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# MODIFIED APPROACH FOR PROPPANT CONDUCTIVITY MEASUREMENT

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**Abstract:** The main goal of this study is to combine two widely used standard proppant conductivity measurement methods in order to harvest some of their advantages in case of resin-coated proppants. The available literature was studied to determine which elements can be eliminated or modified for the measurement to simplify the method and shorten its length. The proposed measurement procedure provides as short a solution as possible while maintaining suitable accuracy. An additional object of the study is to investigate the effect of different flow rates through a propped pack and find the limit of non-Darcy flow. Since higher than recommended flow rates can be utilized, less complex differential pressure measurement devices can be used. Different evaluation methods have been tried out for improved solution.

***Keywords:*** *proppant, conductivity, non-Darcy flow, evaluation method*

## 1. INTRODUCTION

In general, the purpose of proppant measurements is to obtain near-in-situ information about the permeability and conductivity of different proppants. Selecting a proppant with the right properties is one of the key aspects for well productivity and thus for the economy of a hydraulically fractured and propped reservoir [1]. In most cases, the proppant selection is based on measurements done under laboratory conditions. Although measurements have been made since the 1940s to investigate proppant behavior and the conductivity of hydraulic fracturing, there was no established standardized method until the end of the 1980s [2]. The first standardized measurement method was introduced by the American Petroleum Institute in 1989 under the name of "Recommended Practices for Evaluating Short Term Proppant Pack Conductivity" and with the identification number of API RP 61 [3]. As the measurement method involved a high degree of uncertainty, a modified measurement method and equipment for it began to spread in the industry [4]. This modified method became the standard in the industry and in 2006 it was established by the International Organization for Standardization as ISO 13503-5 [5]. In 2008 this standard was adopted by the American Petroleum Institute under the name of "Measuring the Long-term Conductivity of Proppants" and with the identification number of API RP 19D [6]. The main differences between API RP 61 and API RP 19D are summarized in *Table 1.*

It is important to note that significant differences can be found in the literature between measurements performed under the same conditions with API RP 19D, so the measurement uncertainty is high. In general, the variance between measurements is ±20%, although variance of more than 80% can be found in the literature as well [7]. During our investigation, we set a target to create a modified measurement method with which the results can be duplicated within the average range of ±20% and with a sufficiently high correlation coefficient. At the same time we attempt to reduce the measurement time as much as possible, since one measurement series with the API RP 19D standard requires more than 250 hours, not including preparation.

## 2. EXPERIMENTAL PROCEDURE

In order to modify the current processes, first we needed to study the literature and compare the already available methods. The main differences between API RP 61 and API RP 19D conductivity measurement methods are represented in the table below.

***Table 1***

*Main differences between API RP 61 and API RP 19D measurement standards* [7]

| | API RP 61 | API RP 19D |
|---|---|---|
| **Circulated fluid** | Deionized water | 2% KCL solution |
| **Closure body** | Stainless steel platens | Sandstone core |
| **Temperature** | 75 °F (~24 °C) | 150–250 °F (~66–121 °C) |
| **Time under closure stress** | 0.25 hours | 50 hours |

The first suggestion to use 1 to 2% potassium chloride (KCl) water instead of demineralized water appeared in the literature in 1986 [8]. The main assumption was that the water phase probably can be simulated better by this solution. As the effect of this has not been investigated extensively, during our modified method first demineralized water was used; in later studies, the effect of the usage of KCl solution will be analyzed.

The effect of proppant embedment on proppant conductivity is significant and its effect is more obvious under a certain closure value [13]. As 10,000 psi is the final closure stress during our measurements, this effect cannot be disregarded. To obtain more realistic conductivity values consolidated sandstone is used in our modified approach.

Most of the literature suggests higher than ambient temperature during conductivity measurement [2, 5, 6, 8, 9, 12]. The reason behind this is that in case of short loading times the temperature does not have a significant effect on the conductivities, but in case of significantly longer loading times the temperature is important, as stress-intensified corrosion may occur, weakening the grains and increasing the degree of crushing [12]. The investigated proppant in this study has a very low fine value after the ISO 13503-2 crush test. The value of the crush test in case of the investigated proppant is equal to 3.13 wt% at 10,000 psi (~690 bar), which can be considered as low [10]. As the standardized crush test specifies ambient temperature [11] during, measurement, a temperature of 75 °F (~24 °C) was implemented in our modified approach, which is a considerable simplification of the method and further investigation may be necessary.

Three main factors have been identified that can cause variations in the measurement results under the same conditions in case of API RP 19D [1]:

- Variation in pack width: this can be caused by the initial packing arrangement, which is carried through during the different closure stresses and affects the rearrangement and the compression properties;
- Secondary changes in pack width: the main causes are the proppant rearrangement under different loads, grain crushing, and grain embedment (also other parameters like roundness and sphericity of the proppant grains have an impact on these parameters);
- Variations in permeability: caused by the initial proppant arrangement.

To achieve the same initial and during measurement conditions in the above conditions, API RP 19D suggests a relatively long loading time for each closure stress (±50 h). Also, a significant decline can be identified in the conductivities if the proppant pack is under closure stress for a significant time period [14]. In order to adjust to this phenomenon as much as possible, the holding time of the first closure stress after the initial load was 70 hours during our measurement. After that, to reduce the total time (compared to API RP 19D), permeabilities and conductivities were determined after 24 hours at each closure stress. The most important measurement parameters are given in *Table 2,* in which the values recommended by the two standards are also indicated in the last two columns as a comparison.

***Table 2***

*The most important measurement parameters applied in the modified approach*

| | Modified approach | API RP 61 (1989) | API RP 19D (2008) |
|---|---|---|---|
| **Temperature** | 75 °F (24 °C) | 75 °F (24 °C) | 250 °F (121 °C) |
| **Fluid medium** | demineralized water | demineralized water | 2% KCl solution |
| **Closure body** | Kővágószőlős sandstone | stainless steel | Ohio sandstone |
| **Initial load** | 310 psi | – | 1,000 psi |
| **Duration of initial load** | 1 hour | – | 12–24 hours |
| **Closure stresses** | 4,000 psi<br>6,000 psi<br>8,000 psi<br>1,0000 psi | 1,000 psi<br>2,000 psi<br>3,000 psi<br>4,000 psi<br>5,000 psi<br>6,000 psi<br>7,000 psi<br>8,000 psi | 2,000 psi<br>4,000 psi<br>6,000 psi<br>8,000 psi<br>10,000 psi |

| | Modified approach | API RP 61 (1989) | API RP 19D (2008) |
|---|---|---|---|
| | | 9,000 psi<br>10,000 psi<br>11,000 psi<br>12,000 psi<br>13,000 psi<br>14,000 psi | |
| **Loading rate** | Initial to 4,000 psi 725 psi/min, then 260 psi/min | – | 100 psi/min ± 5% |
| **Duration of closure stresses** | At 4,000 psi 70 hours, then 24 hours | 0.25 hours | 50 hours ± 2 hours |

The measurement was carried out by an equipment introduced in the ISO 13503-5 (API RP 19D) standard [22]. A schematic diagram of the experimental setup is shown in *Figure 1*.

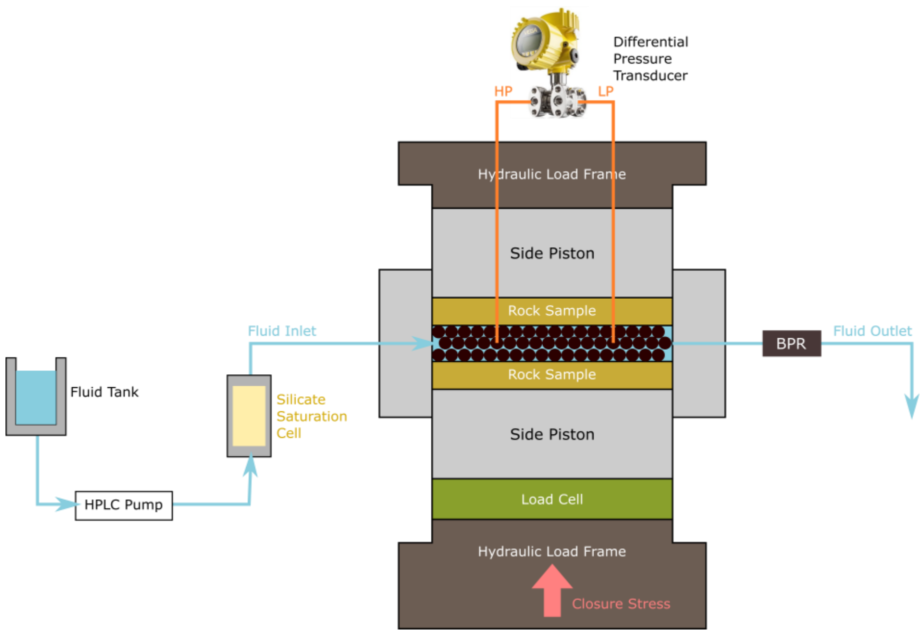


***Figure 1***
*Schematic of experimental setup for proppant conductivity measurements*

Pulsation-free constant flow rate was supported by a chromatographic pump with a built-in pulsation dampener unit. The injected fluid was passed through a silica saturation cell and filtered by a 0.5-micron sintered stainless-steel filter before entering the test cell. Proppant was placed into a proppant conductivity cell between two sandstone wafers from the Kővágószőlős Formation (detrital complex of the Upper Permian of the Mecsek mountains, Hungary). Closure stress was supported within +/– 1% of the setpoint value by a hydraulic load frame with a maximal loading capacity of 667 kN. Pressure drop between the pressure ports was measured with a differential pressure transducer with a resolution of 0.001 kPa. Pore pressure was set up by a back pressure regulator (BPR). The width of the proppant pack was measured with two laser distance sensors. Initial zero pack width was measured without the proppant pack. Pressure, temperature and distance parameters were collected and stored by a computer.

Other preparations for the measurements have been implemented as API RP 19D states, such as the presetting of the sandstone core with high-temperature silicone (RTV) in order to avoid any leakage at the sides of the core or the loading of proppant in the cell. The loading of proppant in the cell is a critical factor to reach nearly identical results. For example, recent studies proved that proppant loading with the application of vibration can significantly reduce the conductivity variations [15, 16]. This method has not been used during our measurements as it is not yet accepted by the ISO and our results indicate that the conductivities can be in an acceptable range without the utilization of any vibration techniques.

In order to be able to examine the effect of time, the data were recorded continuously during the measurement. Instead of the minimum flow rate of 2 ml/min specified in the standard, a flow rate of 2.6 ml/min was used and at the end of the loading cycles, four volumetric flow rates were applied instead of five recommended by the API RP 19D (2.6 ml/min; 3.1 ml/min; 3.6 ml/min; 4 ml/min), which determined the final permeability values.

The following standard equations were used to determine the permeability and conductivity values [5].

$$k = \frac{\mu \times Q \times L}{100 \times w \times (\Delta P) \times W_f} \tag{1}$$

$$C = \frac{\mu \times Q \times L}{100 \times w \times (\Delta P)} \tag{2}$$

where $k$ is the permeability expressed in Darcy; $C$ is the conductivity expressed in Darcy-meter; $\mu$ is the dynamic viscosity of the fluid expressed in cP; $Q$ is the applied flow rate expressed in $cm^3/s$; $L$ is the distance between the pressure ports expressed in cm; $\Delta P$ is the pressure drop (pressure upstream minus pressure downstream) expressed in kPa $w$ is the cell width expressed in cm; and $W_f$ is the proppant pack width expressed in cm.

## 3. Results

The total duration of the measurement was 150 hours, which can be identified in *Figure 2*. Data were continuously recorded during the measurement, so it can be seen in the figure how the permeability values changing with time and under different applied loads. The different closure stress effects can be easily recognized, as the permeability values show a significant drop when greater pressures are applied to them.

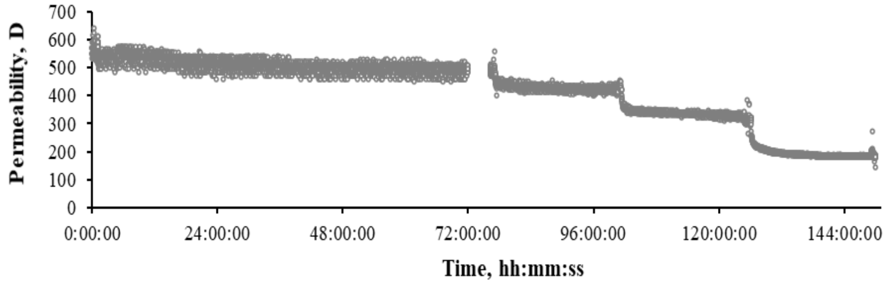


***Figure 2.*** *Permeability values during the whole measurement*

The data recording took place every 5 seconds during the measurement, so more than 10,500 permeability values are calculated and presented in the figure above. Since the API RP 19D standard proposes that permeability values (at different flow rates) are to be determined at the end of the different closure stresses, the average of the values recorded at each flow rate serves as a starting point. The standard does not provide any evaluation method for this, so we propose that the average of the measured values (at each flow rate) be represented on a graph where the abscissa is the $\Delta P/L$ and the ordinate is the $Q/A$ (or $Q/(w \times W_f)$). Interpolating a linear function on these data points, we can determine the permeability values from the slope of the line by the following equation.

$$k = slope \times \mu \times 1\,000 \tag{3}$$

where the slope can be found from the fitted line and is a dimensionless parameter. This method (later also referred to as *4-point measurement*) can be used efficiently, as it helps to eliminate the small irregularities from the result. We also tested the effect of applying more than four flow rates and basically negligible differences can be identified (see *Figure 5*), so it can be stated that the applied four flow rates are adequate to determine the final permeability values. With this approach we can slightly reduce the total measurement time without sacrificing perceptible degradation in accuracy. As can be seen from *Figure 3*, the r-squared values are very close to 1, which indicates that our regression model works well and only limited variance can be detected in the measurement. This was also reinforced by the application of a pulsation dampener in the system that helps to reduce the shocks caused by the increase in flow rates. The results clearly show that at higher applied loads the permeabilities decrease as the slope of the corresponding lines decreases. This is in line with the literature and also it is intuitive, since at higher applied loads the proppant pack is more compressed, so smaller channels are available for the fluids to flow through and thus the differential pressure will increase; based on *Equation (1)*, with increasing ΔP the permeability values should decrease proportionally.

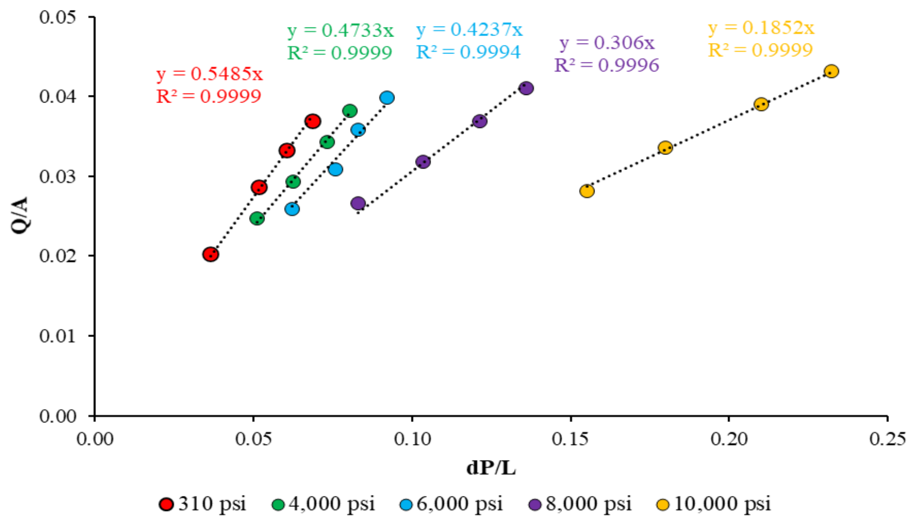


***Figure 3.*** *Determination of permeabilities at different closure stresses*

By adding together, the permeabilities calculated from the presented slopes, the final permeabilty vs. closure stress graph can be determined. As data were registered during the complete measurement process the variations can be determined from the maximum and minimum points at each closure stress *(Figure 2)*. This is presented by a grey stripe in *Figure 4*, while the permeability values from the 4-point measurements are shown with a red line.

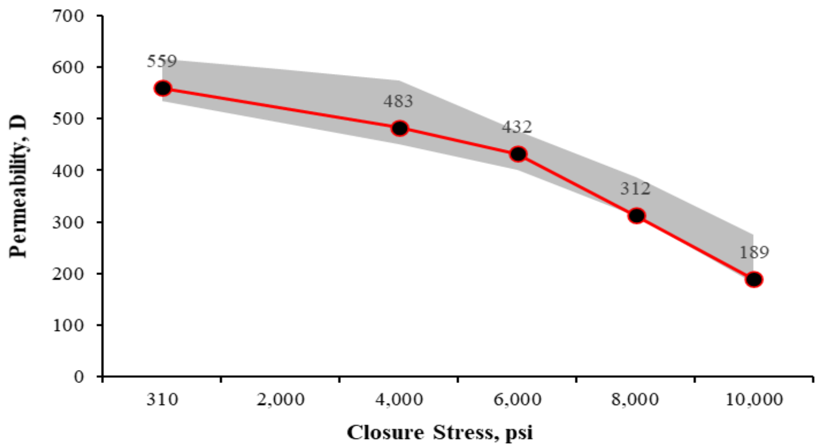


***Figure 4.*** *Result of 4-point measurements and the variance of permeabilities during the whole measurement*

It has been previously stated that measurements can differ from each other despite the fact that the same circumstances are created. Based on the literature this variance is around 20% [1], which was confirmed by our results, although at the highest closure stresses the variance is +46%/–4%. This can be explained by the fact that at high closure stresses the proppant grains are crushed and the effect of embedment is enhanced [2]. With the combination of these two effects a significant permeability performance decline can be identified at the early stages. These results are collected in *Table 3*.

***Table 3***

*Results obtained during 4-point measurements and maximum and minimum permeabilities obtained during the whole measurement (with percentage deviations)*

| Closure stress, psi | 310 | 2,000 | 4,000 | 6,000 | 8,000 | 10,000 |
|---|---|---|---|---|---|---|
| **Max. permeablity from average, Darcy** | 616 | 596 | 575 | 476 | 387 | 275 |
| **Difference, %** | 10 | 14 | 19 | 10 | 24 | 46 |
| **Min. permeability from average, Darcy** | 534 | 492 | 450 | 400 | 310 | 181 |
| **Difference, %** | –5 | –6 | –7 | –7 | –1 | –4 |
| **4-point measurement permeability, Darcy** | 559 | 521 | 483 | 432 | 312 | 189 |

The ISO RP 19D standard specifies low flow rates during measurement to avoid the build-up of turbulent flows. In case of turbulent flow, it is necessary to correct the laboratory values with a non-Darcy coefficient [17]. In practice, this would occur in such a way that the points belonging to the higher flow rates in *Figure 3* would not fit properly after a given limit to the line but would have a slower slope [18]. During our measurement an experiment was conducted to investigate the effect of non-Darcy flow. For this reason, at the highest applied closure stress (10,000 psi) the flow rates were increased intermittently up to 50 ml/min. The closing stress of 10,000 psi was chosen because in this case the smallest channels are formed; thus, the appearance of non-Darcy flow is the most likely due to the higher Reynolds number [19]. Based on the equation proposed by Ergun in 1952 the Reynolds number region in this experiment is between 0.01 and 1 [20]. Results can be found in *Figure 5*.

To be able to identify the turbulent effect two lines were interpolated independently on the upper and lower part of the measurement points. The interpolated lines fit accurately on the points (each with a more than 0.999 r-squared value) and although the linear line fitted on the higher flow rates has a slightly lower slope, there is no significant difference between the slopes of the two interpolated lines. There is only a 2.7% difference between the slopes of the two fitted lines, so it can be stated that even at a volumetric flux of 0.541 cm/sec (that belongs to 50 ml/min of flow rate) no significant turbulent flow develops, which would justify the determination and use of the non-Darcy component. Using this result, higher than recommended flow rates can be used in the future, which consequently generates a higher pressure difference and thus makes the detections more accurate and less sensitive to small pulsation fluctuations.

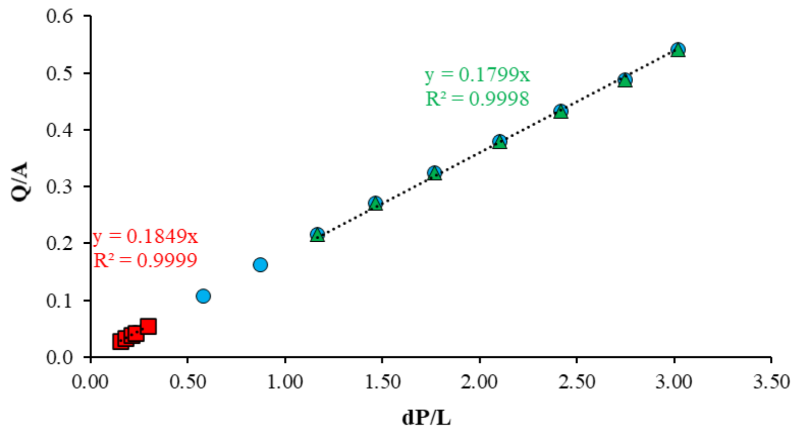


***Figure 5***

*Experimental investigation of non-Darcy flow*

Since several studies suggest the application of long closure stresses (API RP 19D also specifies this), it was worth investigating in detail whether a significant change is indeed observed over time. The *Figure 6* shows the absolute deviation of the calculated values over the entire measurement to the 4-point measurement permeabilities.

Based on the values obtained for the nearly 8,500 measuring points, it cannot be clearly concluded that even the 24-hour closing stress we use is necessary. At the closing stresses of 4,000 psi and 8,000 psi it is clear that continuously decreasing permeability values were measured; however, the values at 6,000 psi show different results. The results obtained at the 10,000 psi closing stress show that a significant decrease in permeability occurs in the first period, but this cannot be observed in the later period. This is presumably caused by the high pressures as the proppant grains crush and deform. Because of the fragmentation of the proppant grains into smaller pieces, the permeability can decrease suddenly (smaller pieces block the channels) but after a relatively short time these fragments become arranged.

In order to obtain a comparable result between our modified measurement and the results performed with the API RP 19D measurement, the technical data sheet of the tested proppant was compared with the values obtained by our measurements. *Figure 7* presents two acquired data series presented with different approaches, namely the results obtained by the 4-point measurement and results obtained by averaging the permeability values over each loading time *(Average of total measurement)*.

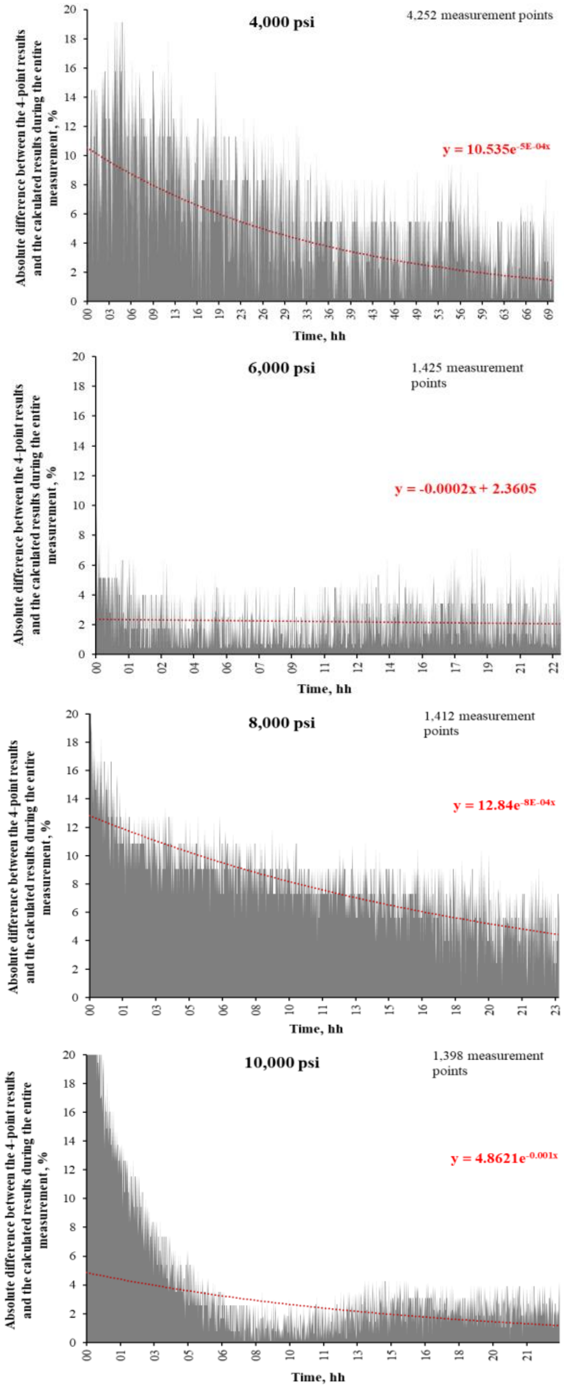


***Figure 6***

*Effect of time on the permeability*

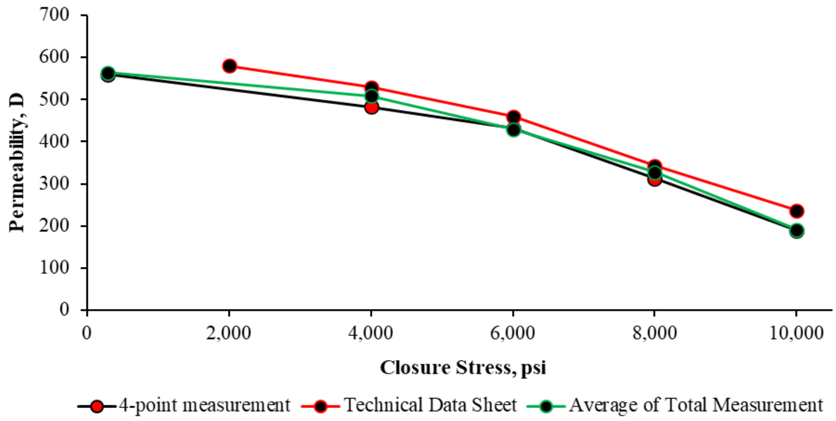


***Figure 7***

*Comparison of the permeabilities with the proppant's technical data sheet*

It can be seen from the figure that although there is a visible difference between the obtained results and the values indicated in the technical data sheet, but the trends of the lines are similar and the variance is between the range that the literature mentions. Also, no notable difference exists between the results obtained by the 4-point measurement and the average values recorded during the entire measurement. In this way the application of the 5-point measurement method proposed by the API RP19D is not necessarily essential to produce reliable results. The correlation coefficients and r-squared values are presented in *Table 4*.

***Table 4***

*Statistical comparison of the two different evaluation methods compared to the permeability values indicated in the technical data sheet*

| | Correlation coefficient, – | $r^2$, – |
|---|---|---|
| **4-point measurement** | 0.9975 | 0.995 |
| **Average of total measurement** | 0.9979 | 0.996 |

It has been found that there is a significant correlation between the obtained results and the results specified in the technical data sheet (where the data were obtained by the API RP 19D standard). This confirms that the modified measurement method can be used to test the permeability of resin-coated proppants. An interesting result is that the permeabilities calculated from the average of the whole measurement series provide a slightly better result, so both methods can be considered adequate. However, it is still suggested to use multi-point measurements since the measurement error due to the nonlinearity of the devices (pressure transducer, A/D converter, pump) can be eliminated.

The proppants were loaded into the measuring cell as specified in the API RP 19D standard. The goal is to achieve almost identical conditions with this method, but there is an obvious difference between the results obtained and the fracture widths calculated from the values specified in the technical data sheets. This can be explained by the variation in the initial packing arrangement of the proppants [1]. The results can be seen in *Figure 8*.

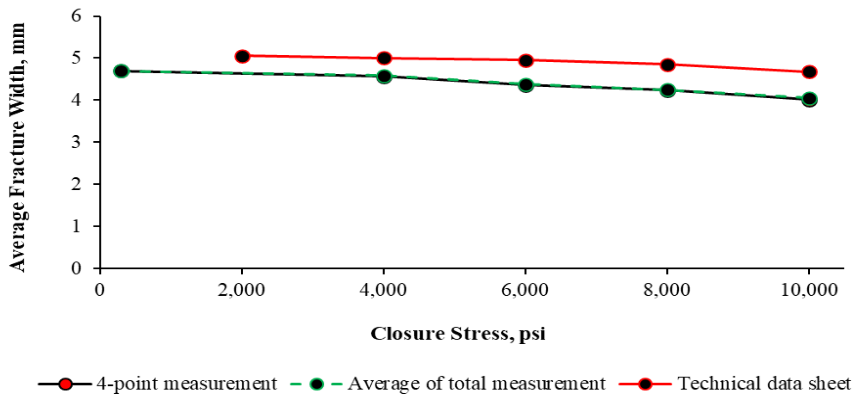


***Figure 8***

*Comparison of the fracture width with the proppant's technical data sheet*

***Table 5***

*Statistical comparison of the two different evaluation method compared to the fracture width values calculated from the technical data sheet*

| | Correlation coefficient, - | $r^2$, - |
|---|---|---|
| **4-point measurement** | 0.9698 | 0.941 |
| **Average of total measurement** | 0.9660 | 0.933 |

Although there is a significant correlation between the obtained results with high r-squared values, the differences can still be seen. The usage of the vibrational filling technique should be investigated in later studies to reach more accurate results. As the fracture width has a direct effect on the conductivity values (see *Equation 2*) it was assumed that the results will be slightly less accurate than in the case of permeabilities. This was confirmed by the results shown in *Figure 9* and *Table 6*.

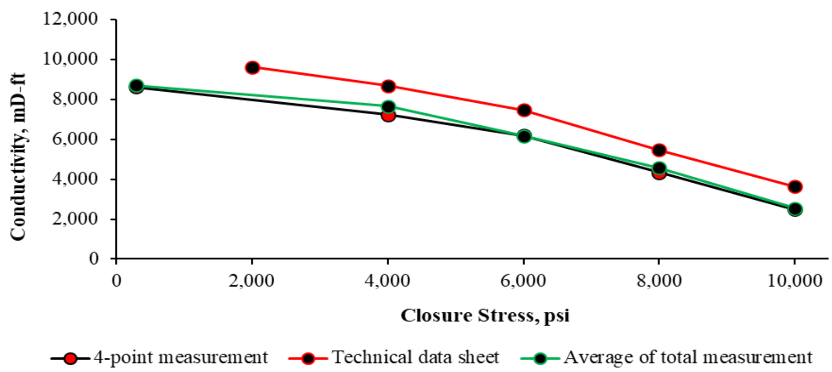


***Figure 9.*** *Comparison of the conductivity with the proppant's technical data sheet*

***Table 6***

*Statistical comparison of the two different evaluation method compared to the conductivity values indicated in the technical data sheet*

| | Correlation coefficient, – | $r^2$, – |
|---|---|---|
| **4-point measurement** | 0.9974 | 0.995 |
| **Average of total measurement** | 0.9977 | 0.995 |

From the results it was found that the modified approach can be used within a suitable accuracy to determine the performance of different proppant packs. Also, no significant difference can be identified between the two offered evaluation methods.

Due to the continuous data recording, it is possible to study the distribution of permeability data and create a histogram. Since most of the results are assumed to be around a certain value, it is possible to fit a Gaussian curve on the acquired histogram. *Equation (4)* was used for this purpose.

$$f(x) = a \times \exp\left(-\frac{(x-b)^2}{2 \times c^2}\right) \tag{4}$$

In the first step, the permeability values were determined at the same intervals and the number of occurrences within each interval was determined. The histograms can then be plotted *(Figure 10)*. Using *Equation (4)*, a curve can be fitted to the histogram, and then the calculated and measured r-squared values can be maximized by changing the parameters. For this optimization, the general reduced gradient method (GRG) was used, which is one of the most popular optimization methods for nonlinear problems [21]. Here only the results are presented without the calculation steps.

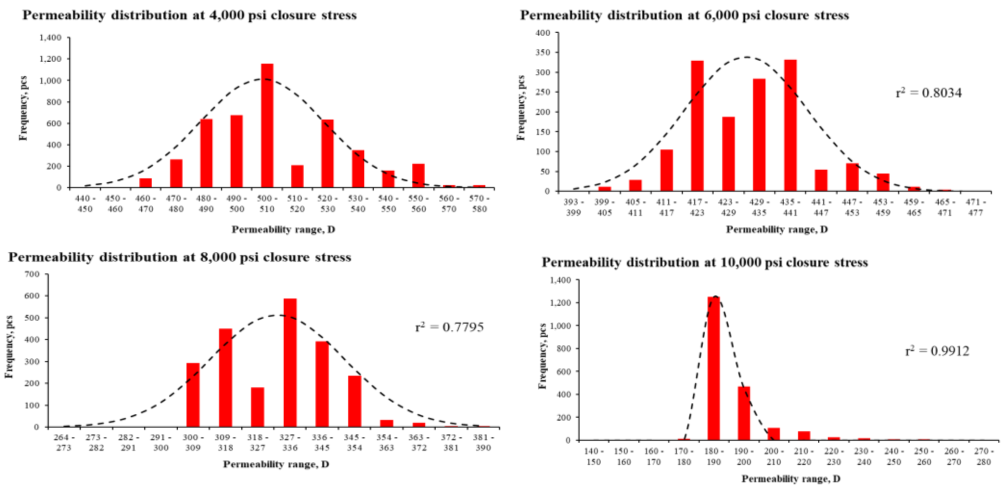


***Figure 10.*** *Distribution of permeability values during the entire measurement*

The maximum of each function obtained gives the most likely accuracy of permeabilities. They can be determined by the derivative of the functions, but an easier way is that the *b* in the *Equation (4)* also determines the maximum value of the functions. *Table 7* represents the results obtained from the Gauss distribution functions and also from the other two proposed methods (4-point measurement, average of total measurements).

***Table 7***

*Comparison of results based on Gaussian distribution*

| Closure stresses, psi | 4,000 | 6,000 | 8,000 | 10,000 |
|---|---|---|---|---|
| **Gauss distribution, D** | 515 | 427 | 328 | 185 |
| **4-point measurement, D** | 483 | 432 | 312 | 189 |
| **Average of total measurement, D** | 509 | 429 | 328 | 191 |
| **Technical data sheet, D** | 529 | 460 | 343 | 237 |

The results obtained with each evaluation method are given in the table. The method based on the Gaussian distribution gives almost the same results as the other methods, especially the method based on the average of total measurement. Based on this, it is found that all of the methods can be applied with sufficient accuracy in the evaluation of proppant permeability results.

## 4. SUMMARY

The most important results from the study are summarized below:

1) The modified measurement approach may be used to measure the permeability and thus the conductivity of resin-coated ceramic proppants within the accuracy that can be reached by the standard method. It should be mentioned that further experiments are necessary to validate the results;
2) The applied method can be used to perform a series of measurements in less than half the time specified in the API RP 19D standard;
3) Based on the obtained results, the applied temperature has no significant effect on the permeability of resin-coated ceramic proppants. Further measurements are required to confirm this statement;
4) Volumetric flux can be increased up to 0.541 cm/sec without the occurrence of non-Darcy flow, resulting in higher pressure differences that are easier and more accurate to detect;
5) There is no significant difference between the result of the proposed evaluation methods. The evaluation method of 4-point measurement, the average of total measurement, or the Gauss distribution method provides nearly the same results.

The future plans of the research are summarized below:

1) It is necessary to perform measurement with several types of proppant in order to present more statistically representative results;

2) Sensitivity analysis should be required to further reduce the measurement time without deteriorating the results;
3) It is necessary to examine the modification of additional measurement parameters (such as temperature, proppant loading, fluid type) in order to achieve values even closer to the results acquired with the API RP 19D standard method.

## ACKNOWLEDGEMENT

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