. J. Petol Sci Eng 2015, 130, 37–45.
(13) Tan, P.; Pang, H.; Zhang, R.; Jin, Y.; Zou, Y.; Kao, J.; Fan, M. Experimental investigation into hydraulic fracture geometry and proppant migration properties for southeastern Sichuan deep shale reservoirs. J. Petol Sci Eng 2020, 184, 106517.
(14) Xu, Q.; Fan, F.; Lu, Z.; Sheng, M.; Tian, S.; Zhang, Y.; Pan, L.; Zhou, Y. Reversible adhesion surface coating proppant. Chin. Chem. Lett. 2020, DOI: 10.1016/j.clet.2020.02.014.
(15) Wei, G.; Hai, H.; Babadagli, T.; Lei, H.; Li, H. Z. Determination of the Effect of Resin-Coating on Ceramic Proppant Settlement for Optimal Hydraulic Fracturing Applications. Powder Technol. 2020, 373, 109–117.
(16) Gomez, V.; Alexander, S.; Barron, A. R. Proppant immobilization facilitated by carbon nanotube mediated microwave treatment of polymer-proppant structures. Col. Surf. A 2017, 513, 297–305.
(17) Gu, M.; Xiao, E.; Mohanty, K. K. Investigation of ultra-light weight proppant application in shale fracturing. Fuel 2015, 150, 191–201.
(18) Horadam, W.; Venkat, N.; Tran, T.; Bai, L.; Josyula, K.; Mehta, V. Leaching studies on Novolac resin-coated proppants-performance, stability, product safety, and environmental health considerations. J. Appl. Polym. Sci. 2018, 135, 45845.
(19) Mohghadasi, R.; Rostami, A.; Hemmati-Sarapardeh, A. Application of nanofluids for treating fines migration during hydraulic fracturing: Experimental study and mechanistic understanding. Adv. in Geo-Energ. Res. 2019, 3, 198–206.
(20) Jia, C.; Zheng, M.; Zhang, Y. Unconventional hydrocarbon resources in China and the prospect of exploration and development. Adv. Pet. Explor. Dev. 2012, 39, 139–146.
(21) Liang, F.; Sayed, M.; Al-Muntasheri, G. A.; Chang, F. F.; Li, L. A comprehensive review on proppant technologies. Petroleum 2016, 2, 26–39.
(22) Xu, Q.; Wan, Y.; Hu, T. S.; Liu, T. X.; Tao, D.; Niewiarowski, P. H.; Tian, Y.; Liu, Y.; Dai, L.; Yang, Y.; Xia, Z. Robust self-cleaning and micromanipulation capabilities of gecko spatulae and their biomimetics. Nat. Commun. 2015, 6, 2041–1723.
(23) De Campos, V. P. P.; Amaral Labat, G. A.; Sansone, E.; Gouvea, D.; Lenz e Silva, G. F. B. Development of Sodium Hydroxide-Activated Metakaolin with Nanocarbon Materials as Synthetic Ceramic Proppants. Mater. Sci. Forum 2018, 912, 251–256.
(24) Guo, W.; Wang, Q.; Wang, G.; Yang, M.; Dong, W.; Yu, J. Facile hydrogen-bond-assisted polymerization and immobilization method to synthesize hierarchical Fe3O4@poly(4-vinylpyridine-co-divinylbenzene)@Au nanostructures and their catalytic applications. Chem. – Asian J. 2013, 8, 1160–1167.
(25) Yang, M.; Ma, J.; Ding, S. J. Phenolic Resin and Derived Carbon Hollow Spheres. Macromol. Chem. Phys. 2006, 207, 1633–1639.
(26) Allen, J. D.; Ishida, H. Polymerization of Linear Aliphatic Diamine-Based Benzoazine Resins under Inert and Oxidative Environments. Polymer 2007, 48, 6763–6772.
(27) Cheng, Y.; Guanbing, J.; Bin, Q.; Xiaohui, L.; Zixin, Z.; Jieming, C.; Youwei, D. Magnetic and electromagnetic properties of Fe3O4/Fe3O4 composites prepared by a simple one-step ball-milling. J. Alloys Compounds 2017, 708, 587–593.
(28) Ni, X.; Zheng, Z.; Hu, X.; Xiao, Y. Silica-coated iron nanocubes: preparation, characterization and application in microwave absorption. J. Colloid Interface Sci. 2010, 341, 18–22.
(29) Xiang, J.; Li, J.; Zhang, X.; Ye, Q.; Xu, J.; Shen, X. Magnetic carbon nanofibers containing uniformly dispersed Fe/Co/Ni nanoparticles as stable and high-performance electromagnetic wave absorbers. J. Mater. Chem. A 2014, 2, 16905–16914.
(30) Qi, B.; Zhu, C.; Li, C.; Zhang, X.; Chen, Y. Coupling Hollow Fe3O4–Fe Nanoparticles with Graphene Sheets for High-Performance Electromagnetic Wave Absorbing Material. ACS Appl. Mater. Interfaces 2016, 8, 3730–3735.
(31) Tian, X.; Xiao, X.; Deng, L.; Tian, W.; Wang, X.; Mahmood, N.; Dou, S. Heterostructured Nanorings of Fe–Fe3O4@C Hybrid with Enhanced Microwave Absorption Performance. ACS Appl. Mater. Interfaces 2018, 10, 9369.
(32) Du, Y.; Liu, W.; Qi, Y.; Wu, Y.; Han, X.; Ma, J.; Xu, P. Shell thickness-dependent microwave absorption of core-shell Fe3O4@C composites. ACS Appl. Mater. Interfaces 2014, 6, 12997–13006.
(33) Christy, A. G. Causes of anomalous mineralogical diversity in the Periodic Table. Mineral. Mag. 2015, 79, 33–49.
(34) Xu, Q.; Li, M.; Zhang, L.; Niu, J.; Xia, Z. Dynamic Adhesion Forces between Microparticles and Substrates in Water. Langmuir 2014, 30, 11103–11109.
(35) Xu, Q.; Wan, Y.; Hu, T. S.; Liu, T. X.; Tao, D.; Niewiarowski, P. H.; Tian, Y.; Liu, Y.; Dai, L.; Yang, Y.; Xia, Z. Robust self-cleaning and micromanipulation capabilities of gecko spatulae and their biomimetics. Nat. Commun. 2015, 6, 8949.
(36) Li, M.; Wu, X.; Li, W.; Xia, Z. Tough Reversible Adhesion Properties of a Dry Self-Cleaning Biomimetic Surface. ACS Appl. Mater. Interfaces 2018, 10, 26787–26794.
(37) Xu, Q.; Zhang, R.; Sheng, M.; Tian, S.; Li, W.; Wang, T.; Zhang, Y. Nanoscale mechanical property of marine and continental organic kerogen in shale. Chin. Chem. Lett. 2019, 31, 509–512.
(38) Quan, X.; Meng, X.; Chuanlu, L.; Qing, Z.; Rui, Z.; Xiaoxiao, D.; Zha, S.; Shouceng, T.; Tian, Y.; Zhenhai, X. Metal Coordination Mediated Functional Grading and Self-healing in Mussel Byssus Cuticle. Adv. Sci. 2019, 6, 19020.
(39) Hansson, P. M.; Claesson, P. M.; Swerin, A.; Briscoe, W. H.; Schoeklop, J.; Gane, P. A.; Thomann, E. Frictional forces between...
hydrophilic and hydrophobic particle coated nanostructured surfaces. 
*Phys. Chem. Chem. Phys.* **2013**, *15*, 17893−17902.

(40) Wang, F.; Li, B.; Chen, Q. Simulation of proppant distribution in hydraulically fractured shale network during shut-in periods. *J. Pet. Sci. Eng.* **2019**, *178*, 467−474.

(41) Meng, W.; Jiao, G. Y.; Luo, X. Experimental study on the conductivity of coated sand and its combination proppant. *J. Chongqing Univ. Sci. Technol., Nat. Sci. Ed.* **2019**, *21*, 43−46.