



**METHODS FOR ENHANCING FRACTURING  
PROPPANT CONDUCTIVITY**

BY

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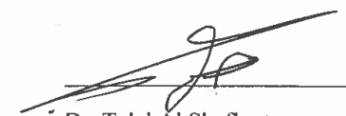


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*To my family, whose endless encouragement, boundless love, and belief in me have been  
my constant source of strength and inspiration.*

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## **LIST OF ABBREVIATIONS**

|                      |   |                                                |
|----------------------|---|------------------------------------------------|
| <b>API</b>           | : | American Petroleum Institute                   |
| <b>ISO</b>           | : | International Organization for Standardization |
| <b>RCS</b>           | : | Resin-Coated Sand                              |
| <b>UHSP</b>          | : | Ultra-High-Strength Proppants                  |
| <b>T<sub>g</sub></b> | : | Glass Transition Temperature                   |
| <b>LWC</b>           | : | Lightweight Ceramic                            |
| <b>IDC</b>           | : | Intermediate-Density Ceramic                   |
| <b>HDC</b>           | : | High-Density Ceramic                           |
| <b>LRC</b>           | : | Liquid Resin Coating                           |
| <b>RPM</b>           | : | Revolutions Per Minute                         |
| <b>LVDT</b>          | : | Linear Variable Differential Transformer       |
| <b>XRD</b>           | : | X-ray Diffraction                              |
| <b>PCT</b>           | : | Proppant Crush Tester                          |

## **ABSTRACT**

Full Name : Vahid Ramazanov

Thesis Title : Methods for Enhancing Fracturing Proppant Conductivity

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Hydraulic fracturing is a key method used to boost the extraction of hydrocarbons from unconventional oil and gas reservoirs. This technique involves injecting fluid into the formation at a pressure high enough to fracture the rock. Proppant is then introduced into the created fractures to hold them open, allowing for a substantial increase in hydrocarbon flow from the well. The most widely utilized proppant for treating fractures at the moment is sand. Significant volumes of sand are required to properly support both artificial and natural fractures. However, proppant can be a significant expense during the well completion phase, making it crucial to reduce costs without compromising the well's performance and success. For example, high-strength ceramic proppant is known for its reliability for fracturing job, but using it exclusively is often not cost-effective. Therefore, it is often combined in smaller proportions with other more affordable, lower-grade, and widely available sand types. Selecting an appropriate proppant is vital for the success of hydraulic fracturing operations. Several factors are considered when choosing a proppant for hydraulic fracturing, including its size and shape, density, durability, ability to maintain conductivity under high temperatures and overburden stresses, and compatibility with reservoir fluids. This study investigates methods to enhance fracturing proppant

conductivity by evaluating the short-term conductivity and mechanical behavior of various proppant types and combinations, including 40/70 sand, resin-coated sand 40/70 resin-coated sand (RCS 40/70), 40/70 ceramic, 100-mesh sand and mixtures of these materials. For conductivity measurement, both metal platens and sandstone slabs were used. A mixture of 40/70 sand with 40/70 ceramic in a 3:1 ratio by weight (wt%) improved the conductivity of the pack by 1.34–1.56 times. Similarly, a mixture of 100-mesh sand with 40/70 ceramic resulted in a 1.55–3.13 times improvement in conductivity. Coating raw 40/70 sand with phenolic resin resulted in a five-fold increase in conductivity at 6,000 psi closure stress. Resin coating resulted in a significant reduction in proppant crushing, decreasing the crushing rate of 40/70 sand by 42.1% at 10,000 psi closure stress. Long-term conductivity using 40/70 ceramic and sandstone slabs was evaluated, and the conductivity values were compared with short-term conductivity values up to 9000 psi. The embedment mechanism and conductivity reduction were investigated by comparing the compaction and conductivity values of 40/70 ceramic with steel platens and sandstone slabs. Conductivity reduction due to the embedment mechanism was significant, reaching up to 78% at 8000 psi. Although these results were obtained under ideal laboratory conditions, further research is needed to evaluate proppant performance under reservoir-specific conditions, including high temperatures, formation fluids, and cyclic stresses.

## خلاصة

الاسم الكامل : وحيد رمضانوف

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التخصص: هندسة البترول

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التكسير الهيدروليكي هو أحد الأساليب الرئيسية المستخدمة لتعزيز استخراج الهيدروكربونات من خزانات النفط والغاز غير التقليدية. تتضمن هذه التقنية حقن السوائل في التكوين عند ضغط مرتفع بما يكفي لكسر الصخور. ثم يتم إدخال الدعامات في الكسور الناتجة لإبقائها مفتوحة، مما يسمح بزيادة كبيرة في تدفق الهيدروكربون من البئر. الدعامات الأكثر استخدامًا على نطاق واسع لعلاج الكسور في الوقت الحالي هي الرمل. تتطلب عمليات التكسير الاصطناعي والطبيعي كميات كبيرة من الرمل. ومع ذلك، قد يشكل استخدام الدعامات تكلفة كبيرة أثناء مرحلة استكمال البئر، مما يجعل من الضروري خفض التكاليف دون المساس بأداء البئر ونجاحها. على سبيل المثال، يُعرف الدعامات الخزفية عالية القوة بموثوقيتها في عمليات التكسير، ولكن استخدامها حصريًا غالبًا ما لا يكون فعالاً من حيث التكلفة. لذلك، غالبًا ما يتم دمجها بنسب أصغر مع أنواع أخرى من الرمل الأقل تكلفة والأكثر جودة والمتوفرة على نطاق واسع. يعد اختيار الدعامة المناسبة أمرًا حيويًا لنجاح عمليات التكسير الهيدروليكي. يتم أخذ العديد من العوامل في الاعتبار عند اختيار الدعامة للتكسير الهيدروليكي، بما في ذلك حجمها وشكلها وكثافتها ومتانتها وقدرتها على الحفاظ على التوصيل تحت درجات الحرارة العالية والإجهادات الزائدة والتوافق مع سوائل الخزان. تبحث هذه الدراسة في طرق تعزيز توصيل دعامات التكسير من خلال تقييم التوصيل قصير المدى والسلوك الميكانيكي لأنواع ومجموعات الدعامات المختلفة، بما في ذلك الرمل 70/40، والرمل المغطى بالراتنج 70/40 الرمل المغطى بالراتنج (RCS 40/70)، والسيراميك 70/40، والرمل 100 شبكة ومخاليط من هذه المواد. لقياس الموصلية، تم استخدام كل من الألواح المعدنية وألواح الحجر الرملي. أدى خليط من الرمل 70/40 مع السيراميك 70/40 بنسبة 3:1 بالوزن (%) إلى تحسين موصلية العبوة بمقدار 1.34-1.56 مرة. وبالمثل، أدى خليط من الرمل 100 شبكة مع السيراميك 70/40 إلى تحسن في الموصلية بمقدار 1.55-3.13 مرة. أدى طلاء الرمل الخام 70/40 براتينج فينولي إلى زيادة بمقدار خمسة أضعاف في

الموصلية عند إجهاد إغلاق 6000 رطل لكل بوصة مربعة. أدى طلاء الراتينج إلى انخفاض كبير في سحق الدعامات، مما أدى إلى انخفاض معدل سحق الرمل 70/40 بنسبة 42.1٪ عند إجهاد إغلاق 10000 رطل / بوصة مربعة. تم تقييم الموصلية طويلة المدى باستخدام ألواح السيراميك والحجر الرملي 70/40، وتمت مقارنة قيم الموصلية بقيم الموصلية قصيرة المدى حتى 9000 رطل / بوصة مربعة. تم التحقيق في آلية التضمين وتقليل الموصلية من خلال مقارنة قيم الضغط والموصلية للسيراميك 70/40 مع ألواح الصلب وألواح الحجر الرملي. كان انخفاض الموصلية بسبب آلية التضمين كبيراً، حيث وصل إلى 78٪ عند 8000 رطل لكل بوصة مربعة. على الرغم من أن هذه النتائج تم الحصول عليها في ظل ظروف عملية مثالية، إلا أن هناك حاجة إلى مزيد من البحث لتقييم أداء الدعامات في ظل ظروف محددة للخران، بما في ذلك درجات الحرارة المرتفعة وسوائل التكوين والإجهادات الدورية.

# **CHAPTER 1**

## **INTRODUCTION AND LITERATURE REVIEW**

### **1.1 Hydraulic fracturing of unconventional reservoirs**

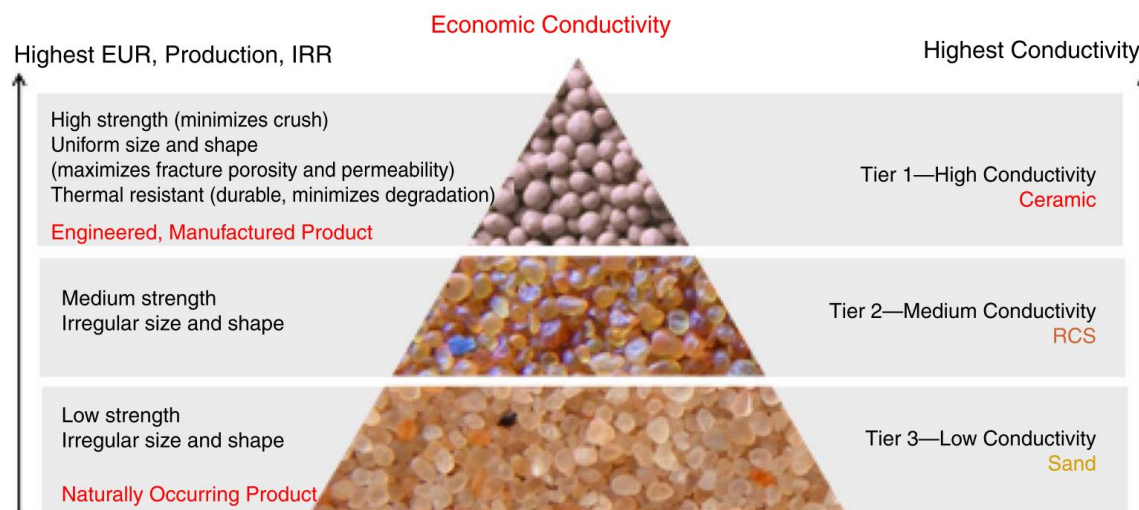
In reservoir stimulation, the combination of multi-stage hydraulic fracturing and horizontal drilling has greatly advanced shale gas production. Hydraulic fracturing is essential for extracting oil and gas from unconventional reservoirs by creating fracture networks that allow fluid flow in tight formations (Chen et al., 2022). Since its initial field test on a gas well at the Hugoton field in 1947 (Carter et al., 2000), hydraulic fracturing has been the subject of extensive research through experimental studies, field trials, and numerical simulations, conducted by both academic institutions and industry professionals (Montgomery & Smith, 2010). From a geomechanics standpoint, hydraulic fracturing occurs in three stages: initiation, propagation, and flow-back of the fractures. The fracture network that forms is influenced by the fracturing approach, such as the perforation method, proppant and fluid characteristics, and injection timing, along with local geological factors like rock properties and natural fracture patterns (Chen et al., 2022). In hydraulic fracturing (HF) treatments, proppants play a crucial role in maintaining fracture conductivity. These small particles, introduced along with fracturing fluid, prevent the newly created fractures from closing once the pumping pressure is released. Proppants can be broadly categorized as conventional or advanced. Conventional proppants typically consist of naturally occurring materials like sand, ceramic, nutshells, or glass beads. In contrast, advanced proppants are engineered for enhanced performance, often featuring a

polymer coating applied to their surface. This coating can improve various properties, such as proppant strength and flowback control (Zoveidavianpoor & Gharibi, 2015).

## 1.2 Literature review

### 1.2.1 Types of proppant

Despite the development of various proppant technologies, it is important to note that over 99% of proppants used today fall into three conductivity tiers: Tier 3 (uncoated sand), Tier 2 (resin-coated sand), and Tier 1 (ceramics) (see **Figure 1**). Ascending these tiers corresponds with increased conductivity and durability, resulting in improved hydrocarbon production and estimated ultimate recovery. This enhanced conductivity is a function of several factors, including proppant shape, size uniformity, surface characteristics, and compressive strength. In the highest tier (Tier 1), engineered ceramic proppants exhibit superior strength, uniform sizing, relatively smooth surfaces, and round, spherical shapes (Palisch et al., 2015).



**Figure 1. Hierarchy of Proppant Value** (Palisch et al., 2015)

**Silica Sand:** Hydraulic fracturing operations continue to use processed and graded quartz sand with a high silica concentration, which is commonly referred to as "sand," "frac sand," or "silica sand." Its widespread use stems from its economic advantages, a factor that has persisted since the earliest days of hydraulic fracturing. Sand from the Arkansas River was used for trial hydraulic fracturing by Stanolind Oil in the Hugoton field in 1947, which is the earliest recorded use of sand as a proppant. Because it is still relatively inexpensive, sand is still a popular proppant material in the industry even with the introduction of more sophisticated technologies (Liang et al., 2016). Frac sand, while naturally occurring, typically undergoes significant processing to optimize its performance in hydraulic fracturing applications. The first step in this operation is the raw material extraction from silica sand deposits. After that, the sand grains are crushed, cleaned and washed to get rid of contaminants, dried, and then sized to get the right distribution. There are two main varieties of frac sand that are used: brown and white sand (C. J. Stephenson et al., 2003). The characteristic light color of white sand is attributed to its high purity and low concentration of impurities. This contrasts with brown sand, which exhibits a lower silica content and a higher proportion of impurities, contributing to its brownish hue. The presence of these impurities not only affects the color but also influences the mechanical properties of the sand. Brown sand, due to its composition, is generally less expensive than white sand but exhibits increased susceptibility to crushing under lower stress conditions (Benson & Wilson, 2015). Usually sand cannot withstand closure stress higher than 6000 psi (Liang et al., 2016). However closure stress that sand can withstand during hydraulic fracturing is a complex issue and depends on several factors such as mineralogy, grain size and shape, sorting and cementation (Boggs, 2006; Folk, 1980; Larsen & Chilingarian,

2010). To guarantee the best possible performance in hydraulic fracturing operations, strict requirements control the selection of frac sand. Key criteria include mineralogical purity, with a high silica content being paramount; grain size distribution, typically ranging from medium to coarse; sphericity and roundness, generally 0.6 or greater; high crush resistance to withstand downhole stresses; low solubility to minimize formation damage; and low turbidity to prevent impairment of fluid flow. High-quality frac sand has a silica ( $\text{SiO}_2$ ) content of more than 99 percent, while most of the frac sand that is used has a silica content of between 95 and 99 percent (Zdunczyk, 2018). This high level of mineralogical purity is typical of supermature or mature sand deposits that have been subjected to geological processes of dissolution or removal of tiny particles and less resistant minerals, leaving behind a deposit that is suitable for hydraulic fracturing applications (Benson & Wilson, 2015).

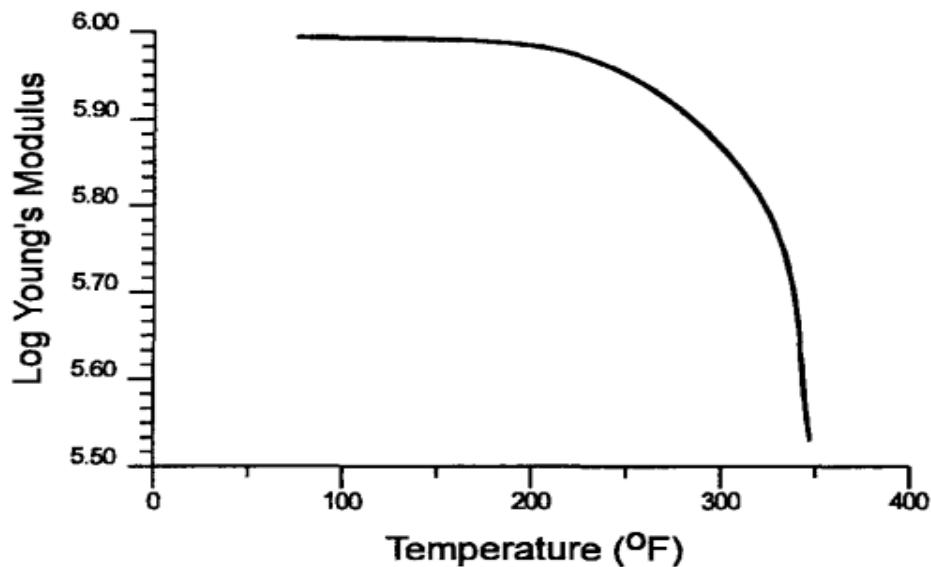
***Ceramic proppant:*** The limitations of sand in withstanding high closure stresses, often exceeding 6000 psi in deeper formations, led to the development and introduction of higher-strength ceramic proppants (Liang et al., 2016). These engineered proppants are manufactured from materials such as sintered bauxite, kaolin, magnesium silicate, or a combination of bauxite and kaolin.<sup>2</sup> Compared to sand, ceramic proppants offer superior crush resistance, enabling them to maintain fracture conductivity under significantly higher stress conditions (Dilireba & Wang, 2024). Ceramic proppants are broadly categorized into three classifications based on density: lightweight ceramic (LWC), intermediate-density ceramic (IDC), and high-density ceramic (HDC). The density of these proppants is primarily determined by the alumina content of the raw materials used in their production. LWC typically contains 45 to 50% alumina, IDC contains 70 to 75%, and HDC contains

80 to 85%. As alumina content and density increase, so does the proppant's ability to withstand closure stress (Liang et al., 2015). While increasing the alumina content of ceramic proppants is known to improve their strength, Palisch et al. (2015) observed that this approach has limitations. Even with alumina content approaching 100%, the desired gains in conductivity performance were not achieved. To address this, they developed a novel manufacturing process utilizing high-alumina raw materials to produce ultra-high-strength proppants (UHSP). These UHSPs exhibit exceptional characteristics, including high sphericity, uniform particle size, and a fully dense structure, minimizing internal porosity. Consequently, these proppants demonstrate superior crush resistance, withstanding closure stresses up to 20,000 psi.

***Resin coated sand (RCS):*** Polymers have become indispensable in the petroleum industry, serving as crucial components of fluids and additives to address challenges in hydrocarbon drilling and production. As noted by Mahoney et al. (2013), coating proppants with a thin polymer layer can significantly enhance the efficiency of hydraulic fracturing treatments. This enhancement stems from several factors, including improved fracture conductivity (Nguyen et al., 2000), reduced proppant flowback (Nguyen and Weaver, 1997), and minimized production of formation fines (Gidley et al., 1995). While various resins are employed for proppant coating, including epoxy, furan, polyester, vinyl ester, and polyurethane, epoxy resins are the most prevalent (Zoveidavianpoor & Gharibi, 2015). Furan resins, though offering strong heat and water resistance, lack the necessary mechanical strength for many hydraulic fracturing applications. Polyurethane, another potential coating material, exhibits good mechanical strength, heat resistance, and chemical resistance, but its performance is limited to temperatures below 250°F (Pangilinan, De

Leon, et al., 2016). A key advantage of resin-coated proppants is their ability to mitigate proppant flowback which is a common challenge in hydraulic fracturing (Sinclair et al., 1983a). Broken proppant grain pieces are successfully encapsulated by the resin coating, which stops them from migrating back to the wellbore. Moreover, the coating creates interconnections between individual proppant particles, further enhancing their stability within the fracture and minimizing flowback (Nguyen, Dusterhoft, et al., 1998). This contributes to maintaining long-term fracture conductivity and optimizing hydrocarbon production. There are two primary methods for applying resin coatings to proppants. The first involves pre-coating the proppant with resin at a production facility before transporting it to the well site. Alternatively, proppants can be coated on-site using liquid resin coating (LRC) systems. This allows for greater flexibility and customization, as the coating properties can be tailored to the specific well conditions (Liang et al., 2016; Nguyen, Dusterhoft, et al., 1998). Currently, two types of resin-coated proppants (RCP) are available: pre-cured and curable. Pre-cured proppants are coated with fully or partially cured resin at the manufacturing facility before being transported to the well site. These proppants do not clump together; instead, they are held in place within the fracture by the in-situ formation stress. If the resin coating is only partially cured, the high temperature and pressure conditions within the wellbore facilitate complete curing. Curable proppants, on the other hand, involve combining the proppant with a liquid resin system at the well site (Zoveidavianpoor & Gharibi, 2015). Crosslinking occurs downhole under high temperature and pressure conditions. After hydraulic fracturing, the well is shut in to allow for complete curing, resulting in a consolidated proppant pack with each grain encapsulated in resin. Chemical crosslinks within the cured resin prevent it from melting at high

temperatures. However, when the temperature exceeds the glass transition temperature ( $T_g$ ) of the resin, the coating softens, leading to a decrease in strength. The glass transition temperature ( $T_g$ ) is a critical point at which amorphous polymers transition from a rigid, glassy state to a more flexible, rubbery state due to the onset of segmental motion (Liang et al., 2016). This transition is marked by a change in the stress/strain relationship, specifically a deviation from linearity (see **Figure 2**). Therefore, the  $T_g$  of a cured resin can be identified as the point where the slope of the Young's modulus versus temperature curve changes (Dewprashad, 1993).



**Figure 2.** Young's modulus as a function of temperature for epoxy resin (Dewprashad, 1993)

Research indicates that liquid resin-coated (LRS) proppants are more effective in preventing flowback than pre-cured resin-coated proppants (RCP) (Nguyen & Barton, 2004). This is attributed to the superior bonding achieved with LRS systems.

### 1.2.2 Proppant performance assessment

Evaluation of proppant performance relies on a variety of techniques designed to assess key characteristics. Proppant performance assessment plays a crucial role in optimizing hydraulic fracturing operations. By evaluating key proppant characteristics, engineers can ensure that the selected proppant is well-suited to the specific formation being fractured, ultimately maximizing well productivity. The API RP 19C, the latest iteration of recommended practices for proppant characterization (Freeman et al., 2009), aligns with ISO 13503-2 and outlines several key tests:

- **Proppant Pack Conductivity Testing:** Conductivity testing measures the ability of the proppant pack to facilitate fluid flow (Penny, 1987). Fracture conductivity is the product of fracture permeability  $K_{frac}$  and fracture width  $W_{frac}$  Equation (1).

$$Conductivity = K_{frac} \times W_{frac} \quad (1)$$

The ISO 13503-5 standard provides a standardized methodology for evaluating the long-term conductivity of proppant packs. This standard utilizes a testing device based on the system developed by Cooke (1973), commonly referred to as the API conductivity cell (see **Figure 3**). In accordance with ISO 13503-5, conductivity measurements should be conducted using Ohio sandstone slabs to simulate fracture faces and a 2 wt% potassium chloride (KCl) solution in distilled or deionized water as the test fluid. A single-phase fluid is flowed through the proppant pack of 2 lbs./ft<sup>2</sup> or 6.35 mm thickness at controlled rates between 1 and 5 cm<sup>3</sup>/min. Each stress level is held for 50 ± 2 hours. ISO 13503-5 mandates a test cell temperature of 250°F for resin-coated and ceramic proppants, while natural sand is tested at a minimum temperature of 150°F.

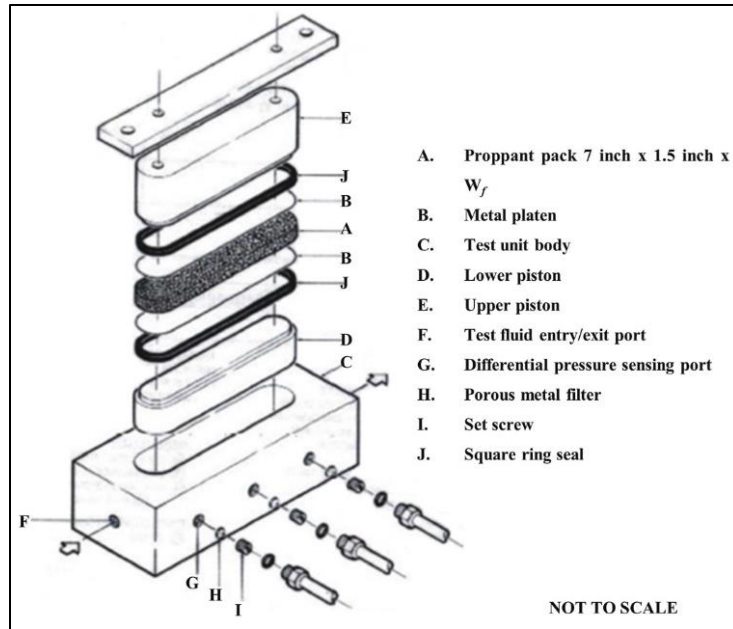


Figure 3. API conductivity testing apparatus (Cooke, 1973)

- Crush Resistance Testing:** This technique involves subjecting the proppant to controlled pressure to determine its ability to withstand the high stresses encountered during hydraulic fracturing. Maintaining proppant integrity under stress is crucial for preserving fracture conductivity (Cheung, 1988). When fracture closure stress surpasses the strength of the proppant, crushing occurs. This leads to the formation of fines and a reduction in fracture width, ultimately diminishing the conductivity of the proppant pack and hindering hydrocarbon flow. The API RP 19C outlines a crush resistance test that determines the amount of proppant crushed under specific stress. This involves incrementally increasing stress on the proppant pack until the crushed material exceeds 10 wt.% of the total sample (RP, 2008).
- Acid Solubility Testing:** This test evaluates the proppant's resistance to dissolution in acidic fluids, which can be encountered in certain reservoir environments.

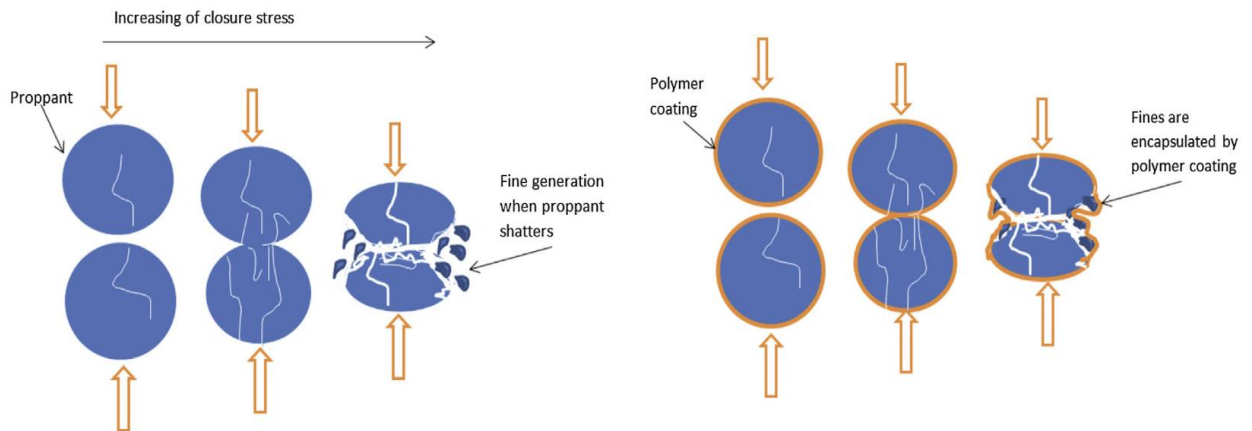
Proppant solubility can lead to formation damage and reduced production (Cheung, 1988).

- **Sieve Analysis:** Determines the particle size distribution of the proppant, which influences its packing and flow properties within the fracture. The API Recommended Practice 19C outlines procedures for sieve analysis and determination of diameter of a proppant particle. This standard mandate that a minimum of 90% of the proppant sample must pass through the coarser sieve while being retained on the finer sieve.
- **Sphericity/Roundness:** Assesses the shape of the proppant particles. Higher sphericity and roundness generally contribute to improved conductivity.
- **Density:** Determines the proppant's density, which influences its settling behavior and transport within the fracture.
- **Loss on Ignition:** Measures the amount of volatile material present in the proppant, which can affect its performance at high temperatures.

### 1.2.3 Proppant enhancement methods

**Polymer coating:** Coating proppants with polymer is the most common proppant enhancement technique in hydraulic fracturing. The coating serves as a protective layer, which effectively encapsulates any broken proppant fragments, preventing their migration and blockage of pores within the proppant pack (see **Figure 4**). Moreover, the polymer coating binds individual proppant particles together, creating a more stable proppant pack and further reducing the risk of proppant flowback (Liang et al., 2015; Zoveidavianpoor & Gharibi, 2015). Polymers are classified as either thermosetting or thermoplastics. Thermosetting polymers are characterized by their cross-linked structures, where the

molecules are permanently linked together during the molding process to form an interconnected network (Green et al., 2018). This cross-linking gives thermosets unique properties, such as high strength, rigidity, and resistance to heat and solvents. In contrast to thermosets, thermoplastic polymers can be repeatedly softened without undergoing permanent chemical changes (Graham & Sinclair, 1988). This ability is due to their linear or branched molecular structure, which allows the polymer chains to flow and rearrange easily when heated. Thermoplastic polymers offer several key advantages, including enhanced mechanical properties such as higher ductility, superior impact resistance, and greater fracture toughness compared to thermosets. Furthermore, their capacity to be repeatedly melted and reshaped makes them highly recyclable and reusable. This combination of properties makes thermoplastics versatile materials with wide-ranging applications in various industries (Zoveidavianpoor & Gharibi, 2015).



**Figure 4. Impact of closure stress on coated and uncoated proppants** (M. Stephenson, 2015)

Despite the advantages of thermoplastics, thermosetting polymers have found more widespread use in proppant coating. This preference is due to the strong affinity of the

epoxy groups commonly found in thermosetting resins to bond to the substrate materials. Compared to thermoplastics, thermosetting polymers have superior thermal stability, making them suitable for high-temperature wellbore environments. Furthermore, thermosetting resins generally offer a cost advantage over their thermoplastic counterparts. However, it is important to acknowledge the limitations of thermosets. Their inability to be reshaped, remolded, or recycled poses challenges in terms of sustainability and waste management.

***Surface Modification Agent (SMA):*** Surface modification of proppants involves modifying the outermost layer of the proppant grains to enhance their effectiveness. This modification can improve various properties, including wettability, adhesion, conductivity, and crushing resistance, ultimately contributing to more effective hydraulic fracturing operations. Nguyen and Weaver (Nguyen, Weaver, et al., 1998) first introduced the concept of a polymer-based SMA, derived from sustainable sources, which coats the proppant when applied in aqueous solutions. This coating is characterized by its viscous and adhesive nature, with limited solubility in both oil and water. The use of SMA in conjunction with resin-coated proppants allows for a swift return to production, eliminating the need for extended consolidation periods. A notable advantage of SMA-coated proppants is their ability to maintain a sticky texture without hardening. Because of this feature, they can endure numerous stress cycles without suffering substantial deterioration. Moreover, the instantaneous action of SMA eliminates the need for extended waiting periods, making it suitable for aggressive flowback strategies. The SMA coating improves the proppant's stability, substantially raising the critical flow velocity needed to trigger fluidization and erosion of the proppant pack. Furthermore, the application of SMA improves the efficiency

of gel breakers in removing guar-based fracturing fluids, potentially leading to enhanced fracture conductivity. Surface modification techniques include silane treatment, plasma treatment, and chemical treatment. One way to modify the surface of the proppant is applying coating (Sinclair et al., 1983b). Surface-modification agent (SMA) is a liquid substance that may be quickly added to water-based fluids during the process of hydraulic fracturing. The friction between grains and fluid velocity necessary to promote fluidization and the proppant movement are greatly increased by this chemical, which instantly encapsulates the proppant with a thin, sticky coating. Its stickiness also greatly lowers the overall density of the settled pack and the rate at which proppant settles resulting in better vertical distribution (Pangilinan, Al Christopher, et al., 2016). Another technique of proppant surface modification is application of superhydrophobic chemicals. Surface modification can convert the proppant surface's initial wettability into neutral wettability, reducing the intermolecular tensions between the fluid and the surface and facilitating simple fluid movement. The unique technique can enhance the proppant's self-cleaning ability to prevent a variety of blockages, including the accumulation of slit, scale, asphalt, and corrosion products at hydrocarbon flow path. In order to prevent water and water-based fracturing fluids from residing in the proppant void space, CARBO has invented an RPM neutral wetting treatment that improves the hydrophobic and lipophilic properties of the proppant surface. A neutral-wettability proppant made by Baker Hughes decreases the pressure loss in multiphase flow and lowers fluid attachment. As a consequence, the fluid can flow freely through the proppant pores for a very long time (Sinclair et al., 1983b).

***Proppant consolidation:*** Consolidation of proppant pack is utilized in hydraulic fracturing operations to keep the proppant particles in place within the fracture. The primary role of

this consolidated proppant pack is to prevent proppant flowback, ensuring that the proppant remains in place to maintain fracture conductivity and support hydrocarbon production. Two techniques were proposed by Nguyen et al (2004) for proppant consolidation within the fracture. The first method employed a liquid resin combined with a hardening agent, utilizing various resin-to-agent ratios. Hydrolyzable ester was used as a hardening agent to disrupt the gelled fracturing fluid films. The second technique also utilized a hydrolyzable ester to disrupt the solidified fracturing fluid films. These techniques aimed to create compacted and conductive proppant packs within the fractures to enhance fluid conductivity and prevent proppant flowback and the migration of fine particles from the formation. Vo et al (2014) investigated methods to achieve both delayed consolidation and agglomeration in proppant packs. Their study involved adding proppant coated with a mixture of tackifier polymer, catalyst, and curable resin to a fracturing fluid. Once placed, the consolidation of the proppant pack increased with time and temperature. The presence of both properties in a single proppant coating ensures effective immobilization of the proppant, thereby blocking the migration of formation sands and fines. This results in a fairly high and stable proppant pack conductivity. Such a proppant pack with a curable resin coating will have high consolidation strength with adequate proppant control in challenging conditions without significant loss of fracture conductivity.

### **1.3 Problem statement and Research Objectives**

While natural sand is both cost-effective and readily abundant, there are a number of issues that must be resolved in order to use it as a propping agent in severely stressed formations. These issues include sand characteristics, treatment design, and well selection. The ability of silica sand to tolerate the in-situ stresses within the formation is a significant obstacle

when trying to replace ceramic proppant in highly stressed formations. In contrast to manufactured proppants with intermediate and high strength, natural sand may experience crushing at relatively lower effective stresses, thereby increasing the potential for a loss of fracture conductivity. Furthermore, most readily available sand does not meet API standards for proppants, particularly in terms of sphericity, roundness, crush resistance, and other properties. However, there are potential methods to enhance the quality of raw, abundant sand for use in hydraulic fracturing, which could increase the efficiency of stimulation jobs and eliminate the workover and re-stimulation jobs. Additionally, there is a notable lack of publications comparing the performance of uncoated proppant to its resin-coated counterpart. While numerous studies examine the conductivity of various proppant samples, there is limited data comparing the long-term and short-term conductivity of proppant packs. Therefore, the primary objective of the proposed study is to conduct a comprehensive assessment of different raw and improved sand samples. The specific objectives are the following:

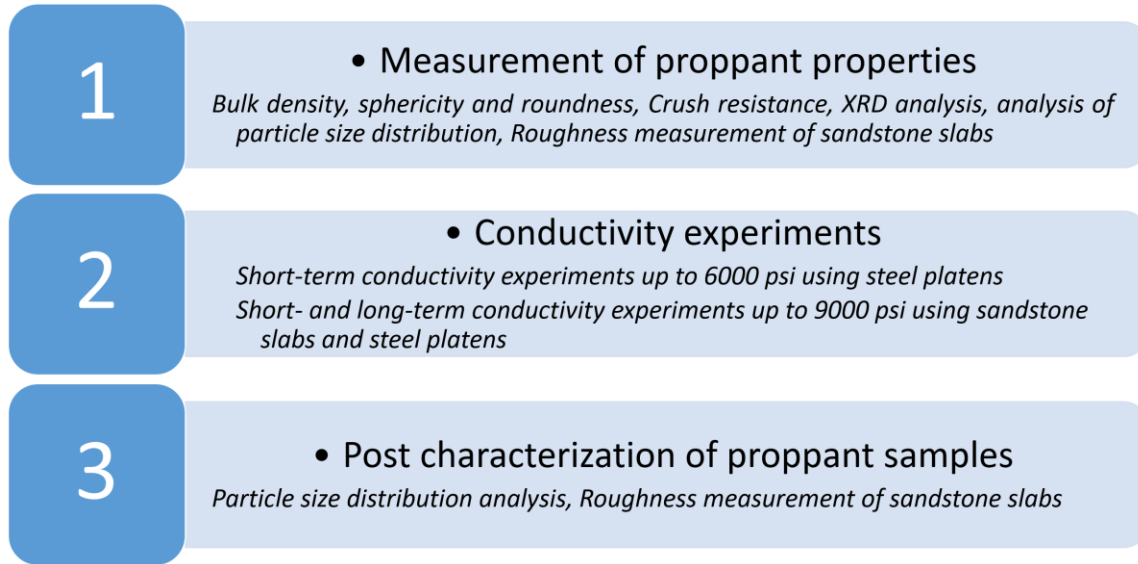
1. Identify the characteristics of fracturing sand.
2. Test the raw and improved sand samples in terms of fracture conductivity and adherence to common industry standards, and compare them with proppants used in the industry.
3. Investigating the performance and long-term stability of sand proppants at high-pressure condition.
4. Identify ideal sand mixture for optimum frac sand

This research has the potential to benefit the industry by identifying alternative proppant materials that are more cost-effective and readily available than ceramic proppant. If these alternative materials prove adequate for creating conductive pathways within fractures, they could offer a more sustainable and economically viable solution for hydraulic fracturing operations. Moreover, this research will address the knowledge gaps in the existing literature regarding the long-term conductivity and stability of raw and enhanced sand proppants.

## **CHAPTER 2**

### **MATERIALS AND METHODOLOGY**

This research was conducted in three phases to achieve its objectives. The first stage focused on characterizing different proppants and sandstone rock slabs. This included measuring bulk density, sphericity and roundness, performing crush tests, conducting XRD analysis of proppants, sieve analysis of proppants, and measuring the surface roughness of rock slabs. The second stage involved conductivity measurements. Short-term conductivity measurements were taken of proppant packs with a width of 6.35 mm under confining pressures up to 6000 psi using steel platens. Additionally, both short-term and long-term conductivity measurements were conducted for 40/70 ceramic proppant under confining pressures up to 9000 psi. The final stage involved post-experiment characterization of the proppant samples and rock slabs. This included particle size distribution analysis and roughness measurements of the sandstone slabs. The experimental process is visually outlined in **Figure 5**.



**Figure 5. Schematic representation of research phases and associated experiments**

## **2.1 Measurement of proppant and rock properties**

Four different types of proppants will be used in this study: 40/70 raw sand, its resin-coated counterpart (RCS 40/70), 40/70 ceramic, and 100-mesh sand. Phenolic resins are cost-effective and provide excellent durability under high-temperature and chemically harsh conditions, making them ideal for hydraulic fracturing. The raw sand is locally sourced from a mine south of Riyadh, Saudi Arabia. RCS 40/70 consists of the same 40/70 raw sand coated with a phenolic resin. Both the 40/70 ceramic and the 100 mesh sand were provided by Schlumberger. Sandstone slabs and steel platens of 7 inches in length, 1.5 inches in width, and 0.35 inches in thickness were used in conductivity experiments (see **Figure 6**).

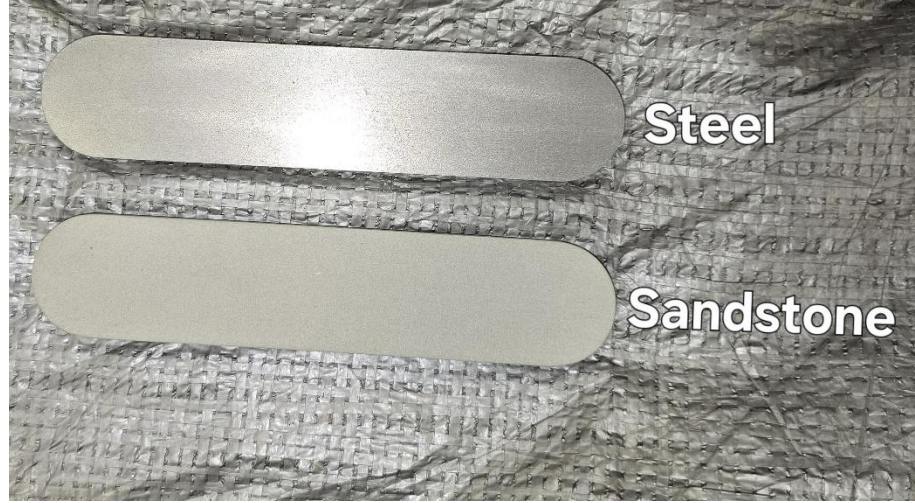


Figure 6. Sandstone slabs and steel platen

### 2.1.1 Bulk density

To determine the bulk density of proppant samples, first, a 100 ml cylinder was placed on a scale and the reading was set to zero. The cylinder was calibrated with distilled water by measuring the weight of water fully filling the cylinder (100 ml). Afterward, the water was discharged and the cylinder was dried. Then, proppant was slowly poured into the cylinder until it was fully filled. A straight edge of a metal piece was passed across the top of the cylinder, in contact with the edge, to level the surface of the proppant.

The bulk density can be determined using the formula below:

$$\rho_{bulk} = \frac{W_{proppant}(g)}{V_{proppant}(cc)} \quad (2)$$

$W_{proppant}(g)$  and  $V_{proppant}(cc)$  are the weight and volume of the proppant, respectively.

### 2.1.2 Particle size distribution analysis

For particle size determination Camsizer X2 device has been utilized (see **Figure 7**). The CAMSIZER X2 utilizes Dynamic Image Analysis (as described in ISO 13322-2) to accurately measure the size and shape of particles in various forms, including powders, granules, and suspensions. This instrument boasts a wide measurement range, capable of analyzing particles from 0.8  $\mu\text{m}$  to 8 mm in size. Employing a high-resolution optical system with an ultrabright LED strobe light and two high-resolution digital cameras, the device analyzes a stream of particles. This system captures over 300 images per second, which are processed in real-time by sophisticated software. This allows the CAMSIZER X2 to quickly and accurately analyze hundreds of thousands in just 1 to 3 minutes.



**Figure 7. Camsizer X2**

### 2.1.3 Sphericity and roundness

Sphericity and roundness have been determined according to the ISO 13503-2 and LEICA S9i digital stereo microscope has been used for this purpose (see **Figure 8**). In this procedure 2g of a proppant sample is placed under the digital stereo microscope and magnified pictures (10x-40x) are captured. Then a minimum of 20 particles are randomly chosen, and their shapes are compared with Krumbein and Sloss chart. For each particle sphericity and roundness are determined and the arithmetic average of recorded sphericity and roundness values are calculated.



**Figure 8. Leica S9i digital stereo microscope**

#### 2.1.4 Crush resistance test

The crush resistance test is used to determine how much fines will be produced for a particular kind of sand under specific stress. For this experiment PCT- Proppant crush tester has been utilized (see **Figure 9**). Proppant was sieved before testing to ensure that every particle falls within the designated size range. For the sieving, Retsch AS 200 sieve shaker has been utilized (see **Figure 10**). For the 40/70 ceramic proppant, the test was conducted from 5000 psi up to 15000 psi in 2500 psi increments. For the 40/70 sand and RCS 40/70 proppants, the test was carried out from 2000 psi to 10000 psi in 2000 psi increments.



**Figure 9. PCT – proppant crush tester**



**Figure 10. Retsch AS 200 sieve shaker**

In order to successfully conduct the crush resistance test following procedures should be followed.

**Procedure:**

- Perform sieve analysis on 80-100g of proppant using only the primary and secondary sieves.
- Discard proppant retained in the upper sieve and pan. Use only the proppant retained in the secondary sieve.
- Find the mass of the sample needed for the crush test using the formula below:

$$m_p = 24.7 \times \rho_{bulk} \quad (3)$$

- Carefully pour the proppant into the cell and place it in the press at the center of the ram.
- Apply the appropriate stress and hold it for 2 minutes.
- Release the stress and take the test cell out of the press.
- Pour the contents of the test cell into the sieve stack used previously and agitate for 10 minutes.
- Weigh the amount of fines retained in the pan ( $m_{pan}$ ) and calculate the percentage of crushed material ( $m'_{pan}$ ) using equation 4.

$$m'_{pan} = \frac{m_{pan}}{total\ mass} \times 100 \quad (4)$$

### 2.1.5 Surface roughness test

Surface roughness of the sandstone slabs was measured with a KRÜSS roughness analyzer (see **Figure 11**). This instrument employs confocal microscopy, an optical method that captures three-dimensional images of objects and surface textures. By utilizing a reflected-light method, the analyzer accurately measures surface roughness without any physical contact with the sample.



**Figure 11. Surface roughness analyzer**

### **2.1.6 XRD analysis**

To determine the mineralogy Malvern Panalytical XRD equipment has been used (see **Figure 12**). Basically, equipment derives mineralogy by exposing a material to incident X-rays and subsequently measuring the scattering angles and intensities of the X-rays emitted from the material.



**Figure 12. Malvern Panalytical XRD equipment**

## **2.2 Proppant pack conductivity measurement**

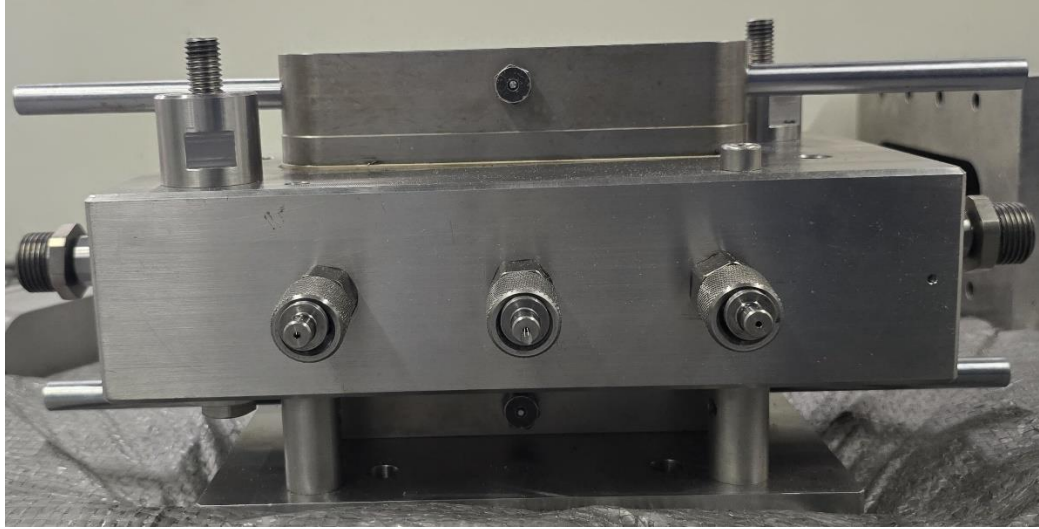
### **2.2.1 Experimental apparatus**

To conduct conductivity experiment PCM1000 – Proppant Conductivity Meter has been used (see **Figure 13**). In this system distilled water was utilized to measure the conductivity. The setup includes a high-pressure injection pump, two accumulators, an inline heater, a conductivity cell, a pack with a measurement system, a hydraulic press, pressure transducers, a back-pressure regulator, and a data acquisition computer station. Another feature of the system is to measure the compaction which is measured by linear variable differential transformers (LVDT). The API conductivity cell is depicted in **Figure 14**. The apparatus consists of three pressure ports, a top and bottom piston, and openings

on the right and left for fluid flow. Proppant pack is sandwiched between two 0.35-inch sandstone slabs or metal sheets depending on objectives of the experiment.

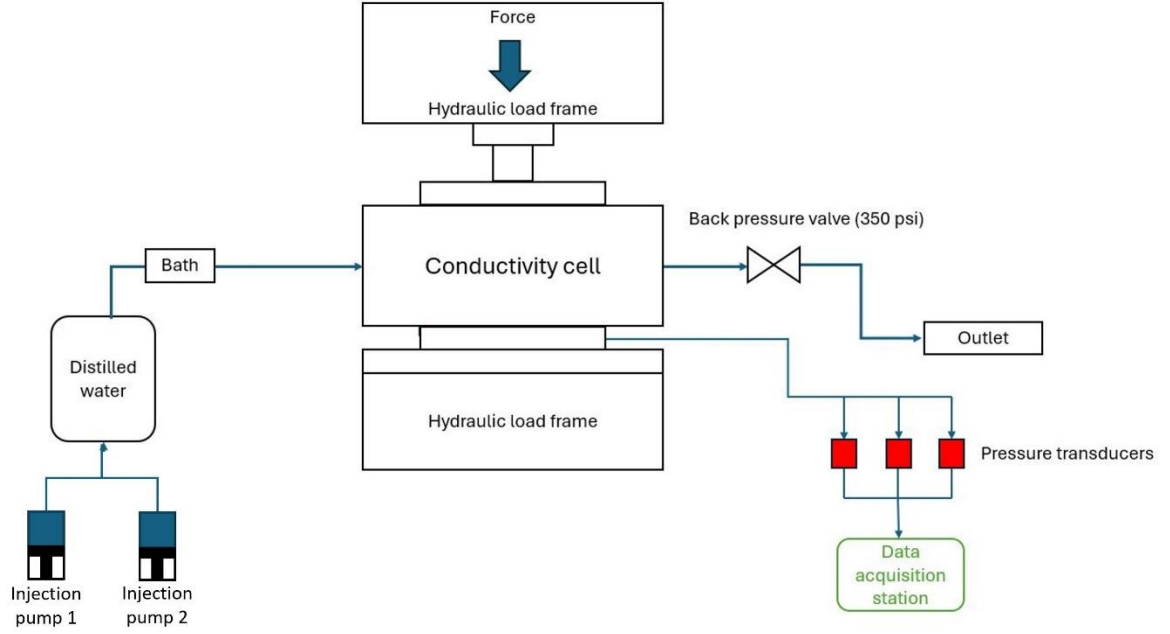


**Figure 13. PCM1000 - Proppant Conductivity Meter**



**Figure 14. API conductivity cell**

The experimental setup, depicted in **Figure 15**, has been designed to determine the conductivity of proppant confined between metal or rock platens. Fluid flow through the system is maintained by two computer-controlled injection pumps in a parallel configuration. Following passage through the conductivity cell, the fluid is collected at the outlet. To create a flow through the conductivity cell, the incoming fluid must overcome a pressure provided by the back-pressure valve that is linked close to the output. Differential pressure transducers, calibrated for a range of 0-9000 mpsi are used to measure the pressure drop across the cell. Additionally, pressure transducers positioned at the center of the cell are used to record cell pressure. Compaction of the proppant pack is recorded by four linear variable differential transformers (LVDTs) with an accuracy of 0.025 mm.



**Figure 15. schematic of proppant pack conductivity measurement apparatus**

The conductivity of the proppant pack was determined using Darcy's law, based on the measured differential pressure and flow rate values (equation 5).

$$C = K_f \cdot w = 3.324 \times 10^9 \times \frac{\mu \cdot q \cdot L}{h \cdot \Delta p} \quad (5)$$

Where:

$K_f$  – fracture permeability (mD)

$w$  – width of the fracture (ft)

$\mu$  – Viscosity of test liquid (Pa·s)

$q$  – flow rate ( $cm^3/s$ )

$L$  – length between pressure ports (cm)

$h$  – test unit width (cm)

$\Delta p$  – pressure difference between pressure ports (Pa)

$C$  – proppant pack conductivity (md-ft)

### 2.2.2 Cell preparation

First, before cell preparation specified amount of the proppant should be prepared. According to ISO 13503-5 2 lb/ft<sup>2</sup> concentration or 6.35 mm thick proppant pack should be used to test the conductivity. In our study 6.35 mm thickness proppant pack was used in all tests. To calculate the amount of proppant needed for 6.35 mm thick pack following equation should be used.

$$M_p = 41 \times \rho \quad (6)$$

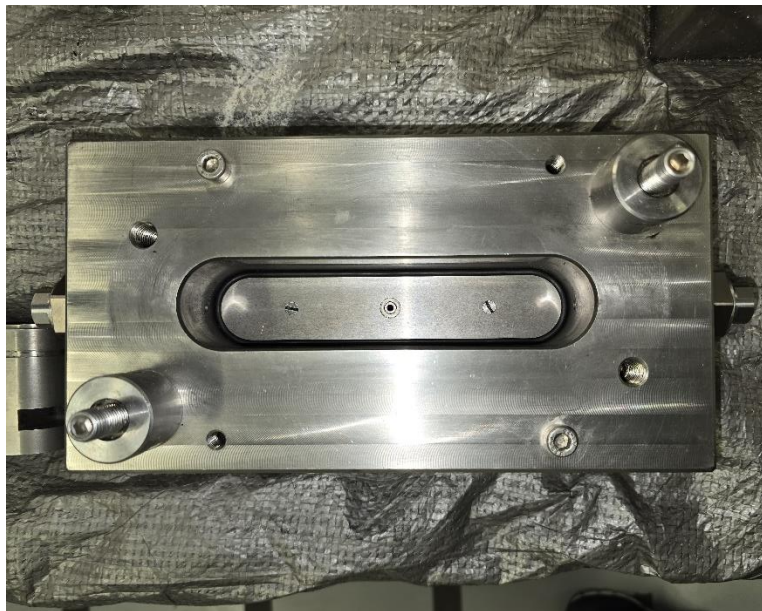
Where  $M_p$  is the mass of proppant and  $\rho$  is the bulk density of the given proppant type. The constant 41 represents the product of the cell surface area (64.52 cm<sup>2</sup>) and the pack thickness (0.635 cm).

1. Position the cell body upside-down. Insert the bottom pusher, attach the bottom plate securely, and return the cell to its upright position.



**Figure 16. Assembled bottom part of API cell**

2. Place an O-ring into the groove between the pusher and the cell body to ensure a proper seal.



**Figure 17. O-Ring placed in groove**

3. Insert the metallic screen in the cell, and apply a small amount of RTV silicone on top of the screen to enhance sealing.



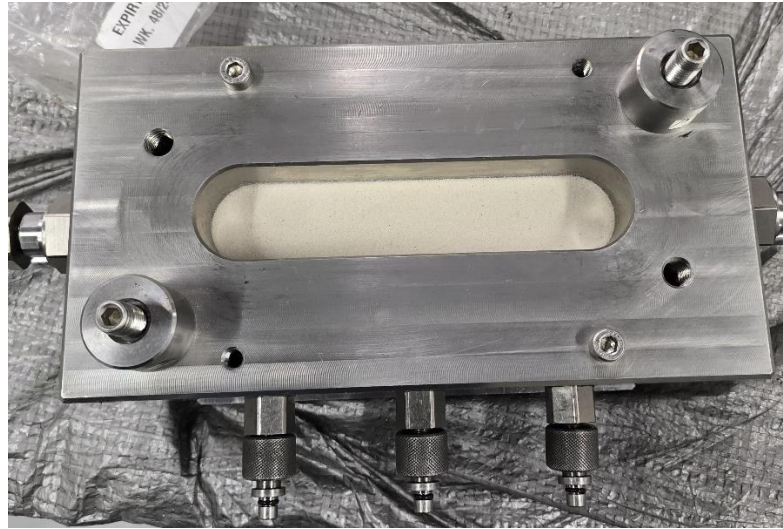
**Figure 18. Metal sheet placed in API cell**

4. Position the API sandstone above the silicone and screen.



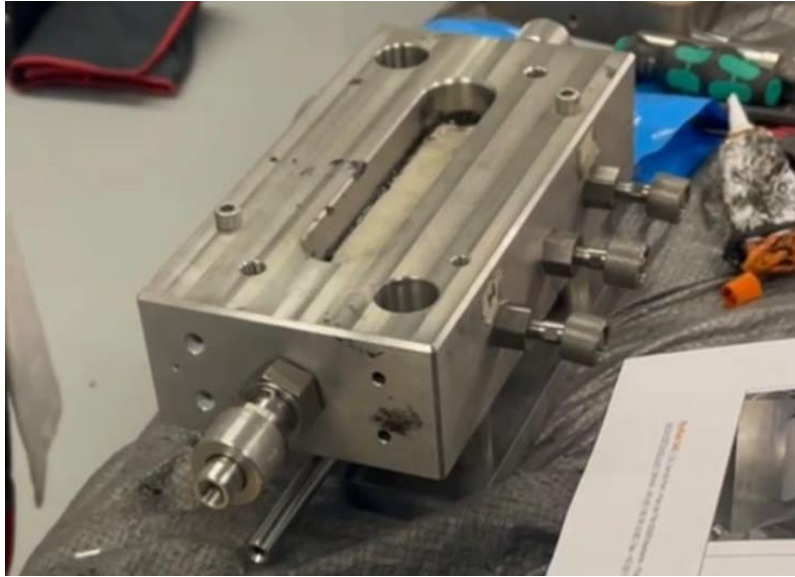
**Figure 19. API Sandstone placed on API cell**

5. Connect three pressure taps and two flow inserts to the API cell
6. Add the proppant in the specified quantity, distributing it evenly across the cell to promote consistent experimental results.



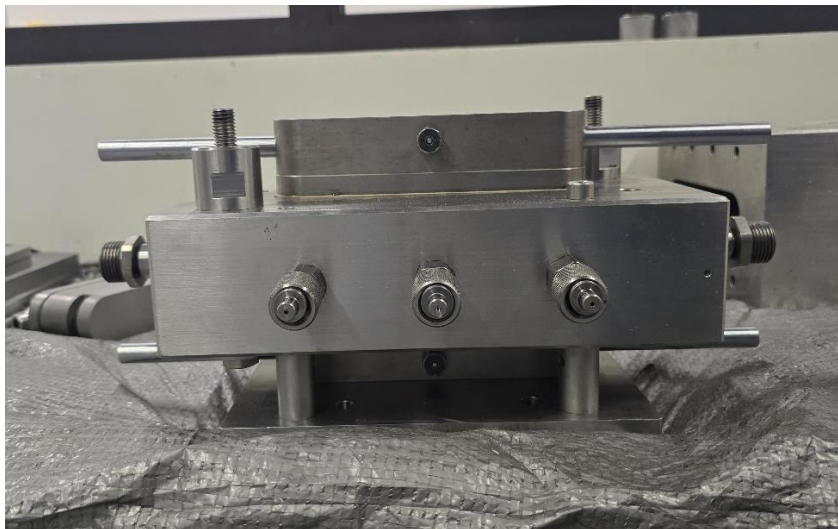
**Figure 20. 40/70 Sand evenly distributed in API cell**

7. Place the top API sandstone and apply a small amount of RTV silicone to seal the slab against the cell walls.



**Figure 21. Top API sandstone placed and RTV silicon applied**

8. Insert the top screen, followed by placing an O-ring above it.
9. Reinsert the top pusher, pressing it firmly by hand to ensure the O-ring is properly seated within the groove.



**Figure 22. Completely Assembled API Cell**

10. Carefully transport the cell using a hydraulic lift cart and position it under the hydraulic press for the experiment.



**Figure 23. API cell placed in PCM-Proppant Conductivity Meter**

### **2.2.3 Short-term proppant pack conductivity experiment**

Each short-term proppant pack conductivity experiment was performed at six static closure stresses, ranging from 1,000 to 6,000 psi in 1,000 psi increments. Moreover, for 100-mesh sand and ceramic 40/70 conductivity experiments were carried out starting from 2,000 psi up to 8,000 psi in 2,000 psi increments, using both sandstone and steel platens. Each stress level was maintained for 30 minutes, after which measurements of two variables, absolute cell pressure and pressure drop, were recorded at five different water flow rates: 1 cm<sup>3</sup>/min, 2 cm<sup>3</sup>/min, 3 cm<sup>3</sup>/min, 4 cm<sup>3</sup>/min, and 5 cm<sup>3</sup>/min. Experiments were performed at room temperature. The step-by-step procedure to measure fracture conductivity is outlined below:

1. After placing the prepared API cell under the hydraulic load frame, connect the flow line to the cell.
2. Place the spacer on top of the top pusher, lower the jack, and wait until it contacts the spacer.
3. Fill the injection pumps with distilled water.
4. Install the LVDT sensors and reset their values to zero.
5. Increase the stress to 1,000 psi.
6. Carefully open the valve of the backpressure regulator until the backpressure reaches 350 psi, then close it.
7. Initiate a flow rate of 6 cm<sup>3</sup>/min until a stable flow through the proppant pack is established, with a visible flow at the outlet. Then, stop the flow.
8. Wait for 30 minutes, then reset the pressure drop values.
9. Start the flow at 1 cm<sup>3</sup>/min and wait approximately 5 minutes for the pressure drop values to stabilize (less than 10 psi/min).
10. Record the pressure drop, cell pressure, and LVDT values.
11. Stop the flow and wait for 10 minutes for the pressure drop values to stabilize. Reset the pressure drop values to zero.
12. Repeat steps 9-11 for flow rates of 2-5 cm<sup>3</sup>/min.
13. Increase the stress in 1,000 psi increments to 2,000-6,000 psi, repeating steps 8-12 at each stress level.
14. After completing the measurements, reduce the stress to 100 psi and simultaneously reduce the cell pressure to 15 psi.
15. Once the pressure reaches 100 psi, remove the jack and terminate the experiment.

Additionally, long-term experiment were conducted using ceramic 40/70 and sandstone slabs. After assembling the cell, the proppant pack was subjected to a stress of 1,000 psi for 12 hours, followed by an increase to 2,000 psi for 50 hours. After 50 hours, the conductivity of the proppant pack was measured at five flow rates: 1-5 cm<sup>3</sup>/min in 1 cm<sup>3</sup>/min increments. The stress was then increased to 4,000 psi and maintained for 50 hours, after which the conductivity was measured again at the same flow rates. This process was continued up to 8,000 psi in 2,000-psi increments and finally to 9,000 psi. This experiment aimed to identify the differences between short-term and long-term conductivity using ceramic 40/70. Moreover, an experiment using steel platens and 40/70 ceramic was carried out up to 9,000 psi to assess the effect of proppant embedment on proppant pack conductivity.

## CHAPTER 3

### RESULTS AND DISCUSSIONS

#### 3.1 Proppant shape

##### 3.1.1 40/70 sand

Compared to the standards for optimal proppant shape the sand 40/70 proppant exhibits moderately high sphericity but relatively low roundness. Measured values indicate a sphericity of 0.77 and a roundness of 0.3, which, while meeting the ISO 13503-2 requirement for sphericity ( $\geq 0.6$ ), falls below the recommended threshold for roundness ( $\geq 0.6$ ). A microscopic image of 40/70 sand proppant illustrates the angular and irregular edges that reduce overall roundness (see **Figure 24**). Based on this irregular shape, the conductivity of 40/70 sand is expected to be lower than that of more rounded proppants, because of higher likelihood of particle interlocking under stress conditions.

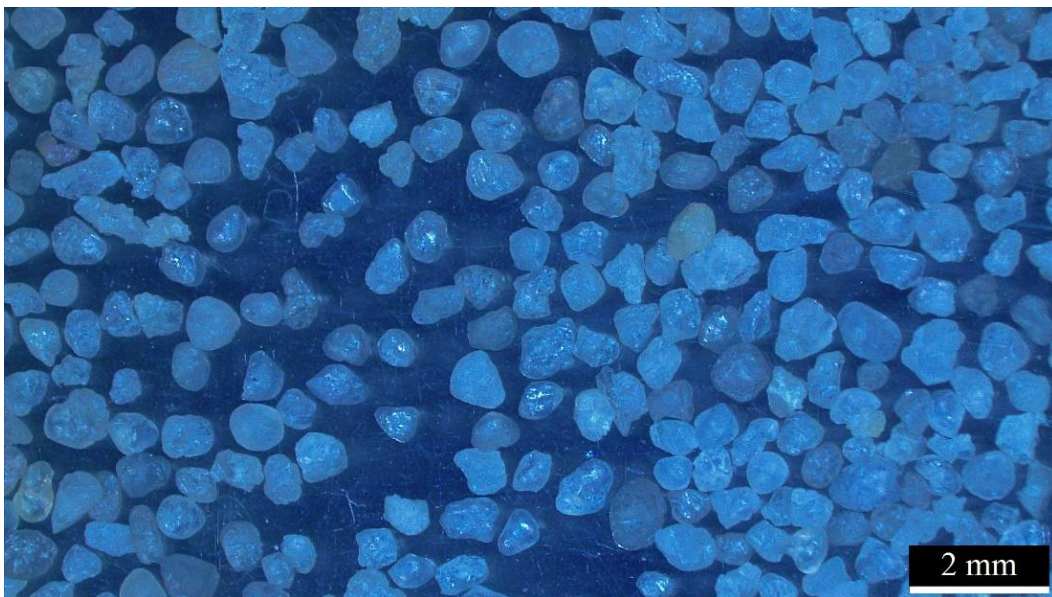
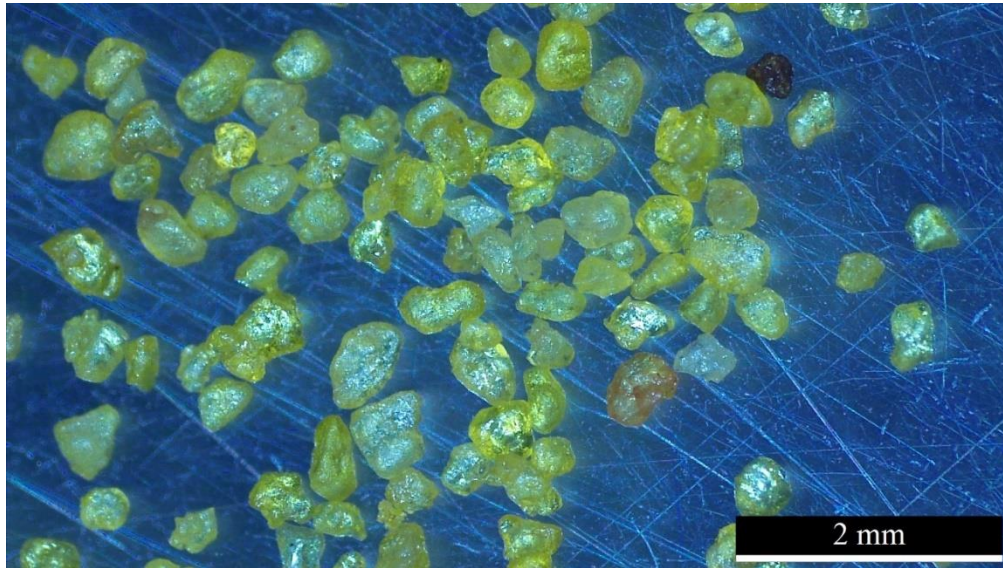


Figure 24. 40/70 Sand under Microscope at 20x Magnification

### 3.1.2 40/70 RCS

Compared to 40/70 sand its resin coated form resulted in the increase of the sphericity from 0.77 to 0.82. However, roundness wasn't to be changed and remain almost the same which is below the ISO 13503-2 recommended minimum for roundness (see **Figure 25**).



**Figure 25. 40/70 RCS under Microscope at 20x Magnification**

### 3.1.3 40/70 ceramic

40/70 Ceramic, with sphericity and roundness both measured at 0.9, indicates a highly spherical and rounded particle shape (see **Figure 26**). With values of 0.9, this ceramic proppant exhibits a near-ideal spherical shape, which helps in providing uniform and stable packing in hydraulic fractures, leading to enhanced conductivity under stress conditions.

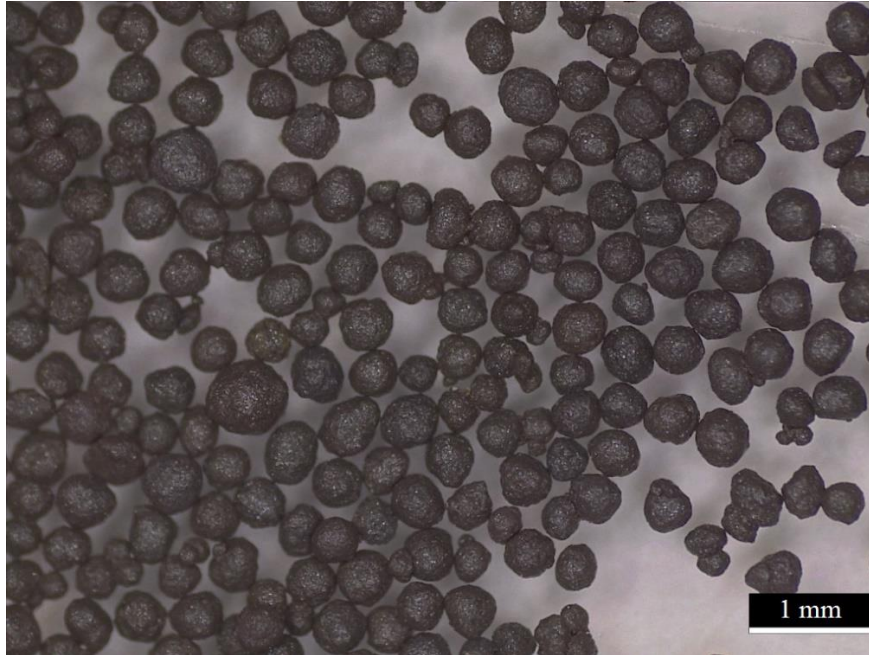


Figure 26. 40/70 Ceramic under Microscope at 20x Magnification

### 3.1.4 100-mesh sand

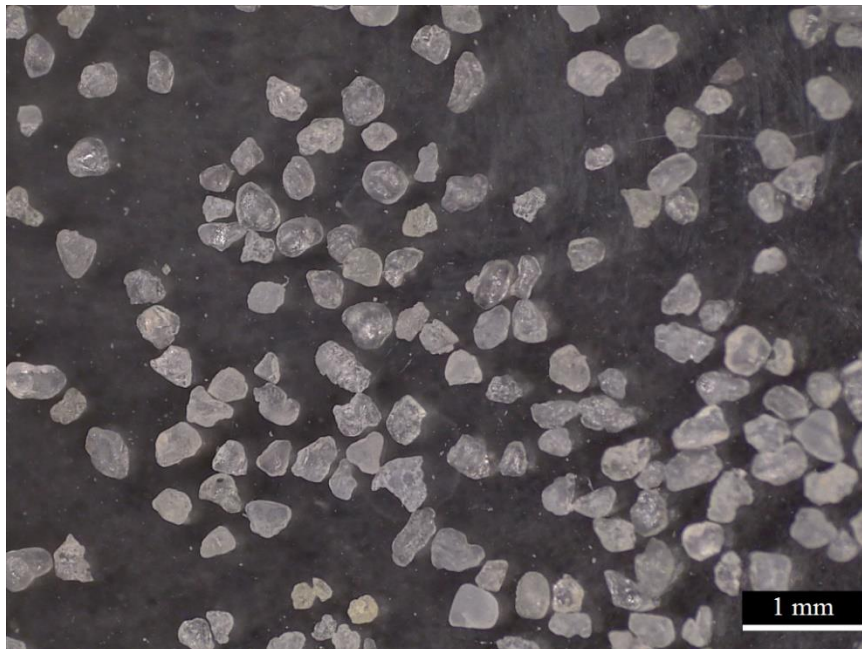


Figure 27. 100-mesh sand under Microscope at 20x Magnification

**Figure 27** illustrates 100-mesh sand under 20x magnification with a sphericity of 0.85 and a roundness of approximately 0.3. **Table 1** summarizes bulk density, sphericity and roundness of the proppants.

**Table 1. Bulk density, sphericity and roundness of the proppants used in the study**

| Proppant      | Bulk density<br>(g/cm <sup>3</sup> ) | Sphericity | Roundness |
|---------------|--------------------------------------|------------|-----------|
| 40/70 ceramic | 2.35                                 | 0.9        | 0.9       |
| 40/70 sand    | 1.652                                | 0.77       | 0.3       |
| 40/70 RCS     | 1.6                                  | 0.82       | 0.3       |
| 100-mesh sand | 1.65                                 | 0.85       | 0.3       |

### 3.2 XRD analysis

The 40/70 ceramic proppant primarily consists 71.3 % of mullite (aluminum chromium silicon oxide), with silicon oxide (28.3%) and 0.4% of eucryptite (lithium aluminum silicate). Mullite is typically formed in ceramics during high-temperature processes and contributes to the proppant's durability under stress. Lithium aluminum silicate, might indicate minor additives or impurities. Eucryptite can influence thermal expansion properties. XRD analysis of 40/70 sand and 40/70 RCS indicated that they are entirely composed of highly crystalline silicon dioxide (SiO<sub>2</sub>). The resin coating is not crystalline and therefore does not produce peaks in the XRD pattern. Instead, the resin is likely an amorphous layer applied to the quartz grains, which does not alter the crystalline signature of the quartz core.

### 3.3 Crush resistance

The 40/70 sand exhibited a relatively high crush rate, particularly at elevated stress levels. As shown in **Figure 28**, 40/70 sand produced 11.1% crushed material at 3,000 psi, which

increased significantly to 46.8% at 10,000 psi. This fragmentation reduces the proppant pack's porosity and conductivity as the sand's structural integrity deteriorates, leading to pore throat blockage. In contrast, 40/70 RCS demonstrated a dramatic improvement in crush resistance. It produced only 0.61% crushed material at 3,000 psi and 4.7% at 10,000 psi, showcasing its enhanced durability compared to uncoated 40/70 sand. The resin coating effectively encapsulates fragmented sand particles, enhances stress distribution across the proppant grains, and increases stress tolerance of the proppant, thereby preserving the porosity of the proppant pack and maintaining higher conductivity under stress. 40/70 ceramic proppant demonstrates excellent crush resistance, outperforming all other proppant samples used in this study. It exhibits a crushing rate of only 2.8% at a high pressure of 15,000 psi. This low crushing rate underscores its remarkable durability and suitability for maintaining fracture conductivity under elevated stress conditions, making it a superior choice for high-stress hydraulic fracturing applications.

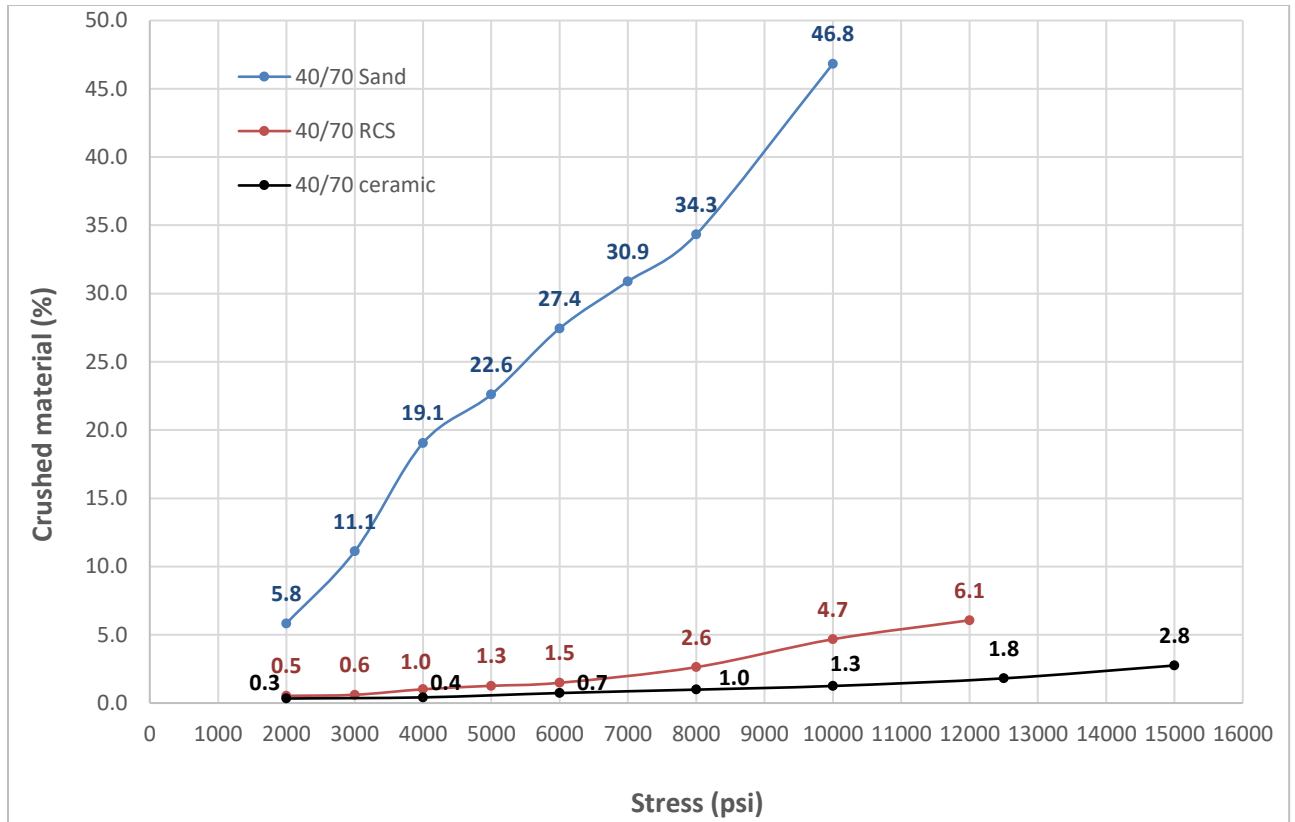


Figure 28. Crush resistance of 40/70 sand, 40/70 ceramic and 40/70 RCS

### 3.4 Short-term conductivity up to 6000 psi

#### 3.4.1 Pure proppant conductivity

**Figure 29** illustrates that 40/70 ceramic proppant demonstrated the highest conductivity across all stress levels (1000 to 6000 psi), with minimal reduction as stress increased. This excellent performance is attributed to its high crush resistance, inherent strength, and structural integrity, as well as its higher sphericity and roundness. 40/70 sand exhibited lower conductivity values across the range of applied stresses (1000 to 6000 psi), particularly after 3000 psi where conductivity dropped by 86% at 170 md-ft. The conductivity performance of 40/70 sand proppant aligns with typical expectations based

on particle size and structure. At low closure stresses (1000 psi), 40/70 sand demonstrated moderate conductivity; however, conductivity diminished as stress increased, particularly above 3000 psi.

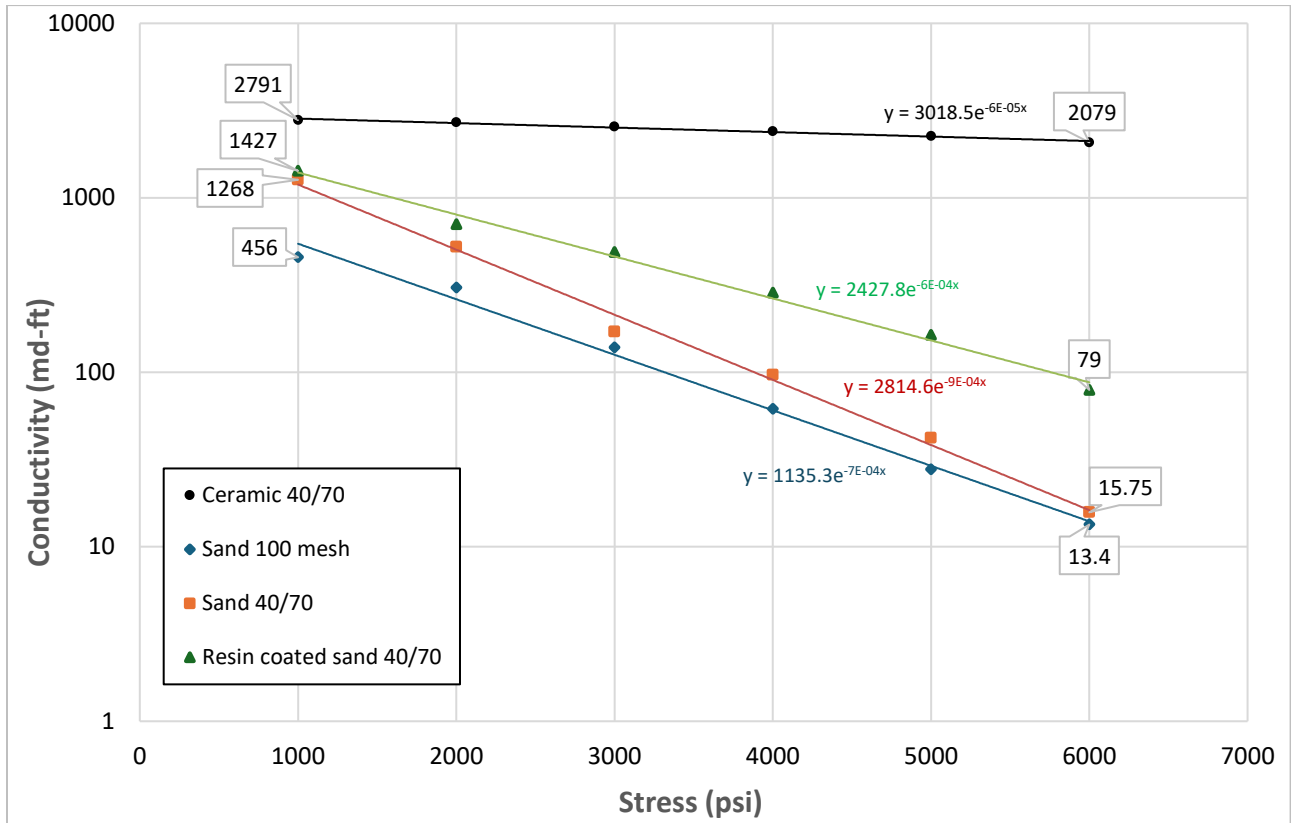


Figure 29. Baseline conductivities of pure proppants

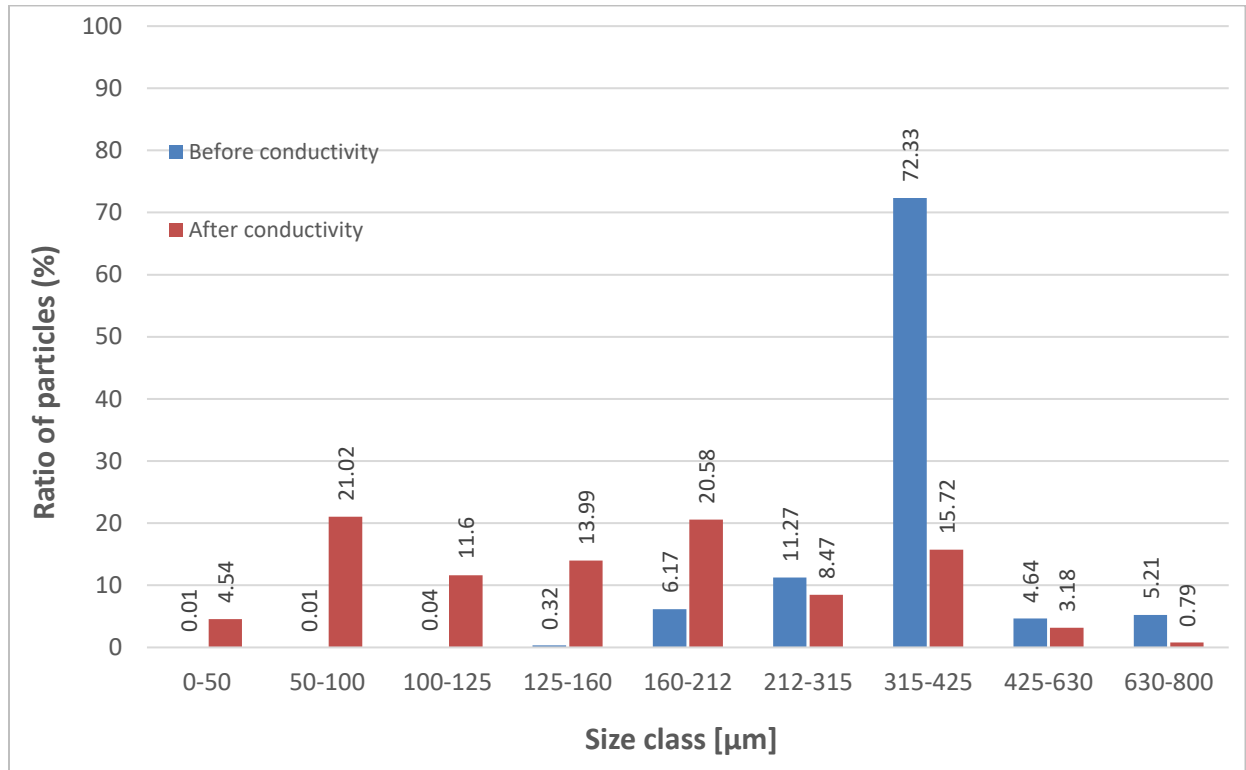
This decline is attributed to particle crushing, as 40/70 sand exhibited a high crush rate under stress. The increase in fine particles from crushing limits conductivity, reflecting the sand's lower mechanical strength at high stresses. In contrast, 100-mesh sand exhibited initial conductivity of 456 md-ft at 1000 psi, which steadily declined with increasing stress due to gradual crushing and compaction. This behavior aligns with the typical performance of finer sands. Comparing 40/70 sand with 100-mesh sand, it is evident that the smaller particle size of 100-mesh sand resulted in lower initial conductivity. However, 100-mesh

sand maintained its conductivity more effectively at higher stress levels due to its lower crush rate. Interestingly, 40/70 RCS exhibited significantly improved conductivity compared to uncoated 40/70 sand. Coating the 40/70 sand with phenolic resin resulted in a fivefold improvement in conductivity at 6000 psi. This improvement is due to the fact that fines generated because of the sand crushing remained within the coating and do not plug the pores. Moreover, coating resulted in more uniform distribution of stress which lead to higher stress tolerance of the proppant. This finding highlights the potential of resin coating as a cost-effective method to improve the performance of sand proppants. Overall, the results emphasize the significant impact of proppant type and properties on conductivity under stress, with 40/70 ceramic emerging as the superior proppant due to its high conductivity and excellent crush resistance.

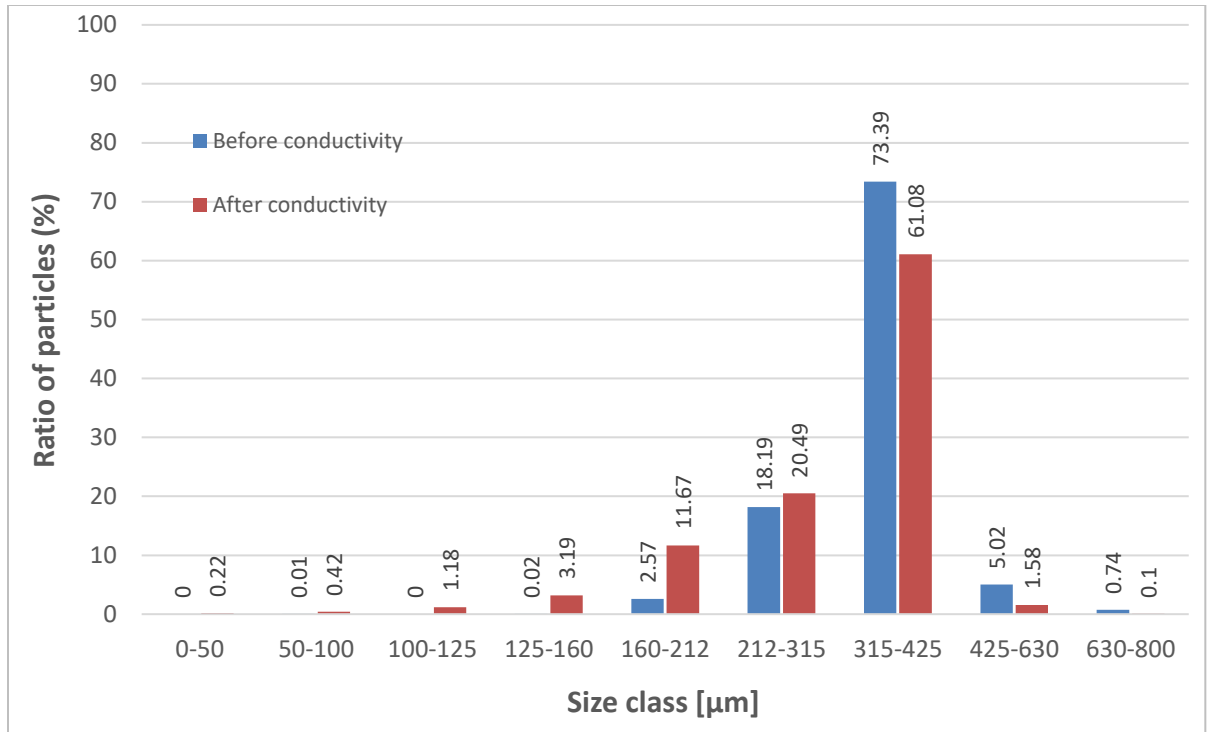
### **3.4.2 Particle size distribution**

The 40/70 sand generated the highest quantity of fines among all tested proppants. **Figure 30** illustrates the particle size distribution of 40/70 sand both pre- and post-conductivity experiment, conducted under a stress of 6000 psi with steel platens. Post-experiment, 40/70 sand yielded 65.18% fines smaller than 212 microns. The 315–425  $\mu\text{m}$  size class is dominant before the experiment, with a ratio of 72.33%, which decreases significantly to 15.72% after the experiment, indicating substantial particle breakdown. This observation aligns with the increased crushing rate recorded in the crushing test, signifying substantial proppant degradation. For 40/70 RCS, the 315–425  $\mu\text{m}$  size class accounted for 73.39% of the particles before conductivity, which decreased to 61.08% after the experiment (see **Figure 31**). The 40/70 RCS produced 14.08% fines below 212 microns. This represents a significant improvement compared to 40/70 sand, producing 51.1% fewer fines below 212

microns. This enhanced performance can be attributed to the encapsulation of crushed material, increased stress tolerance of the proppant, and a more uniform distribution of stress across the particles.



**Figure 30. Particle size distribution of 40/70 sand before and after conductivity experiment**



**Figure 31. Particle size distribution of 40/70 RCS before and after conductivity experiment**

After short-term conductivity experiment up to 6000 psi closure stress 100-mesh sand produced 25.07% fines (see **Figure 32**). The 50–100 μm size class rose from 0.39% to 12.19% while the 100–149 μm size class rose from 10% to 20.68%. The 0–50 μm class saw a modest increase from 0.44% to 3.03%.

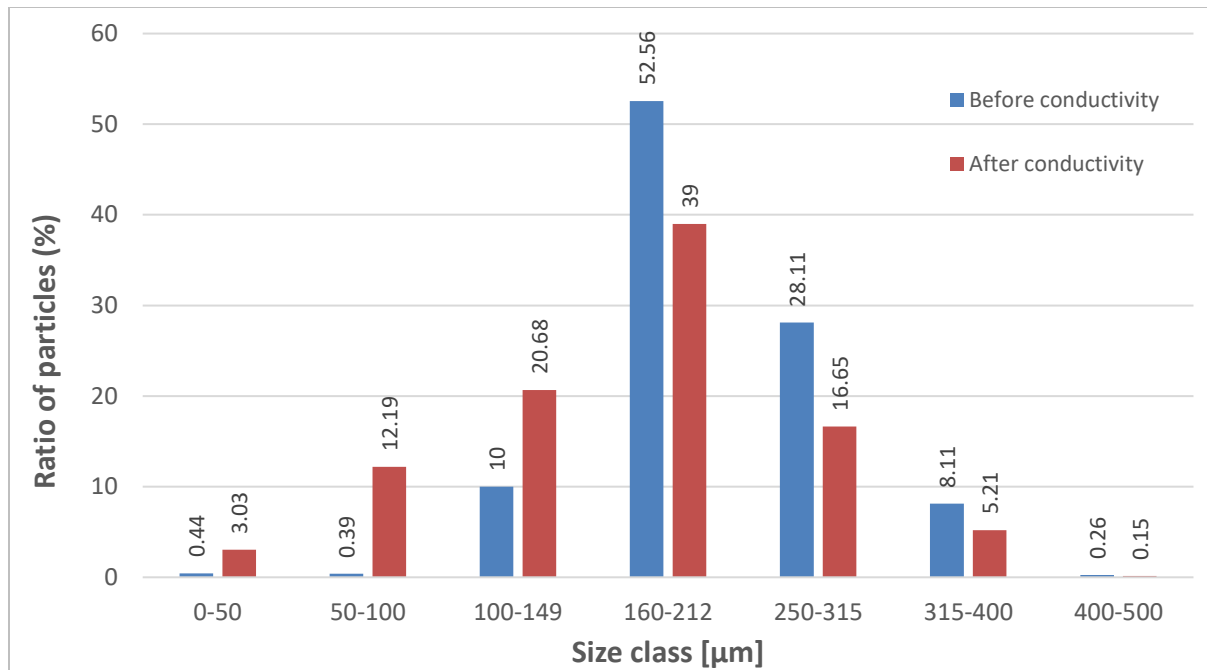


Figure 32. Particle size distribution of 100-mesh sand before and after conductivity experiment

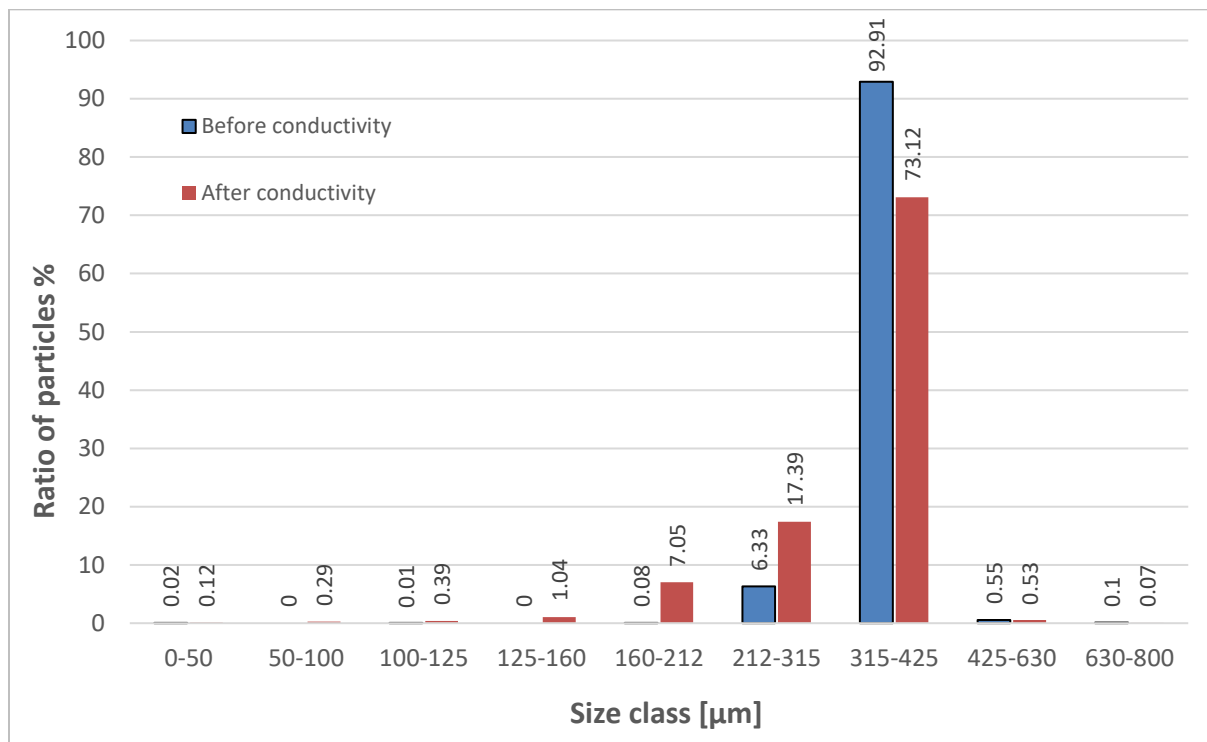
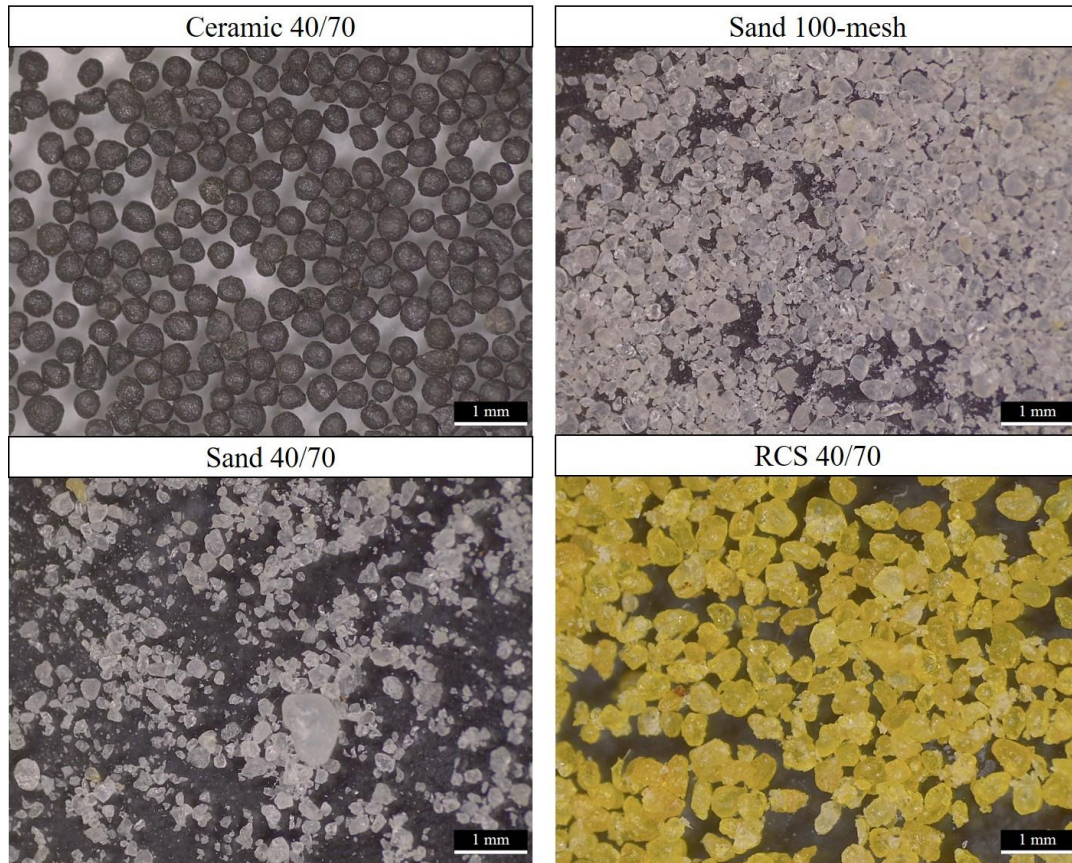


Figure 33. Particle size distribution of 40/70 ceramic before and after conductivity experiment

40/70 ceramic produced the least number of fines (8.78%) below 212 microns (see **Figure 33**). Before the conductivity experiment the 315–425  $\mu\text{m}$  dominated with 92.91% of the particles while after the experiment it decreased to 73.12%. **Figure 34** illustrates the 20x magnified images of proppant samples after a short-term conductivity experiment under 6000 psi. 40/70 ceramic proppants mostly remain intact, retaining their original shape and structure. In contrast, the 40/70 sand particles exhibit significant crushing, breaking into smaller fragments that fill the pore spaces within the proppant mixture. The 100-mesh sand also shows noticeable crushing, though less severe compared to 40/70 sand. 40/70 RCS exhibits moderate crushing, with some particles breaking into smaller pieces, while still maintaining a portion of their original structure.



**Figure 34. Proppant samples following short-term conductivity testing under closure stresses of up to 6000 psi**

### 3.4.3 Proppant mixture conductivity

The mixture of 40/70 sand and 40/70 ceramic in a 3:1 weight ratio resulted in 1.34 -1.56 times conductivity enhancement compared to pure sand 40/70 (see **Figure 35**). This enhancement is due to the addition of 25 percentage by weight (wt%) of 40/70 ceramic. This specific proportion was chosen to balance the cost-effectiveness of using raw sand with the improved mechanical strength and conductivity performance provided by the ceramic proppant. However, these conductivity values remain significantly lower than those of pure 40/70 ceramic. This discrepancy arises because, beyond 3000 psi, most of the 40/70 sand particles are crushed, generating smaller particles that block pore spaces and thereby reduce overall conductivity. Similarly, the mixture of 100-mesh sand and 40/70 ceramic (3:1) also exhibits higher conductivity than pure sand 100 mesh across all stress levels. However, the conductivity of sand 100 mesh improved by 1.55 – 3.13 times (see **Figure 36**). The inclusion of 40/70 ceramic improves the crush resistance of the finer sand, resulting in enhanced conductivity.

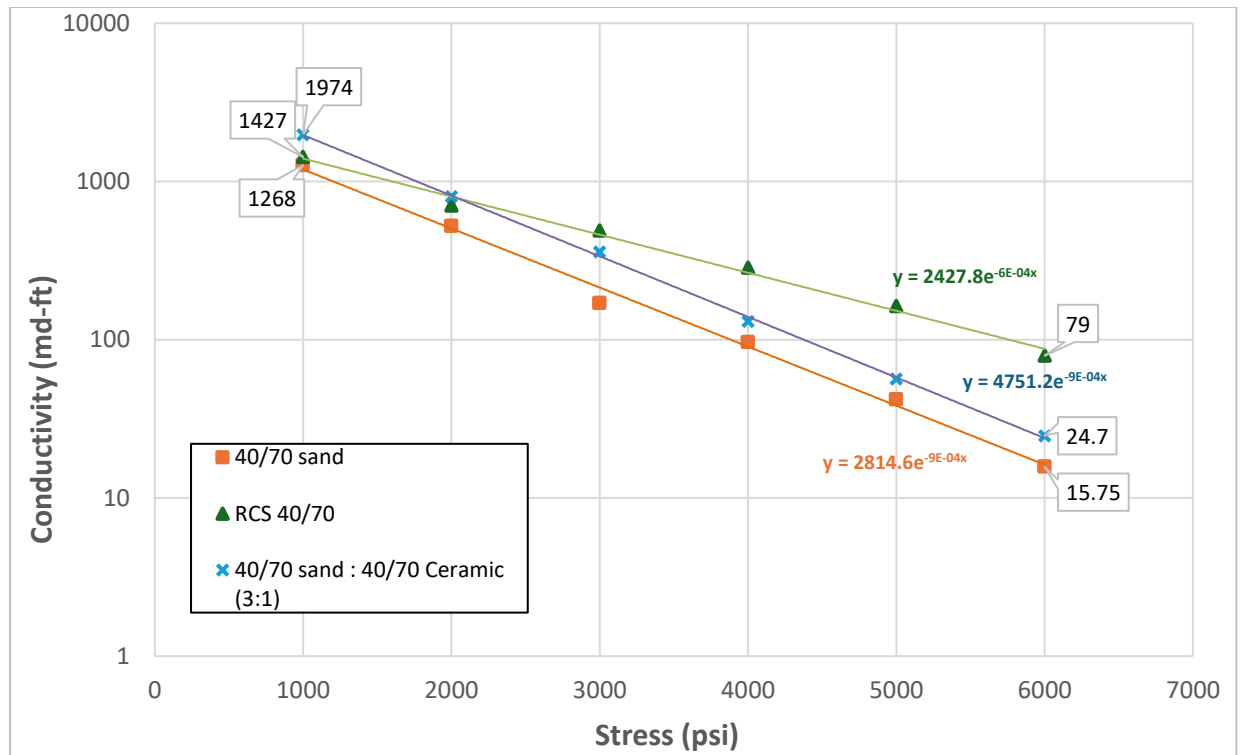
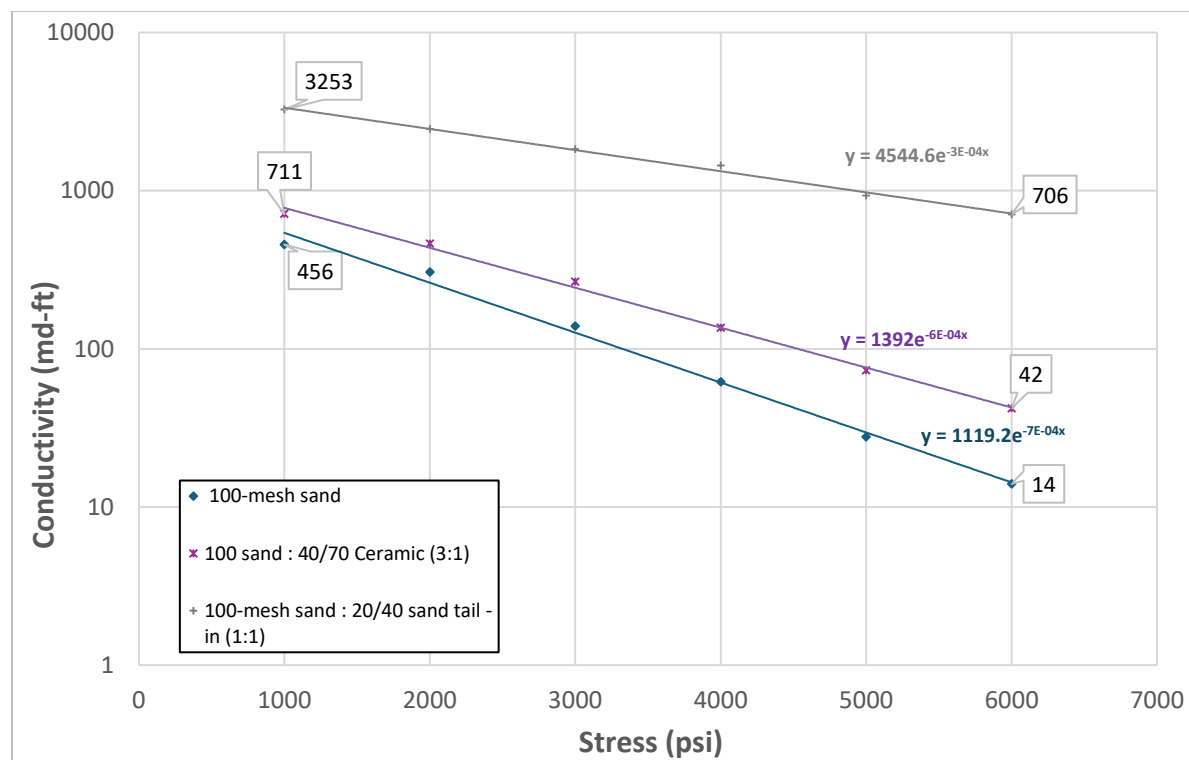


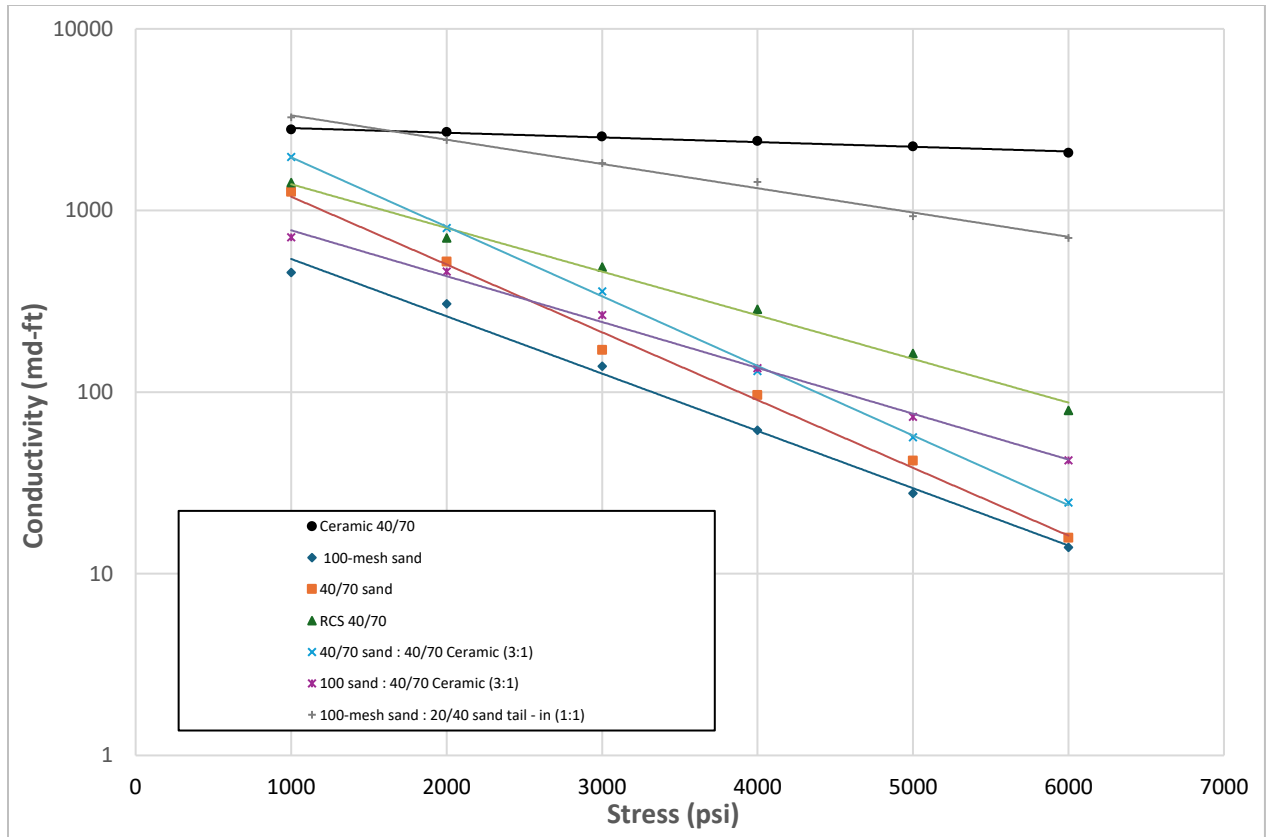
Figure 35. Conductivity of 40/70 sand, 40/70 RCS and mixture of 40/70 sand: 40/70 ceramic (3:1)

Comparing the two mixtures, the blend of 40/70 sand and 40/70 ceramic demonstrates slightly higher conductivity than the mixture of 100-mesh sand and 40/70 ceramic until 3000 psi. This difference can be attributed to the larger particle size of 40/70 sand, which provides better flow paths for fluids even with the same proportion of ceramic proppant added. However, due to poor crust resistance, low values of roundness and excessive fine generation under stress more than 3000 psi its conductivity became less than of 100-mesh sand. The conductivity values of 100-mesh sand are higher in comparison to 40/70 sand after 3000 psi due to the fact that 100-mesh sand produces less fines than 40/70 sand. This is evident from particle size distribution analysis of both sands after conductivity experiments. 100 mesh sand produced 26.13% fines less than 160  $\mu\text{m}$  while 40/70 sand produced 42.3%. In contrast to the mixtures with ceramic proppant, the tail-in mixture of

100-mesh sand and 20/40 sand, with 50 wt% of each sand at opposite ends, demonstrates the highest conductivity among all the combinations. The conductivity of tail-in design was 3253 md-ft at 1000 psi and 706 md-ft at 6000 psi. This behavior is attributed to tail-in design, bigger particle size of 20/40 sand and high strength of both proppants. The varying particle sizes in this arrangement likely create a more complex proppant pack, potentially leading to better packing and higher permeability.



**Figure 36. Conductivity of 100-mesh sand, mixture of 100-mesh sand : ceramic 40/70 (3:1) and tail-in design of 100-mesh sand and 20/40 sand (1:1)**



**Figure 37. Short- term proppant pack conductivity for all tested samples up-to 6000 psi using steel platens**

**Figure 37** presents the short-term conductivity results for seven proppant samples tested under stress levels ranging from 1,000 to 6,000 psi. The ceramic 40/70 proppant demonstrates the highest conductivity and minimal reduction across all stress levels, reflecting its superior crush resistance and structural integrity. In contrast, the 40/70 sand and 100-mesh sand show significant declines in conductivity with increasing stress due to particle crushing and fines generation. Resin-coated sand (RCS 40/70) and proppant mixtures (40/70 sand with ceramic 40/70 in a 3:1 ratio) exhibit improved performance compared to uncoated sand but remain inferior to pure ceramic 40/70. The tail-in design of 100-mesh sand and 20/40 sand shows relatively consistent conductivity, benefiting from

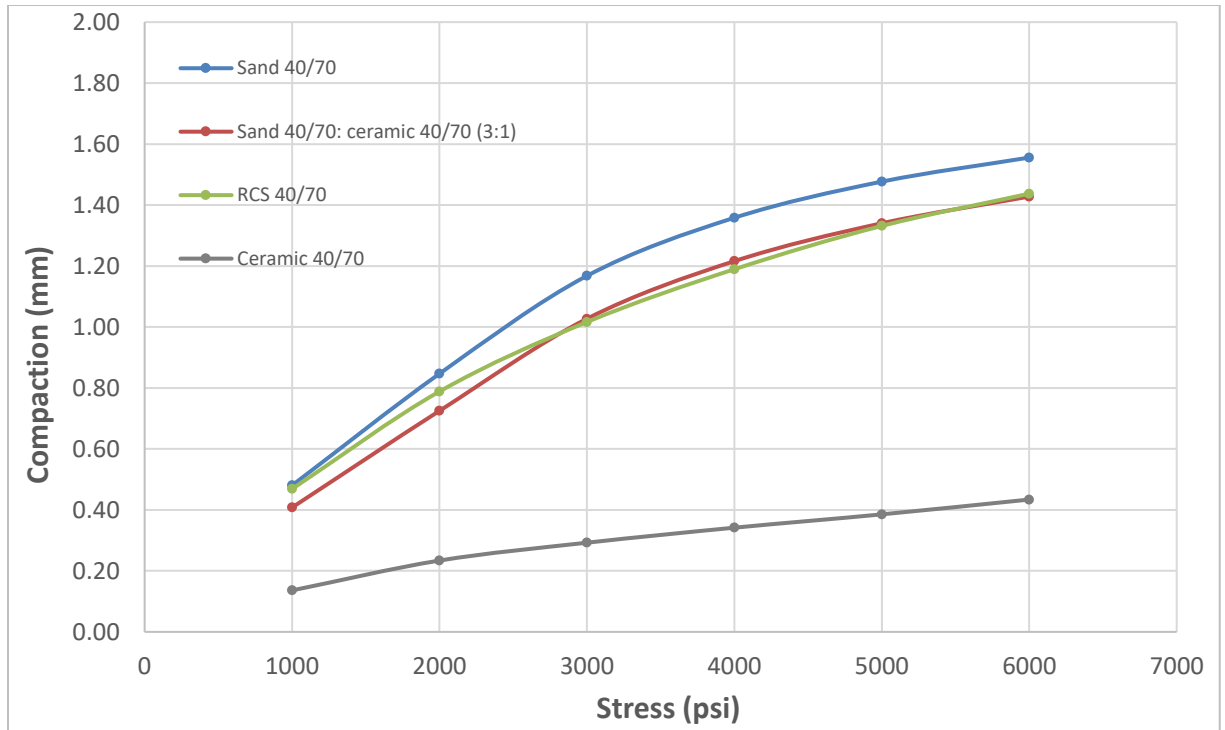
its blend of larger particle sizes. **Table 2** illustrates average conductivity values of all short-term conductivity experiments using steel platens up to 6000 psi closure stress.

**Table 2. Average short-term conductivity values up to 6000 psi closure stress**

| Proppant       | Pure proppant        |            |           |               | proppant mixture                |                                    |                                      |
|----------------|----------------------|------------|-----------|---------------|---------------------------------|------------------------------------|--------------------------------------|
|                | 40/70 ceramic        | 40/70 sand | 40/70 RCS | 100-mesh sand | 40/70 sand :40/70 ceramic (3:1) | 100-mesh sand :40/70 ceramic (3:1) | 100-mesh sand : 20/40 sand (tail-in) |
| Closure stress | Conductivity (md-ft) |            |           |               |                                 |                                    |                                      |
| 1000           | 2791                 | 1268       | 1427      | 456.4         | 1974.0                          | 711                                | 3253                                 |
| 2000           | 2704                 | 523        | 706       | 305.8         | 802.0                           | 462                                | 2446                                 |
| 3000           | 2554                 | 170.5      | 489       | 138.8         | 358.8                           | 266                                | 1824                                 |
| 4000           | 2410                 | 96.5       | 285.9     | 61.7          | 130.7                           | 135                                | 1438                                 |
| 5000           | 2254                 | 42         | 163.3     | 27.8          | 56.4                            | 73                                 | 930                                  |
| 6000           | 2079                 | 15.75      | 79.2      | 14.0          | 24.7                            | 42                                 | 706                                  |

### 3.4.4 Proppant compaction

During the conductivity experiment, the 40/70 sand exhibited significant compaction, measuring 1.56 millimeters at 6,000 psi (see **Figure 38**). The mixture of 40/70 sand and 40/70 ceramic proppants (3:1 ratio) compacted to 1.43 millimeters, while resin-coated sand (RCS) 40/70 compacted 1.44 millimeters. This compaction is not solely attributed to the deformation or fragmentation of proppant grains. Instead, it results from a cumulative effect that includes rock compression, proppant grain compaction, proppant fragmentation, and proppant embedment.



**Figure 38. Compaction of 40/70 sand, 40/70 RCS, 40/70 ceramic and mixture of 40/70 sand : 40/70 ceramic (3:1)**

**Figure 39** illustrates the compaction behavior of 100-mesh sand, the mixture of 100-mesh sand and 40/70 ceramic proppants (3:1 ratio), and tail-in design comprising 100-mesh sand and 20/40 sand. Among all tested proppant mixtures, the tail-in design exhibited the highest compaction under a closure stress of 6,000 psi. This is primarily because the portion of the proppant pack containing 20/40 sand underwent greater compaction due to its larger particle size.

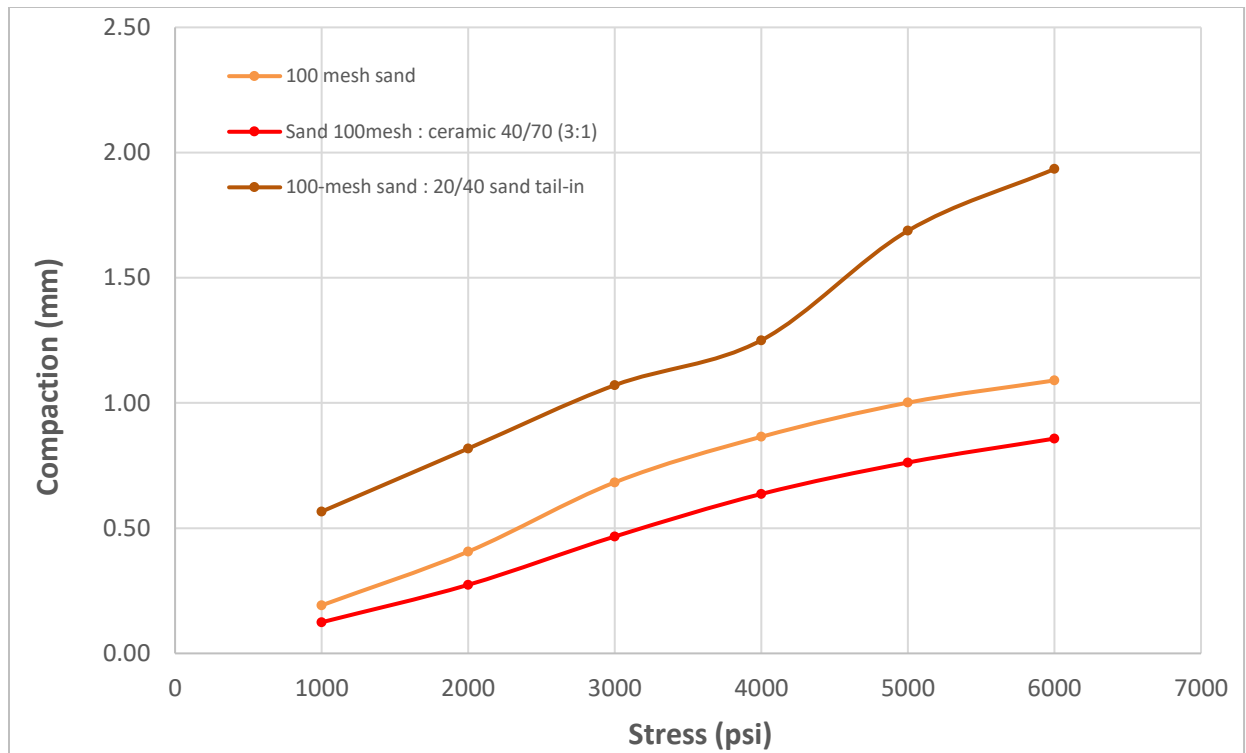


Figure 39. Compaction of 100-mesh sand, mixture of 100-mesh sand: 40/70 ceramic (3:1) and 100-mesh sand : 20/40 sand (tail-in)

### 3.5 Short-term conductivity using steel vs sandstone

The short-term conductivity testing for the 40/70 ceramic proppant revealed distinct trends based on the type of platen material—steel and sandstone—under identical stress levels (see **Figure 40**). At low stress levels (2000 psi), the conductivity for sandstone platens (2858 md-ft) was slightly higher than that for steel platens (2723 md-ft), with a difference of 135.82 md-ft. This indicates that the sandstone interface is initially more conducive to conductivity, likely due to better compatibility with the proppant's surface texture or geometry. At moderate to high stress levels (4000–9000 psi), the trend reverses, with steel platens consistently demonstrating higher conductivity than sandstone. For example, at 9000 psi, the conductivity for steel platens was 1487 md-ft compared to 337 md-ft for

sandstone. This sharper decline in conductivity for sandstone is primarily attributed to proppant embedment into the sandstone surface, which reduces the thickness of the proppant pack and impedes fluid flow. The ceramic proppant, known for its low crushing rate under high stresses, maintains its conductivity well on steel platens, exhibiting only a gradual decline in conductivity up to 9000 psi. However, the hardness of the ceramic proppant causes it to embed into the softer sandstone rock under high stress, leading to a significant reduction in conductivity due to decreased pack thickness.

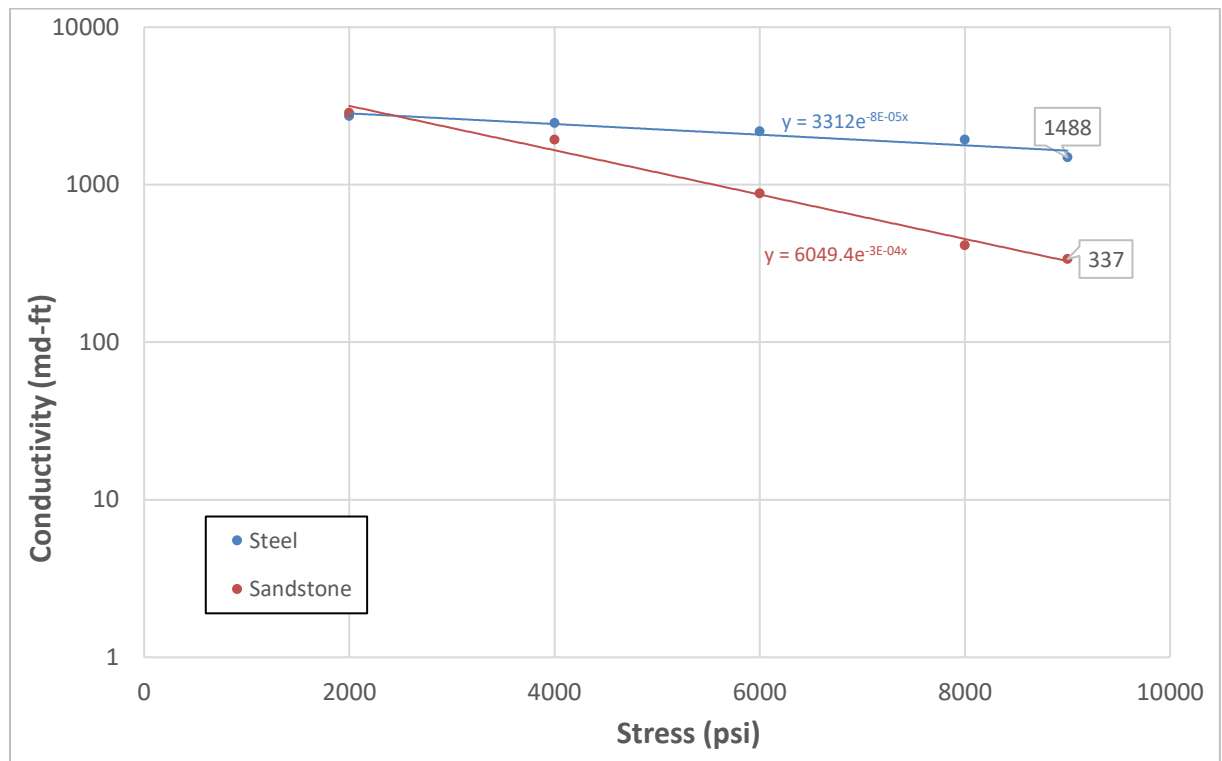


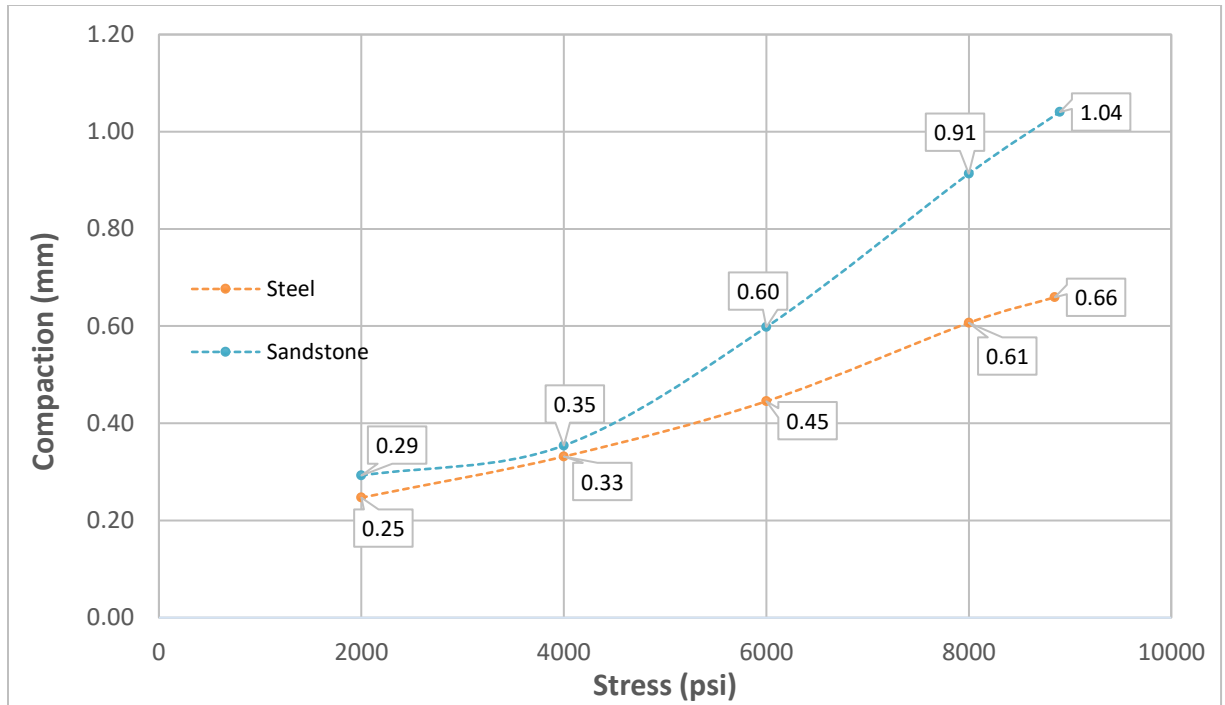
Figure 40. Conductivity of 40/70 ceramic proppant: steel platens vs. Sandstone slabs

**Table 3** summarize the short-term and long-term conductivity values of 40/70 ceramic proppant pack between sandstone slabs.

**Table 3. Average conductivity values of 40/70 ceramic between sandstone slabs and steel platens**

| Rock type      | Sandstone            | Steel  |
|----------------|----------------------|--------|
| Closure stress | conductivity (md-ft) |        |
| 2000           | 2858.9               | 2723.0 |
| 4000           | 1924.9               | 2455.7 |
| 6000           | 879.5                | 2175.8 |
| 8000           | 410.8                | 1929.1 |
| 9000           | 337.3                | 1487.8 |

**Figure 41** illustrates the compaction of a proppant pack during conductivity experiments conducted with steel and sandstone platens. The results show that compaction was 0.38 millimeters greater in experiments using sandstone slabs compared to steel platens. As evident from **Figure 41**, the compaction values begin to deviate significantly starting at 4000 psi and continue to diverge up to 9000 psi. This observation suggests that the effect of proppant embedment becomes more pronounced at stress levels exceeding 4000 psi. This behavior is further supported by **Figure 40**, which shows a similar divergence in conductivity values between sandstone slabs and steel platens at stress levels above 4000 psi. The observed 0.38-millimeter difference in compaction is attributed to a combination of proppant embedment and rock matrix compression.

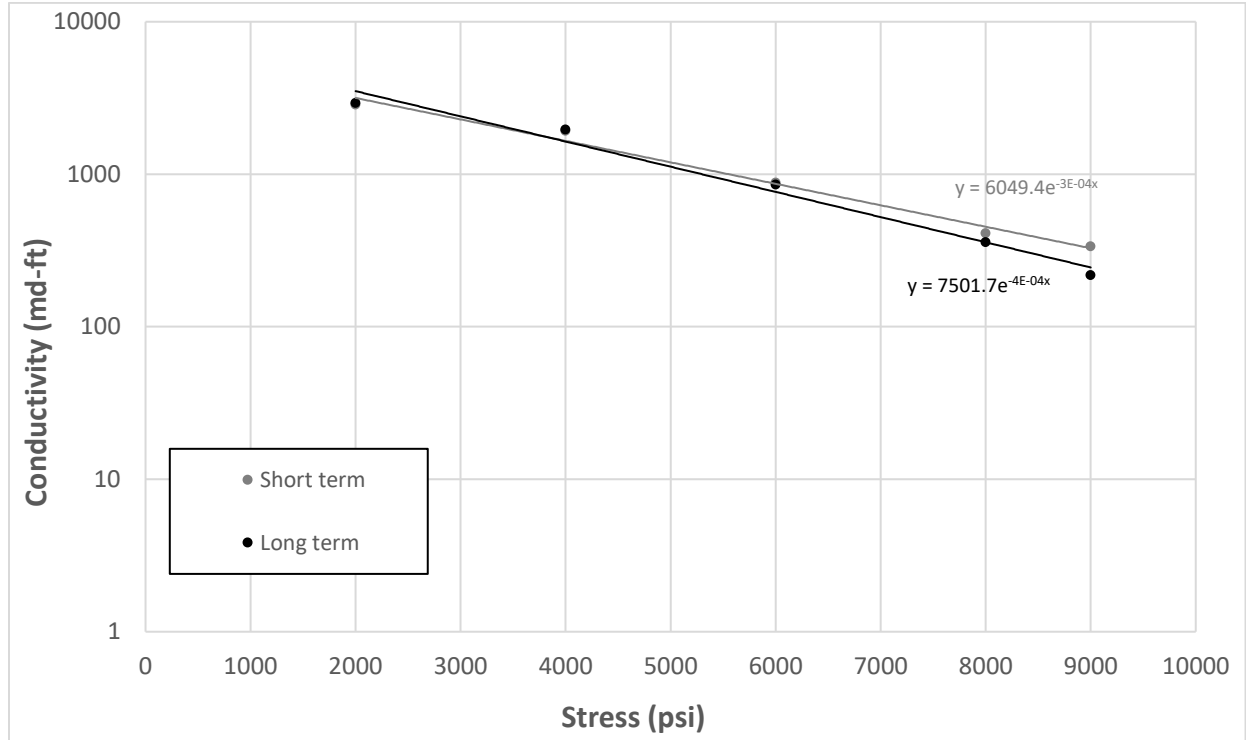


**Figure 41. Compaction behavior of the 40/70 ceramic proppant pack: steel platens vs. sandstone slabs**

### 3.6 Short-term vs long-term conductivity

The long-term conductivity tests, conducted with sandstone slabs under extended stress durations (50 hours) using 40/70 ceramic proppant. Across all stress levels, the conductivity showed only marginal reductions after 50 hours of sustained stress (see **Figure 42**). Up to 6000 psi conductivity are almost in the same level. At higher stress levels, the differences were still minimal, with conductivity being 1.15 times higher with steel platens at 8000 psi and 1.55 times higher at 9000 psi. This study demonstrates that 40/70 ceramic proppant exhibits minimal degradation over time, maintaining its structural integrity and conductivity under prolonged stress conditions. However, this stability may not apply to lower-strength proppants, such as natural sand, which are more susceptible to crushing under high-stress environments. Consequently, while short-term conductivity

offers a snapshot of initial proppant performance, long-term conductivity is a more reliable predictor of sustained well productivity.



**Figure 42. Short-term vs long-term conductivity of 40/70 ceramic**

**Table 4** summarize the short-term and long-term conductivity values of 40/70 ceramic proppant pack between sandstone slabs.

**Table 4. Average short-term and long-term conductivity values of ceramic 40/70 using sandstone slabs**

| Time           | 30 min               | 50 hours |
|----------------|----------------------|----------|
| Closure stress | conductivity (md-ft) |          |
| 2000           | 2858.9               | 2937.3   |
| 4000           | 1924.9               | 1965.4   |
| 6000           | 879.5                | 854.8    |
| 8000           | 410.8                | 358.0    |
| 9000           | 337.3                | 218.2    |

### 3.7 Surface profile scans

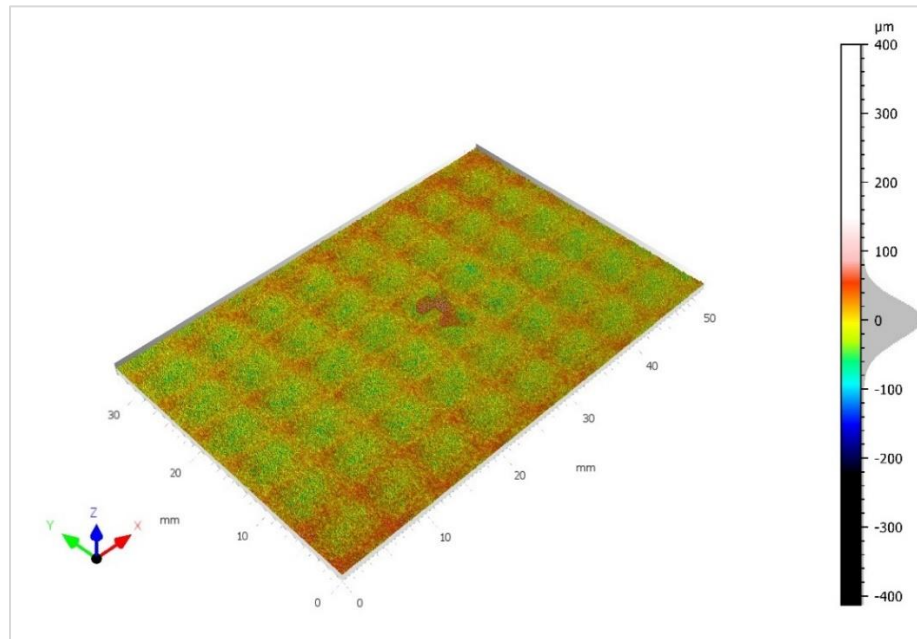


Figure 43. Surface profile scan of the bottom sandstone slab prior to the long-term conductivity experiment using 40/70 ceramic proppant

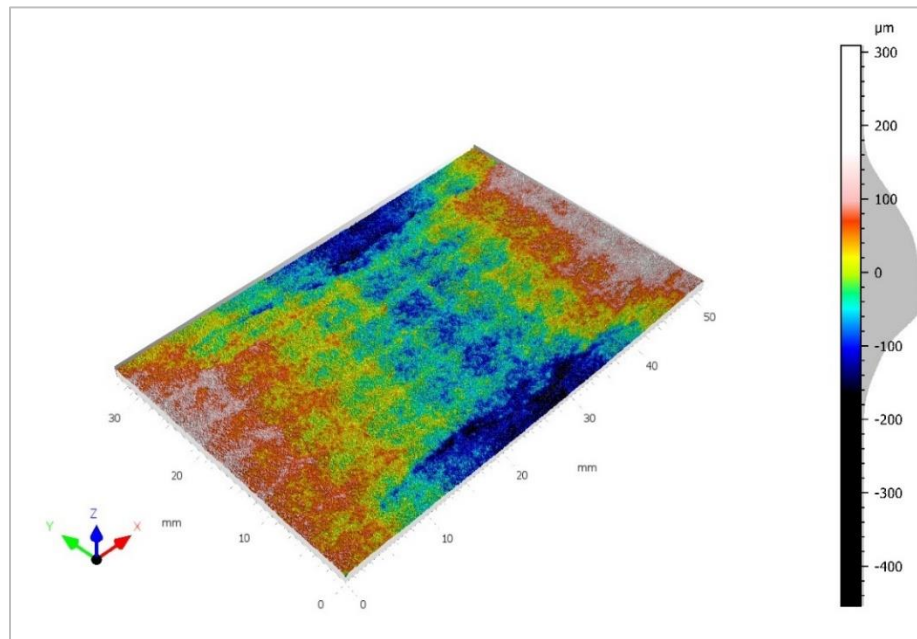


Figure 44. Surface profile scan of the bottom sandstone slab after to the long-term conductivity experiment using 40/70 ceramic proppant

Before the experiment, the surface profile appears more uniformly distributed with alternating green and orange areas, suggesting moderate surface roughness. After the experiment the surface shows significant changes, with the presence of large blue regions (indicating deeper depressions) and red zones (higher peaks), implying an increase in unevenness and wear.

**Table 5. Quantitative roughness measurements of sandstone slabs before and after long-term conductivity using 40/70 ceramic**

| <b>Parameter</b>                    | <b>Before Experiment</b> | <b>After Experiment</b> |
|-------------------------------------|--------------------------|-------------------------|
| <b>Sq</b> (Root mean square height) | 30.80 $\mu\text{m}$      | 70.48 $\mu\text{m}$     |
| <b>Sz</b> (Maximum height)          | 984.4 $\mu\text{m}$      | 763.2 $\mu\text{m}$     |
| <b>Sa</b> (Arithmetic mean height)  | 24.22 $\mu\text{m}$      | 58.08 $\mu\text{m}$     |

From the roughness results in **Table 5**, it is evident that the Sq (root mean square height) and Sa (arithmetic mean height) increased significantly after the experiment, indicating that the surface became rougher overall due to the applied stresses and proppant interaction. The Sz value, representing the maximum height difference, decreased. This suggests that high peaks were worn down during the conductivity test.

## **3.8 Discussions**

### **3.8.1 Optimizing hydraulic conductivity of raw sand**

Ceramic proppants are high-strength synthetic materials specifically engineered to provide superior resistance to crushing. They are believed to withstand higher closure stresses with

less degradation and produce fewer fines. According to Pope et al. (2012), the use of lightweight ceramic proppant (LWC) instead of sand led to a 34% increase in cumulative oil production after 22 months. By analyzing field data, Rankin et al. (2010) found that replacing sand with ceramic proppant increased the initial production rate by 37%. In comparison to sand or resin-coated sand, Vincent et al. (2010) demonstrated a 33% increase in cumulative production using premium quality ceramic proppant after analyzing production data from 750 horizontal wells in the Eagle Ford over a 12-month period. However, the cost of ceramic proppant is considerably higher than that of quartz sand, with ceramic proppant priced three to five times more than quartz sand proppant (Maity & Ciezobka, 2019). This is why, in many instances, it is used in small volumes alongside other, more affordable, lower-quality, and abundant sand. Short-term conductivity experiment using mixture of 40/70 sand and 40/70 ceramic in 3 to 1 ratio by weight could only increase the conductivity up to 2.11 times at 3000 psi across other stress levels the improvement was between 1.34 to 1.57 times. (Sun et al., 2022) conducted similar experimental investigation on a proppant mixture of sand and ceramic. They found that when mixing 40/70 sand and 40/70 ceramic in a proportion of 3:1, conductivity improved by 1.33 and 1.45 times at 40 MPa and 50 MPa, respectively. Similarly, when mixing 20/40 sand with 20/40 ceramic in a 3:1 proportion, conductivity improved by 1.27 to 3 times in comparison with pure sand. The tail-in design combining 100-mesh sand with 20/40 sand demonstrated promising results, achieving up to 50 times greater conductivity compared to a proppant pack composed entirely of 100-mesh sand. This enhancement could be attributed to the use of 50% by weight of the larger and more conductive 20/40 sand. However, due to time constraints, this experiment could not be repeated, and it is

recommended to repeat it to verify the validity of the obtained results. The cost of proppants plays a significant role in the economics of hydraulic fracturing operations, as it directly impacts the overall cost of well completions. According to Pontotoc Sand and Stone (n.d.) the typical price ranges for commonly used proppants are as follows: Silica sand costs between \$25 and \$50 per ton, resin-coated sand ranges from \$45 to \$100 per ton, and ceramic proppant can cost between \$60 and \$200 per ton. The price variation across these proppants reflects not only differences in raw material costs but also processing and performance benefits. For instance, resin-coated sands undergo additional treatment to enhance their mechanical properties, while ceramic proppants require complex manufacturing processes to achieve high strength and uniformity. Proppant selection should ultimately be based on the reservoir's unique requirements and the project's budget, carefully weighing the trade-offs between early investment and long-term production efficiency.

### **3.8.2 Effect of proppant embedment**

From the conductivity experiments conducted on 40/70 ceramic proppant within steel platens and sandstone slabs, it was evident that proppant embedment can significantly affect hydraulic conductivity. It was found that the short-term conductivity of the proppant pack within the sandstone slabs was 77% lower than the conductivity of the proppant pack within the steel platens. As seen in **Figure 40**, the conductivity values at 2000 psi were almost the same for steel and sandstone. However, after 2000 psi, the trendlines began to diverge more with increasing closure stress. This indicates that the proppant started to embed into the sandstone slabs as the stress exceeded 2000 psi. (Wen et al., 2007) investigated the effect of proppant embedment on long-term proppant conductivity. They

concluded that 30/60 mesh haydite proppant within dolomitic cores resulted in a 65.9% conductivity reduction at 10 kg/m<sup>2</sup>, while 20/40 haydite proppant showed a 46.7% reduction due to proppant embedment.

### **3.8.3 Time dependent conductivity**

As illustrated in **Figure 42**, there is no significant difference between the short- and long-term conductivity of the 40/70 proppant pack. The trendlines begin to deviate from each other after 6000 psi, with short-term conductivity being 15% higher at 8000 psi and 55% higher at 9000 psi. The short-term conductivity test lasted 8 hours, while the long-term test lasted for 11 days and 15 hours. This finding shows that for high-strength proppants, such as 40/70 ceramic, short-term conductivity tests are often more suitable than long-term API conductivity experiments. The minimal difference between the short- and long-term conductivity observed in the 40/70 ceramic proppant pack suggests that these high-strength proppants maintain their performance under pressure over extended periods with little degradation. Since they are designed to withstand high closure pressures without significant embedment or crushing, the long-term test, which lasted 11 days and 15 hours, does not provide additional critical information beyond what was already observed in the short-term test. (Mittal et al., 2018) conducted a prolonged conductivity experiment and concluded that 20/40 and 40/70 Ottawa sands experienced permeability reductions of 32% and 56% over 12 days, respectively, while the 60/100 mesh sand showed a 99% decline in just 4 days. This further illustrates that 50-hour long-term API conductivity experiments may not fully represent the long-term conductivity behavior of the proppant pack.

## **CHAPTER 4**

### **CONCLUSIONS, FUTURE WORK AND RECOMMENDATIONS**

#### **4.1 Conclusions**

This study presented the results of testing the conductivity of 40/70 sand, 40/70 resin-coated sand (RCS 40/70), 40/70 ceramic, 100-mesh sand and their mixtures under various stress conditions. The tests followed standard proppant evaluation guidelines and included both short-term and long-term conductivity measurements. 40/70 sand exhibited moderate sphericity (0.77) and relatively low roundness (0.4), meeting minimum ISO standards for sphericity but falling short for roundness. This irregular shape contributed to lower conductivity due to higher particle interlocking and pore space reduction. 40/70 sand demonstrated poor crush resistance, with significant fines generation under increasing stress. At 6000 psi, it produced 47% crushed material, leading to severe conductivity reduction. While 40/70 sand exhibited acceptable conductivity at low stress (1000–3000 psi), its performance declined sharply at higher stresses. This is attributed to the extensive crushing and fines migration that clogged pore spaces. 40/70 RCS demonstrated an improvement in sphericity (from 0.77 to 0.82) while retaining the same roundness. The resin coating encapsulated crushed particles, preventing fines from migrating into the pore spaces. Resin-coated sand showed significantly reduced fines generation (4.67% at 10,000 psi compared to 47% for uncoated sand). This resulted in fivefold improved conductivity at 6000 psi compared to raw 40/70 sand. The resin layer

provided a more uniform stress distribution across proppant particles, enhancing their durability and maintaining better pore connectivity under high stress. Adding 40/70 ceramic to 40/70 sand in a 3:1 ratio improved conductivity by 1.34 to 1.56 times at various stress levels. Despite the inclusion of ceramic 40/70, the mixture's conductivity remained lower than that of pure ceramic 40/70, especially at stress levels exceeding 3000 psi. Mixing 100 mesh sand with a small amount (25%) of 40/70 ceramic proppant can increase conductivity by 1.55 to 3.13 times compared to pure 100 mesh sand. This was due to the crushing of sand particles, which still generated fines and reduced permeability. The conductivity values of the 40/70 ceramic proppant pack were higher between steel platens than between sandstone slabs. This difference can be attributed to the embedment of proppant particles into the sandstone slabs, which reduces effective conductivity. Only minor differences were observed between the short-term and long-term conductivity measurements of ceramic 40/70 proppant in sandstone slabs. The conductivity values remained nearly identical up to 6000 psi; however, at 8000 and 9000 psi, the short-term conductivity was 1.15 and 1.55 times higher, respectively.

## **4.2 Future work and recommendations**

1. Conduct conductivity experiments under simulated reservoir condition
  - Use the temperature, closure pressure and oil composition from the actual well
  - Investigate the effect of cyclic stress
  - Use the rock samples from the actual field

- Conduct the experiments for prolonged time under stress (more than 50 hours)
2. Study other polymers for sand coating to improve sand performance
    - Measure the conductivity of coated sand with different polymers such as epoxy resin, furan, polyester and vinyl ester
  3. Optimizing proppant blends
    - Explore hybrid blends incorporating resin coated sand, sand and ceramic using different completion design such as evenly blended, blended with predominant proppant size and tail- in design
    - Develop models to estimate conductivity of proppant mixture

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