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Recent Progress in Proppant Technology for Improving the Fracture Conductivity in Hydraulic Fracturing

Zahraa Ali Hajool[1,*], Ali Samer Muhsan[1], Husam Kareem Mohsin Al-Jothery[2], Sinan S. Hamdi[2], Fahd Saeed Alakbari[4]

[1] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[2] Mechanical Engineering, University of Al-Qadisiyah I, 58001 Al-Diwaniyah, Qadisiyah, Iraq
[3] Production Engineering and Metallurgy, University of Technology, Baghdad, Iraq
[4] Centre of Advanced Process Safety (CAPS), Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia

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ABSTRACT

Proppants play a crucial role in hydraulic fracturing (HF) operations and in sustaining conductive fractures during well production. However, challenges persist regarding their resilience to closure stress and downhole conditions. Coatings have emerged as a promising solution to enhance proppant efficacy, particularly in addressing mechanical failure. This study highlights the recent advancement in proppant technology and focuses specifically on the impact of different resins coated proppants in improving the fracture conductivity after HF operation. Polymer coatings, especially thermosetting-based resin coatings are widely used due to their ability to improve both the strength and flexibility of the coated proppants. Proppants coated with a thin layer of resin offer several advantages, including good permeability, shape improvement and lower cost compared to regular coatings. Additionally, the incorporation of nanomaterials into resin coatings has shown promising results in augmenting proppant durability and flow conductivity as well as enhancing embedment prevention, reducing the generated fines after proppant crushing and improving the overall oil and gas production rate. For that, a summary was presented of the latest academic discussions and conclusions on the impact of resin coating on proppant and its pivotal role in enhancing proppant performance which led to increased fracture conductivity. Leveraging insights garnered from these discussions can positively contribute to the sustainable extraction of hydrocarbon resources in the oil and gas industry.

1. Introduction

Hydraulic fracturing (HF) is a method used to increase productivity in unconventional reservoirs. It involves injecting a high-pressure, low-viscosity fluid with chemical additives into low-permeability formations to extract hydrocarbons, Figure 1. This process initiates fractures and introduces proppants to maintain reservoir permeability. Proppants play an essential role in enabling the migration of hydrocarbons toward the wellbore. Understanding proppant behaviour is important to

* *Corresponding author*
E-mail address: zahraa_22009591@utp.edu.my

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address potential issues caused by harsh downhole conditions, known as proppant damage mechanisms. The introduction of ceramic and resin-coated proppants in the 1990s improved fracture conductivity and productivity. Recent studies have shown that nanocomposite resin coatings can further enhance proppant attributes, such as crush strength and chemical endurance [26], reversible adhesion surface coatings can improve the self-suspension capability, adhesive properties and fluid conductivity of proppants, making them more effective in supporting shale fractures [41].

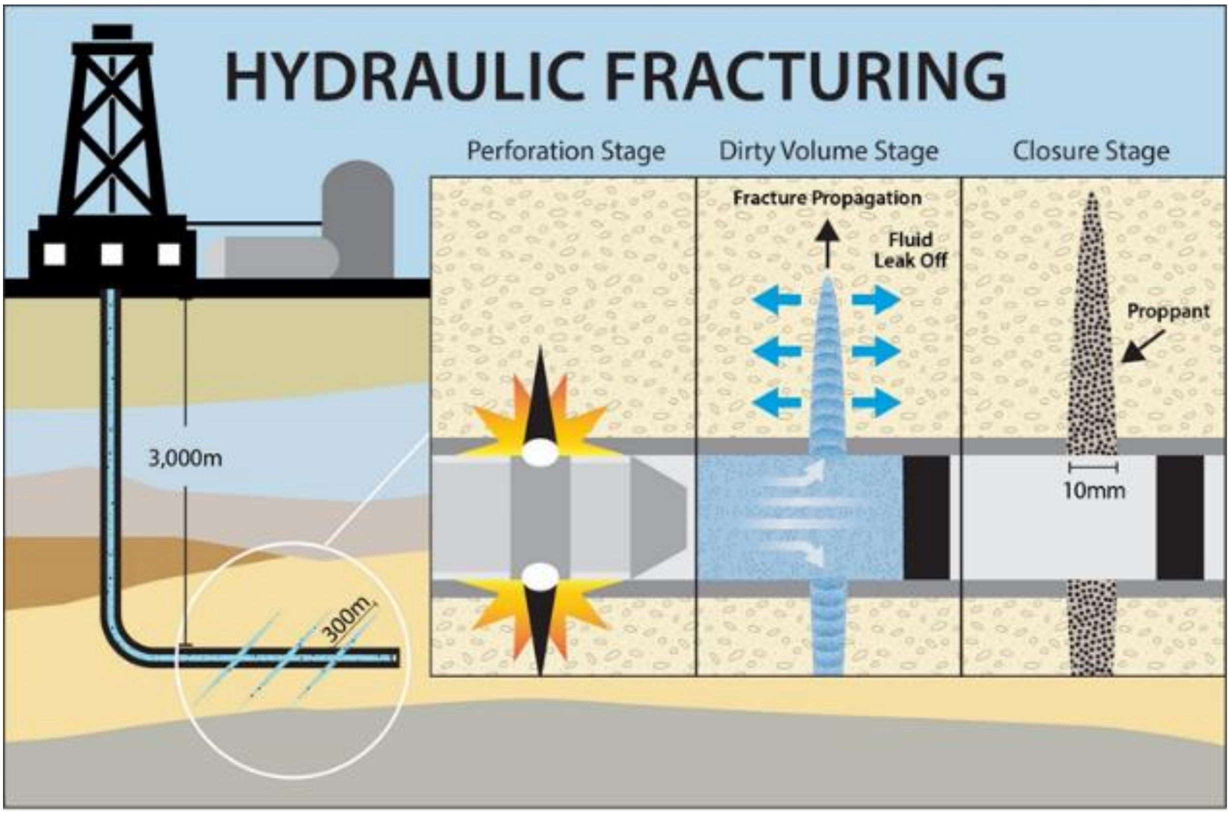

Fig. 1. Hydraulic Fracturing [40]

There are two basic types of proppants used in hydraulic fracturing: conventional and advanced, Figure 2. Conventional proppants include sand, ceramic, nutshells and glass beads.

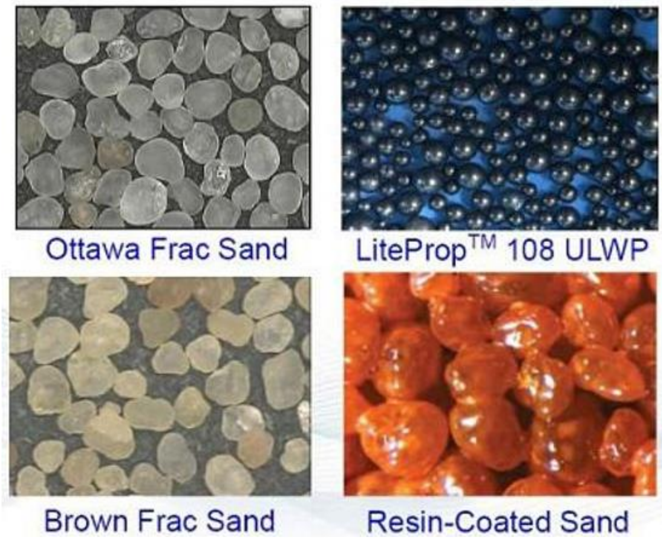

Fig. 2. Proppant types [55]

Frac sand, mostly made of quartz, is commonly used due to its roundness and resistance to fracturing. However, it tends to crush when subjected to high pressure. Frac sand can be white or brown, with white sand being more expensive but having lower impurity levels. Brown sand is cheaper but more prone to breakage and contains a higher impurity percentage [42]. Frac sand undergoes cleaning, drying and sizing processes before being used as a proppant. Ceramic proppants are known for their strength, consistent shape and ability to withstand extreme conditions [39]. They are primarily made of bauxite and have a resistance threshold of 69 to 130 MPa. However, transporting ceramic proppants to fracture sites can be challenging due to their density and mass characteristics. This requires high-density fracturing fluids and increased pumping rates, which complicates the selection process [3]. Advanced proppants, on the other hand, have a thin polymer layer coating. Coating the proppant is a significant advancement, especially for uncoated sand proppants that are prone to fines formation and crushing [81]. The resin coating encapsulates fines within the proppant, preventing their release. However, resin coatings have limited mechanical properties, so additional treatment is necessary [15].

Elastomeric polymers and thermoplastic polymers have distinct advantages over resin coatings. They offer ductility, superior impact resistance, great fracture toughness, excellent corrosion resistance and moisture resistance [52]. The strong bonding ability of thermosetting resin with the substrate elements has led to the extensive use of proppant coatings. Thermosetting resins provide better heat resistance compared to thermoplastic polymers and are more cost-effective. However, there are drawbacks to using thermosetting resins [60]. They cannot be reshaped or recycled and their limited thermal stability is a notable issue. When exposed to temperatures higher than the Glass Transition Temperature (Tg), the resin coatings undergo a transition from a solid to a rubbery state, resulting in a decrease in hardness [37].

There are notable variations in benefits between elastomeric polymers and thermoplastic polymers when it comes to ductility, impact resistance, fracture toughness, corrosion resistance and moisture resistance [71]. The high affinity of the thermosetting resin group with substrate elements leads to the widespread use of proppant coatings. Thermosetting polymers offer greater heat resistance than thermoplastic polymers. Additionally, the thermoset resin in the design offers superior elasticity compared to the thermoplastics in the backing coating. Additionally, thermoset resins are more economically advantageous than polymer thermoplastics [79]. Nevertheless, they experienced various disadvantages since they are unable to reform, modify and reuse. In addition, the restricted heat resistance of resin coatings is an eloquent disadvantage because when they are exposed to temperatures higher than the Glass Transition Temperature (Tg), they change from being solid to rubbery, resulting in reduced hardness.

By providing a summary of the latest academic discussions and conclusions regarding the impact of resin coating on proppants, this study aims to underscore the efficacy of polymer coatings, with a specific emphasis on resin coatings, which are widely utilized for their ability to enhance both the strength and flexibility of coated proppants. Proppants coated with resin offer numerous advantages, including improved permeability, shape enhancement and cost-effectiveness compared to traditional coatings. Moreover, the integration of nanomaterials into resin coatings has shown promising results in augmenting proppant durability, flow conductivity, embedment prevention and fines reduction after proppant crushing, consequently enhancing overall oil and gas production rates.

2. Types of Resin Employed for Coating Proppant

Various types of resin are utilized in proppant coating, each offering unique advantages, as shown in Figure 3.

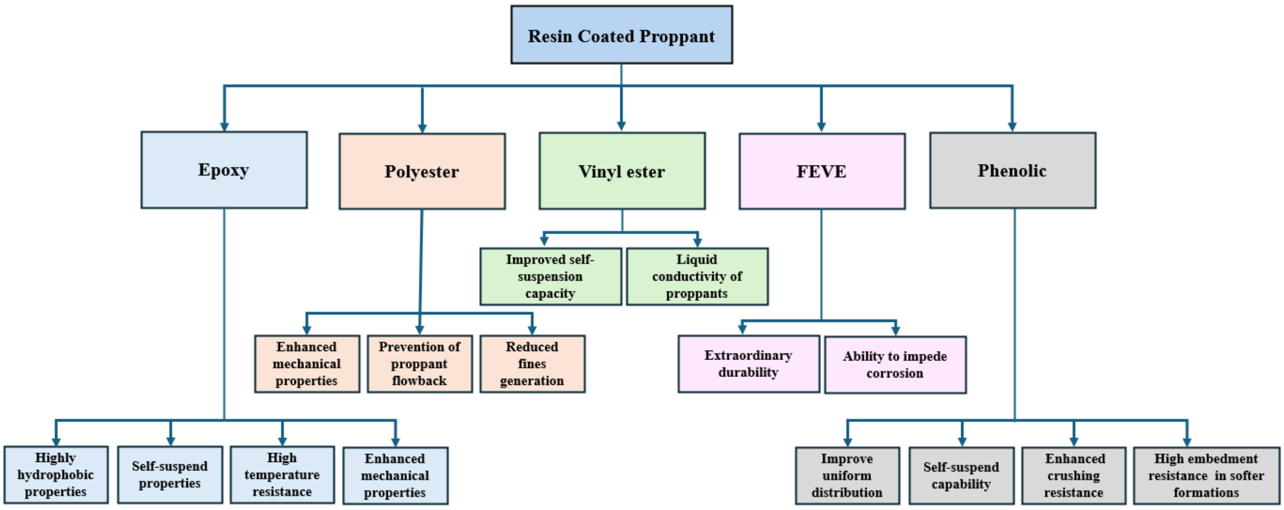

Fig. 3. A diagram of different types of resin used in proppant coatings and their advantages

Resin-coated proppants proved their significance for sustaining conductive fractures and their thermal, chemical and mechanical stability [51], as shown in Table 1.

Table 1
Coating polymers and their properties [81]

Resin Type	Dry temperature (°F)	Resistance to heat	Resistance to acid	Resistance to water	Strength	Hydrophobic capability
Epoxy Polyester	250-400	Excellent	Good	Good	Good	Good
Vinyl ester	212-300	Fair	Fair	Good	Fair	Fair
Phenol	212-300	Fair	Good	Good	Fair	Fair
	250-400	Fair	Good	Good	Good	Good

2.1 Epoxy

Epoxy resin coatings are utilized to improve the efficiency of proppants as shown in Figure 4. Epoxy resin coated proppants provide several benefits, such as being highly hydrophobic, having the ability to self-suspend and conducting liquids efficiently [21].

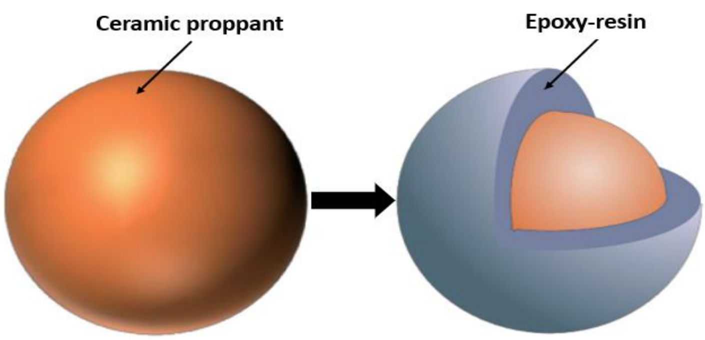

Fig. 4. Structure diagram of Epoxy Coated Proppant (ECP) [78]

Epoxy resin coatings have various benefits in improving the performance of proppants. These coatings enhance crush strength and water shutoff ability, boosting effectiveness in hydraulic fracturing. Moreover, they offer high-temperature resistance, crucial for preserving proppant integrity in high heat settings. Moreover, adding specific modifiers like polymers to epoxy resin coatings can boost their mechanical properties in cold conditions, enabling their application in chilly regions. Additionally, utilizing nanofillers modified epoxy resin coatings can enhance the corrosion resistance, adhesion strength and overall durability of proppants in harsh settings.

2.2 Polyester

Extensive research has been done on using polyester resin coating. The advantages of this coating, such as enhanced mechanical characteristics [49], prevention of proppant flowback and decreased fines generation emphasize its importance in improving the performance of proppants in hydraulic fracturing [81]. The mechanical strength of the proppant can be enhanced by using polyester resin coatings along with nanofiller such as multiwalled carbon nanotubes, which also helps maintain its performance and prevents stiffness reduction from water absorption or UV exposure [50,54].

2.3 Vinyl Ester

The use of vinyl ester resin coating provides multiple benefits for improving proppant effectiveness. It was shown that it can greatly improve the self-suspension capacity and liquid conductivity of proppants [9]. Furthermore, the strength of resin coated proppants can be increased by using hybrid material [81].

2.4 Fluoroethylene Vinyl Ether (FEVE)

Studies have indicated that the application of FEVE resin coatings exhibits the capability to considerably augment the effectiveness of proppants in hydraulic fracturing operations. This is assigned to their extraordinary durability, resistance to various environmental conditions and ability to impede corrosion. The introduction of nano-platelets in downhole settings can elevate the strength of proppants coated with resin [33]. Additionally, perfluoropolyether (PFPE) resins, a variant of FEVE resin, have the potential to improve the longevity and weather durability of polyurethane coatings [72]. The addition of polymers, such as FEVE resins, in coating proppants to improve fracture conductivity and lower fines production [81].

2.5 Phenolic

Coating with phenolic resin provides multiple benefits for improving the performance of proppants. It can enhance the equal spread of proppants in fracture networks, boost their self-suspending capability and improve their liquid conductivity [41]. The coating additionally stops flowback around the wellbore, shields proppants from being crushed and withstands embedment in softer formations [67]. Figure 5 shows a proppant coated with epoxy/phenolic resin.

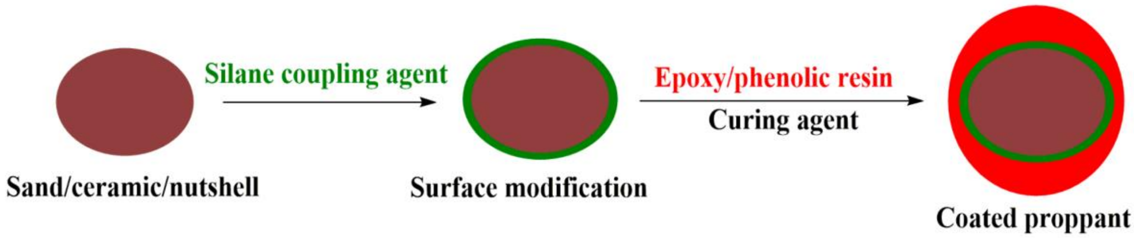

Fig. 5. Schemes of the coating process of traditional proppant [11]

Phenolic resin coatings offer benefits in improving proppant performance by providing high heat resistance, superior mechanical properties and enhanced compressive strength and water resistance, making them ideal for harsh environments in industries like petrochemicals and hydraulic fracturing [12,53,66]. The incorporation of nano-titanium into phenolic resin coatings has demonstrated a significant enhancement in the protection against corrosion for proppants, thus extending their durability in challenging settings [48].

3. Factors Influence Proppant Performance

3.1 Resin Type

Various kinds of resins, like alkyd/melamine, alkylenedioxydiphenol-based epoxy and phenol-formaldehyde resol, display various characteristics and performances when employed as coatings for proppants [19,45,59]. These characteristics consist of the time needed to cure, the ability to stick and the capacity to withstand chemical breakdown. Research has shown that the characteristics of the coating can be significantly influenced by the ratio of alkyd/melamine resin and curing temperature, yielding optimal outcomes at a ratio of 75/25 and a temperature of 130 °C [59]. Similarly, modifications can be made to the structure of epoxy resins, including flexibility, crosslinking and concentration of OH groups, to improve coating performance [19,45] observed that adjustments in pH and the addition of silane to phenol-formaldehyde resol resins can alter their properties. The selection of different resins for coating proppants can have a substantial impact on various characteristics and behaviours of the coated proppants, such as curing time, adhesion strength and resistance to chemical degradation. For example, research on new hybrid materials made in place showed enhanced strength and adhesion of proppants when a particular solid resin-based emulsion system was used for coating [33,58,75]. This suggests that the choice of resin can significantly impact the adhesion strength and overall effectiveness of the coated proppants [33,58]. The properties of phase change proppants are influenced by the type of resin used, like the bisphenol A-type epoxy resin. Other factors that can affect the performance of resin-coated proppants include the resin curing agent and additional materials added for density reduction.

3.2 Proppant Properties

Various factors impact the adhesion and mechanical support of resin coatings on proppant particles. Performance of the proppant can be influenced by its size and heating rate, with a smaller size and a narrow distribution being preferable for the sintering process [42]. The selection of resin type and the properties of the proppant, such as composition, size, shape and surface characteristics, play a crucial role in determining the efficacy of resin coatings. Further, the toughness of some types of coating materials such as solid polystyrene resin, the importance of molecular weight, monomer conversion rate, manufacturing method, testing conditions and specimen size can influence the performance of the proppant [8].

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3.3 Coating Process Parameters

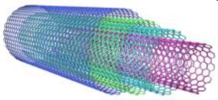
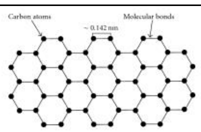
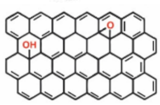
The quality of resin-coated particles for hydraulic fracturing applications is significantly influenced by the coating process parameters, such as temperature. The research discovered that different variables like temperature have a notable impact on the effectiveness of the coating. More precisely, the temperature impacts the complex relationship between the flow properties of resin, the movement of molecules and the rate of curing [31].

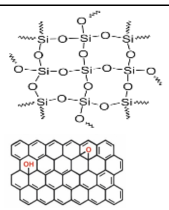
Various parameters affect the resin coating process. The crucial factor for material application is the liquid's ability to stay on the polymer surface and create capillary forces [32]. Size distribution and degree of aggregation of secondary particles in resin are crucial factors that impact the gelation process [30].

4. Nanofiller/Composite Coated Proppant

In addressing certain limitations encountered by polymer coatings, such as low softening temperatures and polymer degradation, the incorporation of nanomaterials into the polymer matrix is advocated. This strategy reinforces the polymer layers, imparting high strength, chemical stability and thermal stability to the proppants. Commonly utilized nanomaterials for this purpose include graphene, nano-silica, nano clay and nanotubes. For instance, the addition of trace amounts of graphene oxide and polyurethane coatings to carbon nanotubes has been shown to significantly enhance the compressive strength of proppants, owing to the unique properties of graphene [2,12,18,26]. Additionally, other studies have explored the synergistic interactions of dissimilar functional fillers, such as carbon nanotubes and carbon-coated iron nanoparticles, to achieve unique multifunctional capabilities in polymer matrix composites [4,36,74] The introduction of silicate nanoparticles into the paint matrix leads to a substantial increase in Young's modulus of epoxy resins. Table 2 summarizes the impact of nanofiller coatings on proppants.

Table 2
Summary of nano-filler coating proppant

Nanofiller	Structure	Impact	Ref
Nano-scale MWNT		High mechanical strength. An improvement in resistance to chemical exposure at elevated temperatures. Enhanced conductivity performance	[26]
MWCNT		Mechanical strength, flow back control, thermal stability and surface wettability properties of the sand proppants.	[2]
Graphene		Substantial improvement in the electrical conductivity of the proppant. Improve the efficiency of electric heating in the in-situ modification technology of shale oil.	[13]
rGO/CNT	 	Mechanical strength improved by 84% 40% reduction in fines generation.	[29]

SiO2 @ rGO		Good thermal conductivity and good frequency stability.	[28]

The role of particle size and distribution impacts the powder coatings' manufacturing, application and coating properties [14].These studies emphasize how crucial these factors are in deciding the thickness, uniformity and adhesion of resin coatings.

5. Factors Effect on Proppant Performance

While proppants are intended to keep fractures open and provide pathways for oil/gas flow in deep rock formations under high pressure, various factors can impact their performance in real-world reservoir conditions. Furthermore, the reservoir's effective conductivity relies heavily on how well the proppant performs. Time, high temperatures, stress cycling from well-shutting, proppant embedment, multi-phase flow and non-Darcy effects can all lead to a 100-fold decrease in effective fracture conductivity. Nevertheless, the impact of these mechanisms varies depending on various factors including the mechanical properties of proppants, mineralogy of the formation, type of proppant, fracture fluid type and existing closure stresses. Enhanced comprehension of proppant embedment in reservoir conditions. Prior research has shown that resin-coated sand has higher resilience to failure in comparison to lightweight ceramic and uncoated fracturing sand as shown in Figure 6.

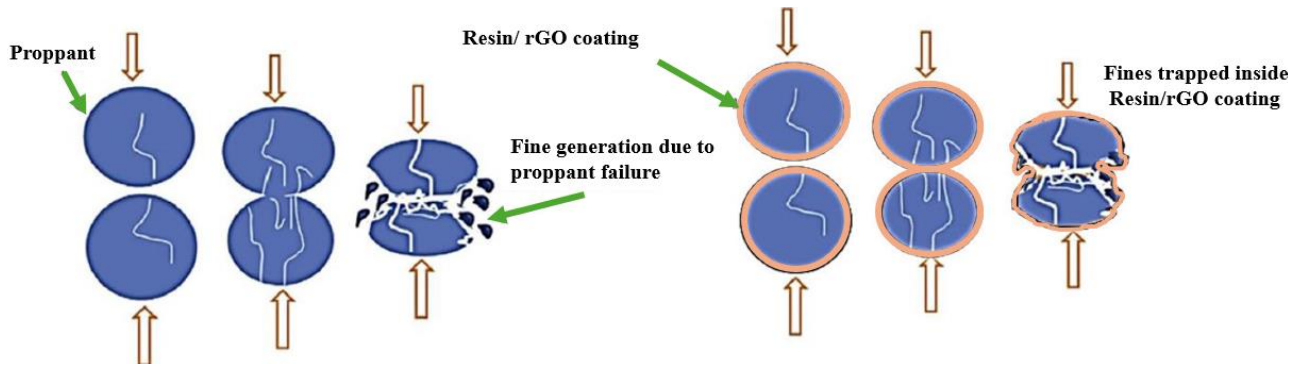


Fig. 6. The response of uncoated (left) and coated (right) proppants to closure stress (modified from [10])

Figure 7 demonstrates factors that influence the proppant performance [7,22,27].

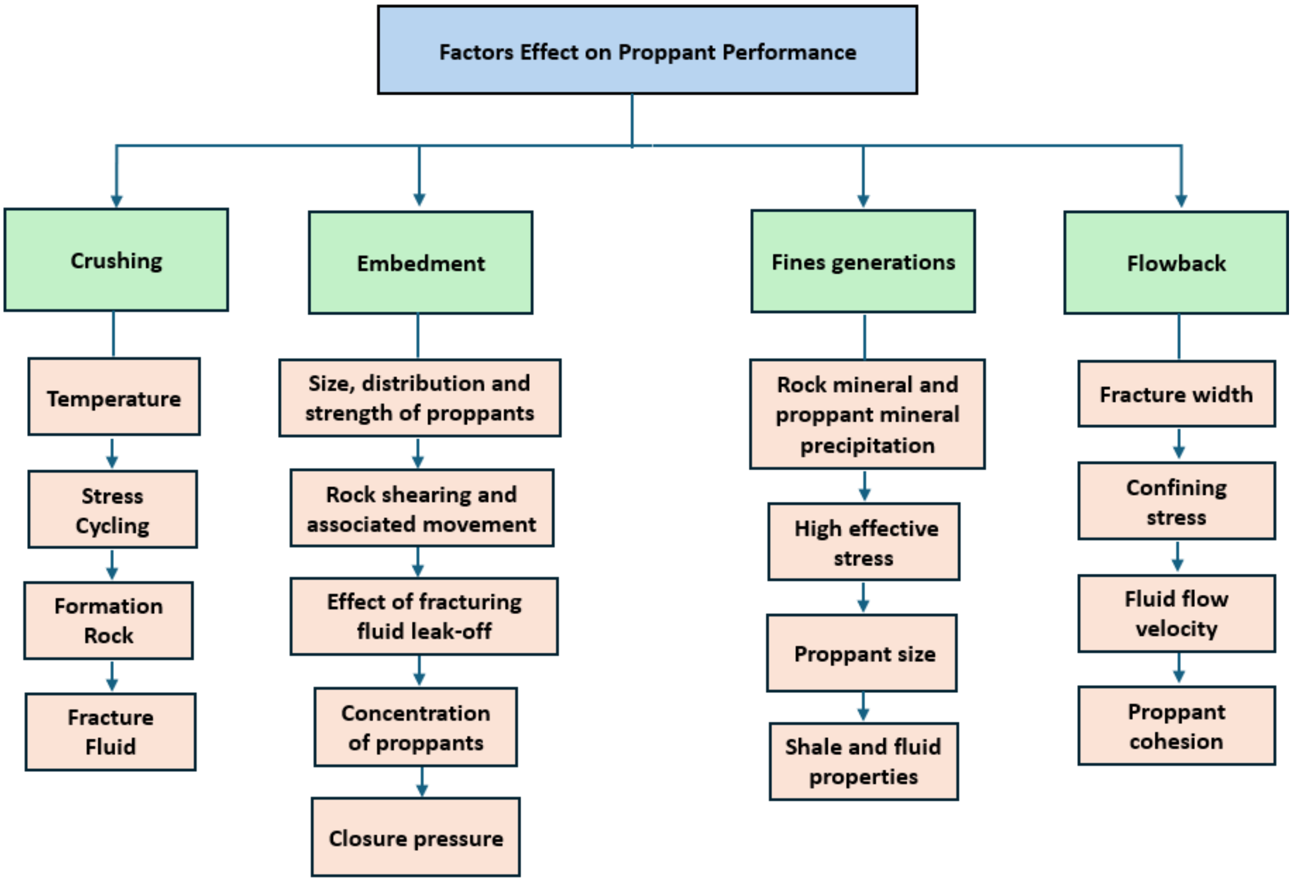


Fig. 7. Factors that influence the proppant performance

5.1 Proppant Crushing

All proppant materials experience different forms of deformation in downhole conditions, regardless of their classification. The primary mode of proppant failure is often caused by crushing, which occurs when their pressure-bearing capacity is exceeded under load. Consequently, a reduction in fracture conductivity is experienced, contributing to diminished reservoir productivity. Moreover, the generation of fines resulting from proppant fracturing hampers hydrocarbon mobility by obstructing flow pathways. Fines generated from proppant breakage can diminish both porosity and conductivity within proppant packs, leading to constricted flow channels within the wellbore [73]. Proppant conductivity declines when fines generation approaches 5% [43]. Additionally, fracture strength is a key factor in the mechanical effectiveness of proppants in well environments.

Resin coatings have demonstrated significant enhancements in the crush strength of proppants employed in hydraulic fracturing operations [13,26,57,62].

The incorporation of nanocomposites into resin coatings enhances proppant crush resistance [62]. Specifically, the addition of nanomaterials to urethane resin coating increased compressive strength by 41 and 35%, After conducting crushing tests by the Universal Testing Machine (UTM) the results found that applying a urethane coating effectively reduces fines generated by proppant crushing compared with uncoated proppant. This containment is enhanced with higher concentrations of carbon nanotubes (CNTs) in the coating, which strengthen it and reduce proppant crushing, as shown in Figure 8 [29].

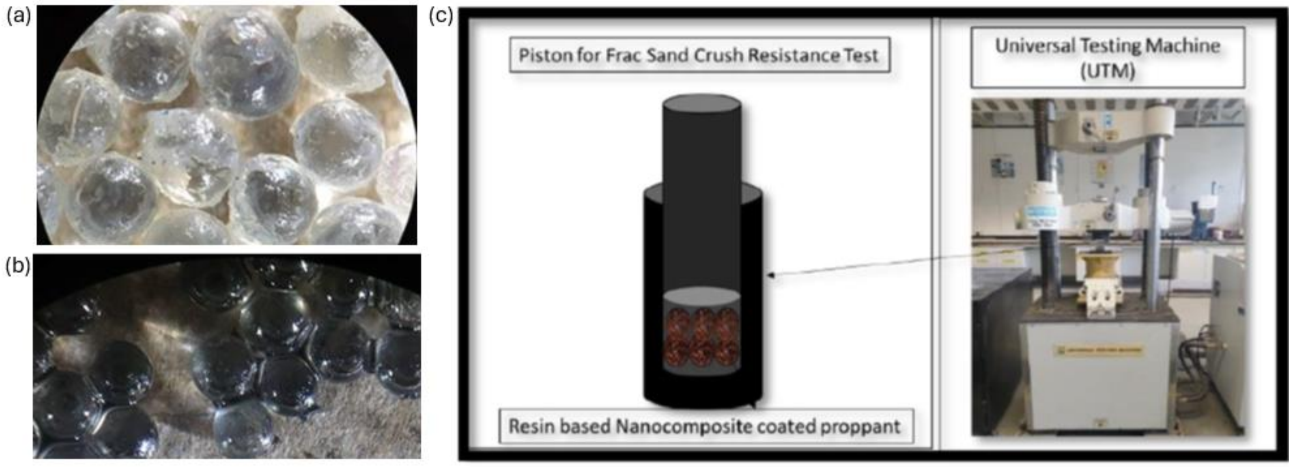


Fig. 8. (a) Glass beads urethane\rGO coated proppants, (b) Glass beads urethane\CNT coated proppants and (c) Universal Testing Machine (UTM) [29]

Resin coatings also improve the sphericity, roundness and flow conductivity of the proppants, leading to cost reduction and increased oil yield [13]. Furthermore, resin-coated proppants prevent flowback and resist embedment, making them ideal for downhole conditions [67]. The development of a nano-composite resin coating has further enhanced proppant crush strength as shown in Table 3, conductivity and chemical resistance, making it suitable for field applications at higher stresses [26].

5.2 Proppant Embedment

Proppant embedment denotes the occurrence whereby proppant particles are lodged within the fracture faces or matrix of the rock formation during hydraulic fracturing. This process can occur due to various factors, such as high closure stresses and insufficient proppant strength. Proppant embedment can lead to decreased fracture conductivity and diminished well performance by impeding fluid flow pathways and reducing the effectiveness of hydraulic [34], as shown in Figure 9 [67]. Strategies to mitigate involve the selection of proppants with enhanced crush resistance, optimization of fracturing parameters to mitigate closure stresses and the utilization of resin coatings to augment proppant adhesion and stability within the fracture network. Adding resin coating to proppants can significantly reduce embedment [6,7]. Furthermore, it has been recommended to choose resin-coated proppants instead of ceramic and sand proppants to reduce the risks of embedment [5].

Resin-coated proppants had shallower embedment depths than uncoated ones. The reduction in embedment attributed to the bonding power of the resin coating prevents proppant particles from sinking into the formation when under closure stress. Resin coating acted as a shield, preventing proppant grains from entering the rock matrix, reducing embedment and maintaining fracture conductivity in the long run [63].

Furthermore, layers of resin coating have a significant impact on proppant embedment in fractures [23]. Studies have shown that the way proppants are placed in fractures, either in monolayer/thin-layer or multilayer configuration, can have significantly different effects on the embedment [17].

Table 1
Summary of the impact of resin coating on proppant crushing resistance

Resin Type	Fine reduction after crushing test	Remark	Ref.
PU-CNT PU-rGO	41% 35%	Nanomaterial coatings exhibited agglomeration on the proppant surfaces, which could lead to uneven stress distribution and reduced compressive strength and resins used in the coatings may have limitations in thermal stability, potentially degrading at temperatures above 121°C, which could affect the long-term performance of the coated proppants.	[57]
Epoxy-Phenolic	1.59 W(crushed)%	Excessive resin can lead to poor conductivity and higher costs. Hindering the movement of nanoparticles to the surface as the resin amount increased.	[13]
FDTS/F-silica NPs)	52%	Excessive resin led to a decrease in surface roughness and hindered the exposure of F-silica nanoparticles, affecting the hydrophobicity of the coating. Additionally, the resin had adverse effects on micro- and nano-roughness and surface energy.	[62]
Novolac-CNT	Increased the API crush resistance stress of the sand by approximately 200%	Challenges in balancing the curing time and temperature to achieve the optimal degree of durability. In addition, insufficient coating leads to low crush resistance stress levels, while excessive coating potentially reduces inter-grain pore space and increases mesh size.	[26]
Polyimide	3.22% under 52 MPa	When the resin content exceeds a certain amount, it can lead to performance degradation due to resin agglomeration on the proppant surface, affecting film uniformity and causing unnecessary energy consumption.	[76]

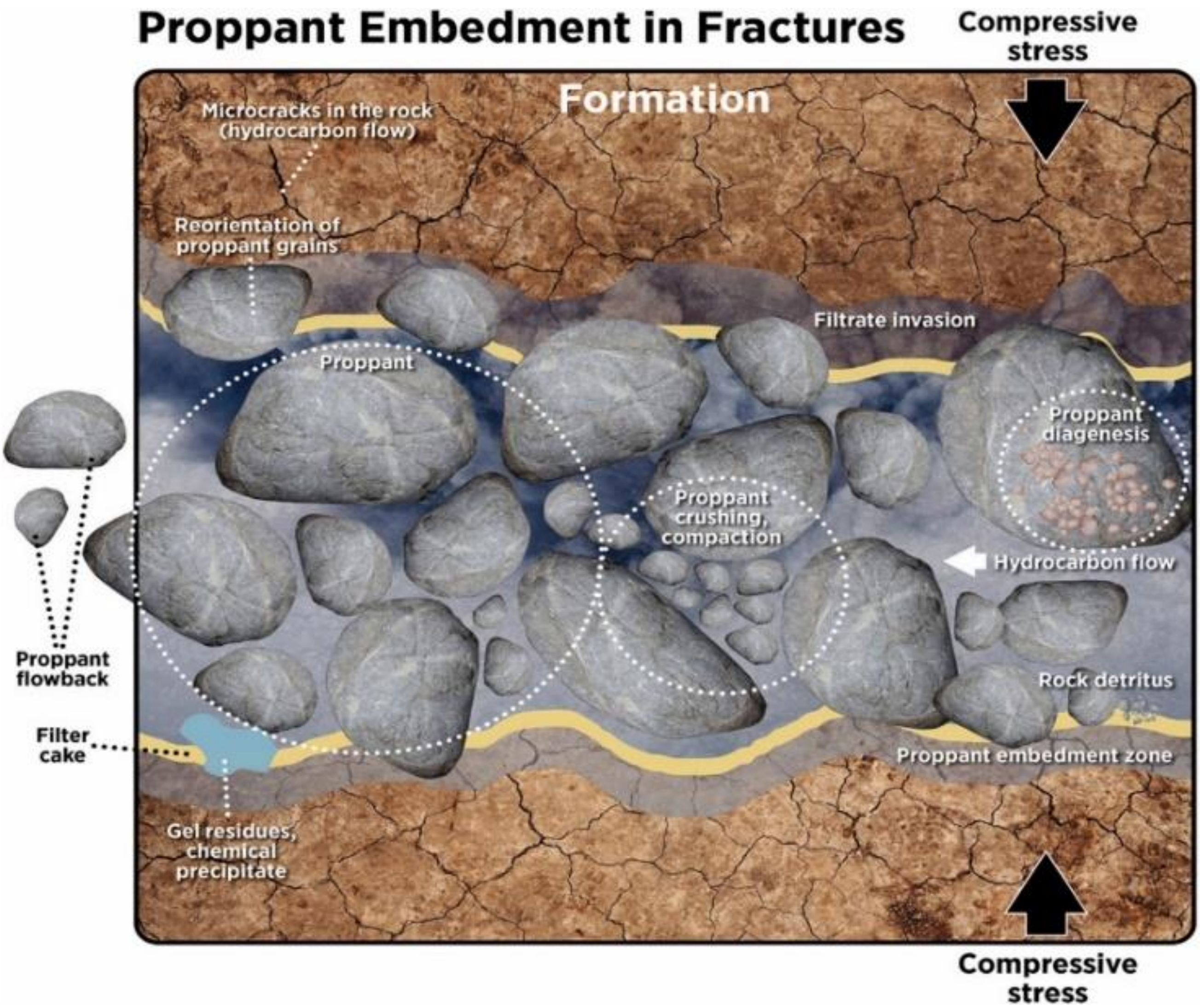


Fig. 9. Illustration of physical phenomena that affect an effectively packed fracture due to proppant embedment after the hydraulic fracturing of a shale reservoir [35]

Research using experiments and simulations has demonstrated that long-term interactions between rocks and fluids can cause substantial embedding of proppants. Fractures with rough rock surfaces tend to have increased conductivity when propped with a single layer of proppants. The leverage of proppant layer count, size, distribution changes and particle crushing on proppant embedment was measured, establishing a significant connection between proppant embedment and rock mechanical characteristics [17,23]. In addition, resin coating layers have been identified as crucial factors in proppant embedment, playing a key role in fracture conductivity performance and anti-corrosion properties [23]. Moreover, adding resin coating layers to the proppant can improve the adhesion between proppant grains and increase the strength of the proppant pack, ultimately enhancing proppant embedment. Resin coating layers play a vital role in fixing proppant grains in place, maintaining their stability and preventing movement. This stabilizing effect helps maintain fracture conductivity and enhances fluid flow efficiency in production.

5.3 Proppant Flowback

Different techniques have been employed to stop proppant flowback in hydraulic fracturing, with the mix of recent Fiber innovation and resin-coated proppant (RCP) proving successful in managing proppant return. Resin-coated proppants (RCPs) are employed to avoid proppant flowback during hydraulic fracturing. Resin coated proppants RCPs can enhance well stimulation outcomes by effectively controlling flowback around the wellbore [67], Figure 10 shows uncured proppant flowback. Surface treatment of the proppant was a novel method to reduce proppant flowback and improve flow resistance and conductivity [44] and utilizing curable resin coated proppants and on-site liquid resin coating systems to decrease proppant flowback [1,16,46,47].

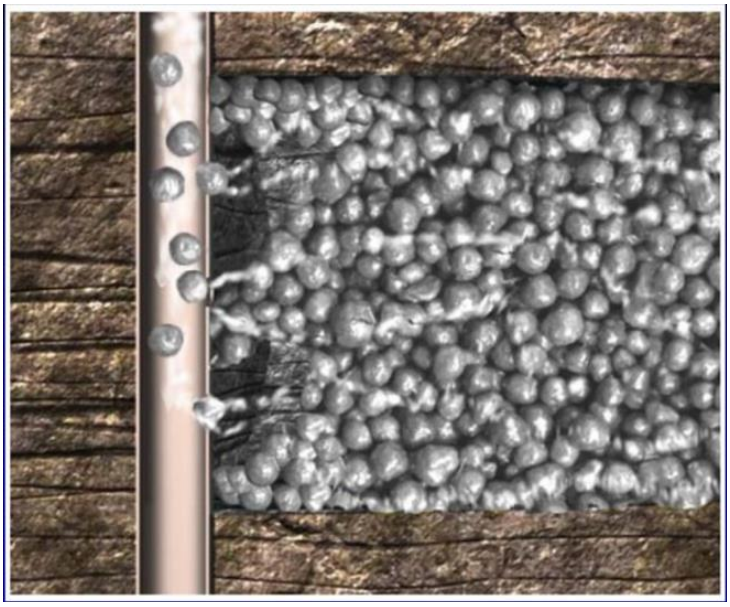


Fig. 10. Proppant flowback from the fracture into the wellbore (uncoated or precured proppants) [73]

However, the method of real-time resin application during fracturing operations offers an economical and adaptable solution for controlling proppant flowback in various reservoir conditions. The liquid resin system provides the benefit of solidifying the proppant once it enters the fracture, preventing fines from returning and ensuring they remain attached to the proppant within the fracture. A new way of approaching environments [47,64]. Moreover, a new type of proppant with a surface modification that induces self-aggregation in fracturing fluids was discovered to enhance fracture conductivity, especially in situations of elevated closure stresses.

5.4 Proppant Wettability

Numerous studies have investigated the wetting properties of resin-coated proppants, aiming to improve their effectiveness in hydraulic fracturing. A new type of proppant that has excellent hydrophobicity, self-suspension capabilities and liquid conductivity has been improved [25]. The self-suspension ability of epoxy resin coated (ERC) proppant is almost sixteen times higher than that of uncoated ceramic proppants. Moreover, the ERC proppant exhibited an 83.8% enhancement in hydrophobic properties and a 16.71% increase in liquid conductivity when compared to uncoated proppants, as shown in Figure 11.

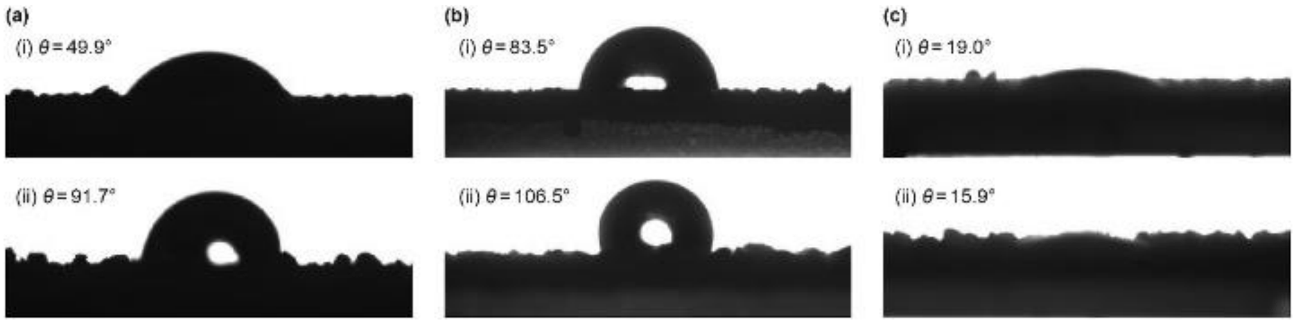


Fig. 11. (a) Contact angle between: (i) water and uncoated proppant (ii) ERC proppant (b) Contact angle between: (i) 0.2 wt% guar gum solution and uncoated proppant (ii) ERC proppant (c) Contact angle between: (i) Daqing crude oil and uncoated proppant (ii) ERC proppant

Ceramic proppant coated with a phenolic resin shell containing Fe_3O_4 nanoparticles had a self-suspending ability five times greater than the uncoated proppant, allowing it to travel further in the fracture network [41].

The employ of graphite nanosheets has a great influence on changing the wettability of proppant surfaces. These studies together help in creating better and long-lasting proppant materials for oil and gas extraction. Different wettability of resin coated proppants to oil and water impacts their permeability and water resistance [70].

6. Effect of Fracturing Fluid on Resin Coated Proppant

The performance of resin-coated proppants in hydraulic fracturing is influenced by the type of fracturing fluid utilized, the interaction between resin-fracturing fluid can affect the stability of the fluid and the strength of proppant consolidation, which is crucial for preventing proppant flowback. The type of resin, along with the temperature and pressure during fracturing, can affect this interaction, as shown in Figure 12. Oxidizing breakers can impact the performance of resin-coated proppants [48].

The use of enhanced resin-coated proppants to improve performance in various fracturing fluid settings [57] and introduce a nanocomposite resin for sand coating, showcasing enhanced strength, resistance and conductivity in high-temperature fracturing fluid environments [26]. Moreover, a new type of proppant with a surface modification that induces self-aggregation in fracturing fluids was discovered to greatly enhance fracture conductivity, especially in situations of elevated closure stresses.

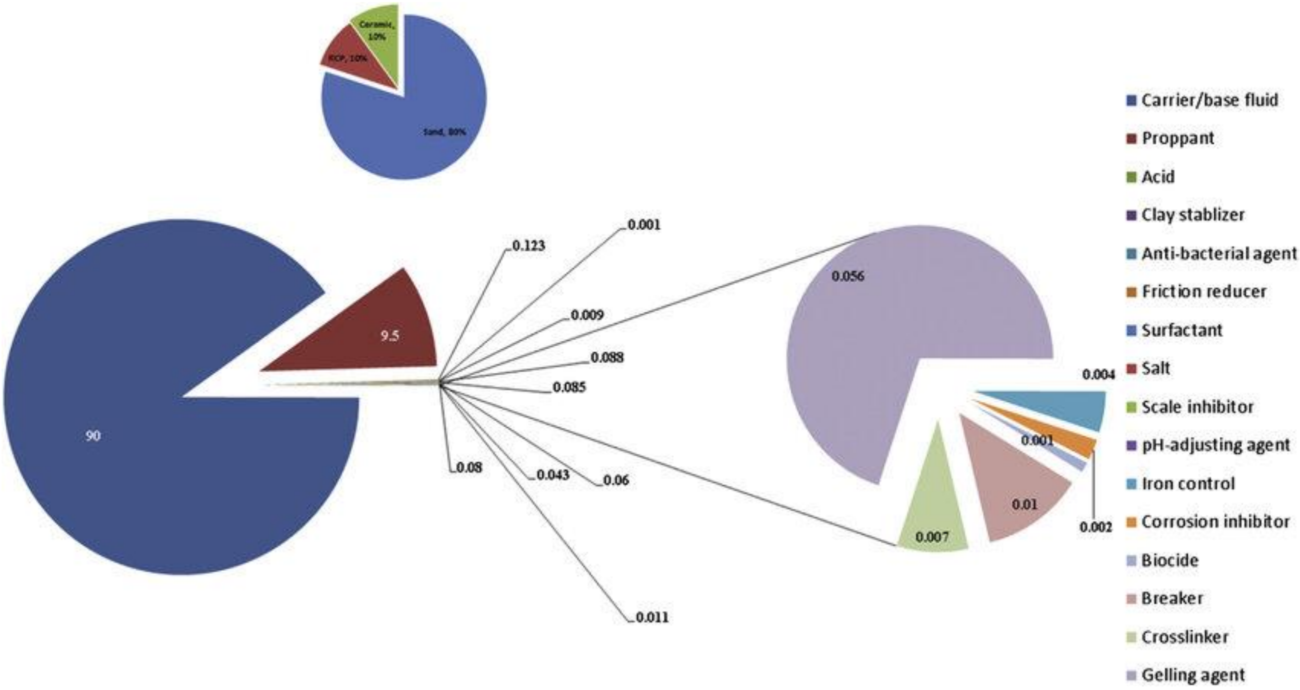


Fig. 12. Composition of a typical fracturing fluid [81]

Finally, a novel high-temperature epoxy resin system was created and tested in the field, demonstrating excellent consolidation abilities and suitability with fracturing treatment fluids. Fracturing fluids can influence resin-coated proppants (RCP) by engaging with the resin and impacting fluid stability, proppant consolidation strength and the likelihood of proppant flowback. Fluid interacting with resin can weaken consolidation strength and hinder resin curing rate or cause a reduction in grain-to-grain contact, which raises the risk of proppant flowback during production [20,69]. Moreover, resin elements have the potential to trigger breakers in the fracturing liquid, resulting in decreased fluid durability. The adjusted concentrations of breaker/crosslinker/buffer and using different LRCP types can help minimize resin-fluid interaction effects [48,69].

7. Proppant Coating Techniques

There are two primary methods for proppant coating. In the first method, the proppant is coated in the factory and then transported to the well site, where it is injected directly with the fracture fluid and settles down into the fracture. The second method entails coating the proppant through a liquid resin system activated at the well site. This allows the coating to be applied to the proppant surface during the curing process. Unique conditions such as elevated temperatures, high flow rates and increased shut-in pressures are managed by drilling deeper and accessing formations at greater depths [43]. Table 4 summarizes the coating techniques used in the proppant coat.

Table 2
Techniques used in proppant coating

Techniques	Advantage	Remark	Ref.
Flotation	Effective Segregation of finely ground valuable minerals from other minerals present in the raw material. High Purity Concentration by eliminating undesirable gangue material.	Inapplicability to Certain Materials, whereas flotation techniques are not suitable for creating resin-coated proppant slurries or materials with inherently hydrophobic surfaces	[80]
Impregnation	Enhance the strength of the proppant, making it more robust and durable and impart flexibility to the proppant, allowing it to absorb shock and stress without undergoing deformation.	. Complex Process, achieving optimal impregnation requires careful control over parameters such as flow dynamics and coating weight, making the process relatively complex and demanding in terms of precision and control.	[81]
Spraying	Uniform distribution of coatings, which enhances their ability to adhere to substrates and primes them for further coating applications also improving the overall quality and resilience of the coatings.	Errors in parameters during spraying may occasionally lead to variations in the uniformity and continuity of the paint layer formed.	[2]
Dipping	Uniformed particle layer, providing consistent coating coverage. The process allows for adjustments in temperature and coating duration to achieve the desired coating thickness and properties.	The surface coating lacks sufficient mechanical stability, especially when subjected to centrifugal forces in the receiver. Requirement for Multiple Coating Steps: To attain denser and more durable coating layers, multiple coating steps may be necessary, increasing the complexity and duration of the process.	[24]
Sputtering	Enhanced step coverage, ensuring uniform coating distribution even in complex surface geometries.	This process is associated with a high cost, potentially limiting its widespread application and accessibility.	[38,49]
Thermal plasma sintering	Efficient consolidation of material powders, ensuring strong bonding and uniformity in the coated particles, leads to enhanced mechanical properties and durability.	Complex and potentially time-consuming process. Low temperatures may hinder the sintering reaction, necessitating increased temperatures to promote consolidation, which could affect energy consumption and cost.	[22,65]
Fluidizing bed powder	Highly uniform coating distribution, resulting in a seamless seal without mechanical impairments or ruptures.	Require substantial volumes of process air, which may trigger static charges and potentially lead to explosions. Implementing safety measures such as relief ducts is necessary to mitigate the risk of explosion and ensure operator safety.	[56,61]
sol-gel	Able to synthesize with varied chemical compositions, making it applicable across a wide range of industries.	Weak compatibility between inorganic fillers and organic monomers, potentially reducing the strength of the composite rather than enhancing it.	[10,68]

8. Results and Discussion

8.1 Effect of Resin Coating on Proppant Roundness

The roundness and sphericity of proppants play a crucial role in hydraulic fracturing operations, influencing the permeability and flow conductivity of the proppant pack. Resin coating is a common method used to enhance the performance of proppants, but its effect on roundness and sphericity. Many studies have demonstrated the effective role of resin coatings in improving the roundness of proppants, as shown in Figure 13 shows an SEM micrograph of the ceramic proppant, Figure 13(a) before coating and, Figure 13(b) after coating with epoxy resin. The surface of the uncoated ceramic proppant is rough, while the surface of the epoxy resin-coated proppant is smoother and rounder compared to the uncoated proppant [78].

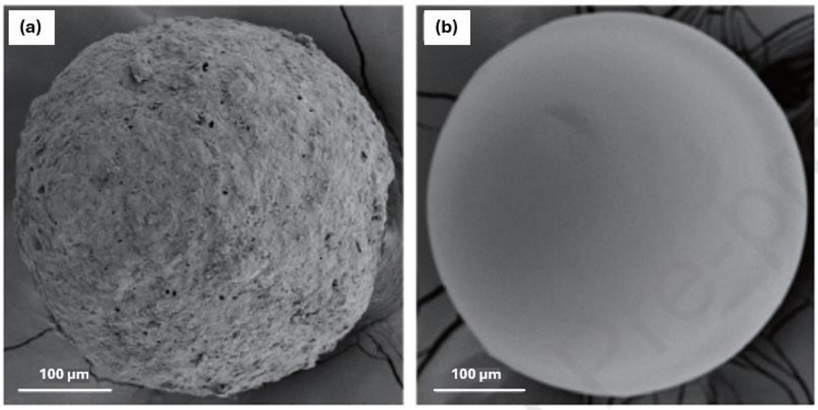


Fig. 13. SEM micrograph (a) Uncoated ceramic proppant and (b) Epoxy resin coated proppant [78]

Another study illustrates the internal structure of an initial inorganic polymer prepared using an optimal formulation. Figure 14(b) presents a scanning electron microscopy (SEM) image of the inorganic polymer proppant. Notably, the proppant exhibited high roundness and sphericity, with a smooth surface devoid of cracks. These attributes are essential for optimizing the permeability and flow conductivity within the fracture network [65]. This near-perfect roundness and sphericity are advantageous for facilitating fluid flow through the proppant pack, thereby enhancing hydrocarbon recovery rates.

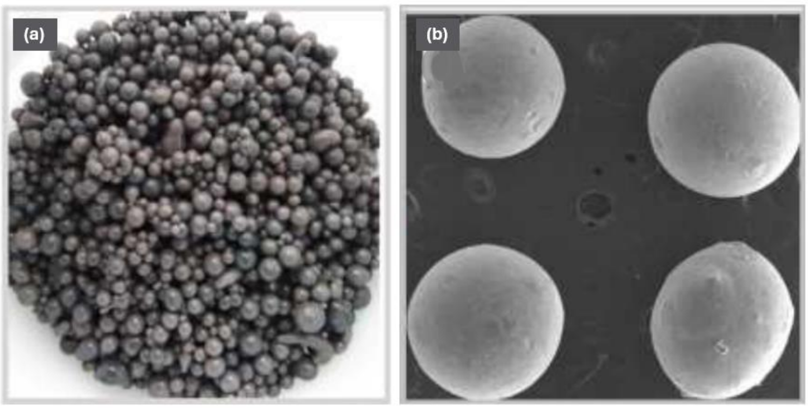


Fig. 14. Schematic representation of preparing the inorganic polymer proppant (a) photo of the proppant (b) SEM image of the proppant

8.2 Effect of Resin Coating on Proppant Fines Generation

Proppant fines generation during hydraulic fracturing operations can impair well productivity and increase operational costs. Resin coatings have emerged as a promising solution to mitigate fines generation, with recent studies focusing on the incorporation of nanofiller coatings to enhance their effectiveness.

The application of urethane coatings containing CNTs has shown significant promise in reducing fines generation resulting from proppant crushing [57]. As depicted in Figure 15(a), the application of urethane coating containing CNTs effectively reduced fines generation resulting from proppant crushing, with the containment of fines becoming more pronounced as the concentration of CNTs increased. This strengthening of the urethane coating led to reduced crushing of proppant grains, as depicted in Figure 15(a). Additionally, CNTs form a fibrous network that contributes to preventing fine release. Consequently, the optimal concentration of CNTs for proppant coatings was found to be 0.5%, while the lowest percentage of fines was generated with a 0.1% loading of rGO in urethane coating, as demonstrated in Figure 15(b) [29].

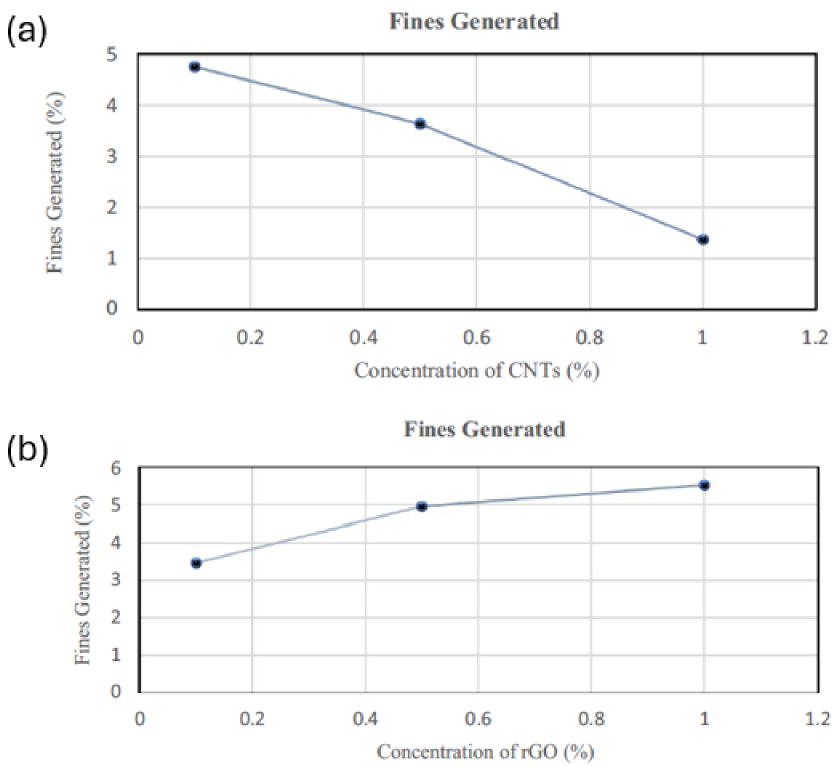


Fig. 15. Fines generations at different loading of (a) CNTs and (b) rGO in urethane coatings [29]

8.3 Effect of Resin Coating on Proppant Embedment

Proppant embedment represents a significant challenge in hydraulic fracturing operations, often resulting in decreased fracture conductivity and the generation of fines (spalling). Recent investigations have demonstrated that Curable Resin-Coated Sand (CRCS) proppants exhibit greater stability in terms of fine formation compared to Lightweight Ceramic (LWC) and Uncoated Fracture Sand (UFS) proppants, as depicted in Figure 16(a) and 16(b) [73].

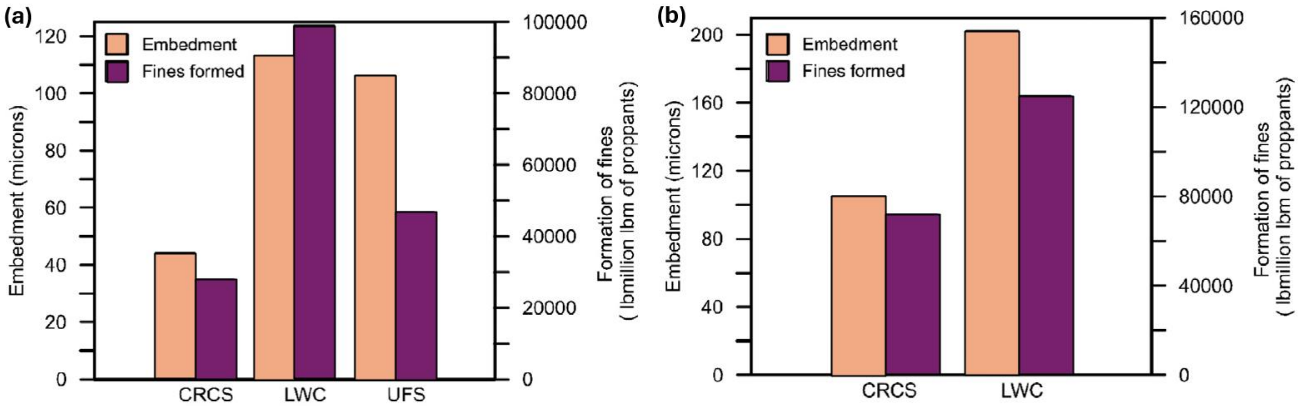


Fig. 16. Embedment and fines generation for different proppant types (a) Bakken shale and (b) Haynesville shale [73]

Studies examined the effect of proppant embedment on Bakken shale, utilizing proppants of uniform size (20/40) at a pressure of 58.6 MPa, CRCS exhibited superior embedment resistance compared to LWC and UFS. Specifically, the embedment of CRCS was measured at 44 µm, while LWC and UFS proppants displayed embedment's of 113 µm and 106 µm, respectively. This disparity suggests that CRCS offers enhanced embedment resistance, attributed to its capacity to form a cohesive proppant pack through grain bonding during fracturing operations. The resulting bonded grains distribute loads evenly across the fracture face, mitigating embedment.

Further investigations conducted on Haynesville shale, employing proppants of the same types but with a mesh size of 40/80 at a temperature of 300°F and a pressure of 69 MPa as referred to in Figure 16(b), yielded similar findings. LWC proppants exhibited nearly double the embedment compared to CRCS, corroborating the superior embedment resistance of CRCS [7,73].

9. Conclusions

Since the inception of hydraulic fracturing, maximizing fracture conductivity in hydraulic fracturing operations is crucial for optimizing well productivity and maximizing hydrocarbon recovery. A multitude of proppants have been utilized in fracturing processes, driven by the evolving demands posed by deeper reservoirs and complex formation environments. These environments necessitate proppants with enhanced strength and lower density, a challenge that has been addressed through advancements in proppant materials. Notably, the durability of proppant materials under extreme conditions of elevated temperature and pressure has shown improvement after coating. Academic discussions and conclusions stemming from an in-depth exploration of advanced proppant coating techniques in hydraulic fracturing operations underscore the pivotal role of coatings in enhancing proppant performance by augmenting fracture conductivity and overall efficiency while mitigating mechanical failure and downhole challenges. Here are some aspects that have improved with the paint effect:

i. <u>Crushing:</u> Resin coatings have demonstrated significant enhancements in the crush strength of proppants employed in hydraulic fracturing operations. The incorporation of nanocomposites into resin coatings enhances proppant crush resistance. Specifically, the addition of nanomaterials to urethane resin coating increased compressive strength by 41% and 35% through optical microscopy testing.

ii. <u>Shape:</u> coatings also improve the sphericity, roundness and flow conductivity of the proppants, leading to cost reduction and increased oil yield
iii. <u>Embedment:</u> resin-coated proppants prevent flowback and resist embedment, making them ideal for downhole conditions. The development of a nano-composite resin coating has further enhanced proppant crush strength, conductivity and chemical resistance, making it suitable for field applications at higher stresses.
iv. <u>Flowback:</u> surface treatment of the proppant was a novel method to reduce proppant flowback and improve flow resistance and conductivity and utilizing curable resin coated proppants and on-site liquid resin coating systems to decrease proppant flowback. By leveraging insights garnered from these academic discussions, operators can make informed decisions to enhance proppant performance and efficiency in hydraulic fracturing operations, thereby contributing to the sustainable extraction of hydrocarbon resources in the oil and gas industry.

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