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Research Title

Evaluating Proppant Performance: Contrasting the API Crush Test and the Novel TrueCrush™ Testing Method

Conducted by:

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1. Abstract

This study aims to introduce a novel proppant testing method named the TrueCrush™ Test, patented by True Crush Testing, LLC, for evaluating proppant performance. Additionally, this study thoroughly examines the API Crush Test to assess its abilities and to determine if it should be replaced by the TrueCrush Test.

Four samples of 40/140 mesh proppants (South Texas sand, Oklahoma sand, white sand #1, and white sand #2) were utilized. Initially, an API crush test was conducted to establish reference data. Subsequently, the TrueCrush Test was performed, isolating each mesh size to estimate the retention of original size under specific applied pressures. The weight score for each size was calculated by multiplying the Maintained Original Size % by its distribution %. To assess total sample strength, an Effective Weight Score (EWS) was introduced by summing all weight scores together. Proppant permeability before and after crushing was measured to gain insights into performance under pressures ranging from 4,000 to 10,000 psi. Correlations between the Effective Weight Score and permeability reduction were then established to enhance estimation of proppant performance under downhole conditions.

Results indicate that South TX sand, OK sand, white sand #1, and white sand #2 passed the API Crush test under pressures of 7,000, 8,000, 10,000, and 11,000 psi respectively, assigning them K-Values (or K-Factors) as 7K, 8K, 10K, and 11K sands. However, it was observed that the manipulation of the distribution, especially the smallest sizes (i.e. 140-mesh) and larger sizes (i.e. 45 mesh), can easily alter the K-Value. Additionally, the 90% threshold used in the API Crush test was deemed excessively stringent, often leading to erroneous evaluations of proppant strength. Consequently, the API Crush test was deemed unsuitable for assessing proppant strength or comparing samples.

Instead of relying on the API K-Value, the TrueCrush Test utilizes the EWS to indicate the percentage of a sample that maintains its original size under specific pressure. Unlike the pass/fail criteria of the API Crush test, the EWS simply provides insight into the proportion of a sample that remains intact versus that which is crushed into smaller sizes. This makes the EWS a more reliable parameter for comparing sample strengths. Applying the TrueCrush Test to the four sand samples yielded vastly different results than the API Test: TrueCrush yielded EWS values under 8,000 psi of 55.5%, 58.7%, 83.9%, and 85.7%, respectively. Furthermore, permeability reduction values under 8,000 psi were determined to be 46.4%, 48.2%, 50%, and 50.2% for the respective samples. Extremely strong correlations were observed between EWS values and permeability reduction, further supporting the efficacy of the TrueCrush Test for evaluating proppant performance.

In conclusion, the TrueCrush Test offers a superior methodology compared to the API crush test for selecting proppant types for hydraulic fracturing. Its implementation promises to maximize well performance, significantly improve cumulative well output, and enhance decline curve forecasting.

2. API Crush Test

2.1. API Crush Test Procedure: API Standard 19C

1. Sieve Analysis: A sieve analysis is performed to precisely determine the size range of the proppant sample. For 40/140 mesh sand, a set of sieves including 40, 70, and 140-mesh sieves is used to filter out sizes 40-mesh and larger and sizes smaller than 140-mesh.
2. Bulk Density Measurement: Bulk density testing is conducted to accurately determine the mass of the proppant sample required for the crush test.
3. Transfer to Crushing Cell: The proppant sample is carefully transferred to a crushing cell using a pluviator.
4. Application of Pressure: Pressure is applied to the top of the crushing cell to subject the sample to a specific pressure.
5. Post-Crush Sieve Analysis: Following the application of pressure, a sieve analysis is carried out to determine the particle weights above and below the 140-mesh sieve. If 90% or more of the crushed sample remains on or above the 140-mesh sieve (10% or less below 140), the sample is classified as "pass"; otherwise, it is labeled as "fail" under this applied pressure.
6. Repeats steps 3-5 for a new sample under a different applied pressure. The goal is to find the highest pressure in which the sample passes (90% on or larger than 140). An example of the API crush test result can be presented as shown in Fig. 1. This sand is labeled as a 10K sand, as it passes at 10,000 psi and fails at 11,000 psi.

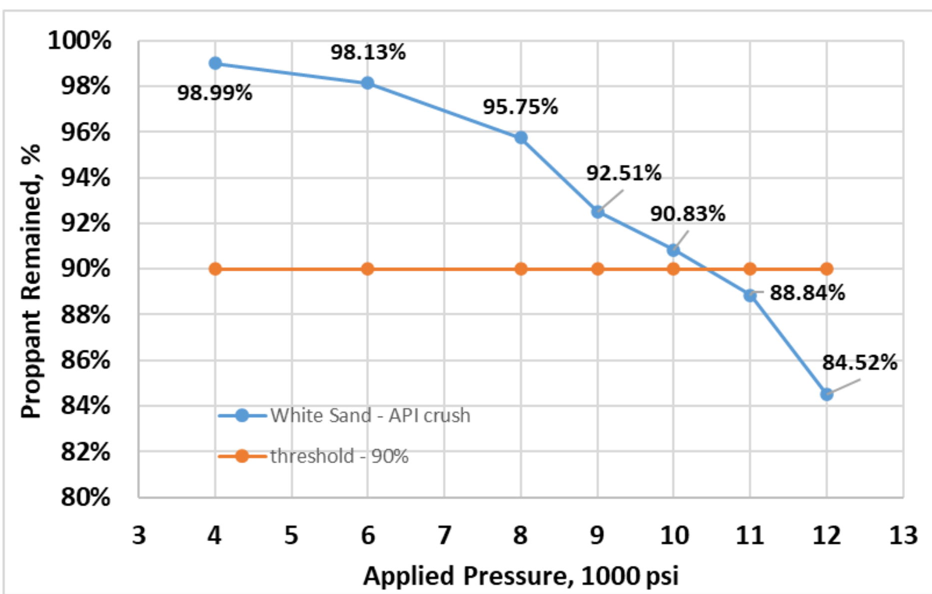

Figure 1. API Crush Test Results for a 100-Mesh Sand

2.2. Potential Problems of the API Crush Test

The following analysis is based on a local sand sample with a K-Value of 8K. As described above in section 2.1, "8K" indicates that the sand sample passed the API test at 8,000 psi and failed at 9,000 psi.

Following the collection of a bulk sample, sieving analysis was conducted to ascertain the bulk size distribution both at 0 psi and after applied pressure of 8,000 psi. The resulting size distribution data is presented in Fig. 2.

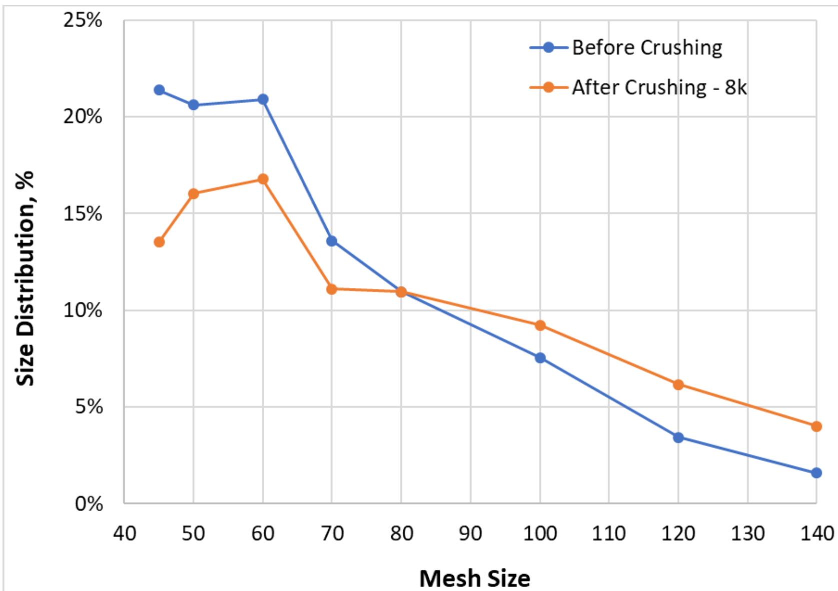

Figure 2: Size Distributions of an 8K Sand Before and After Pressure

Based on the API test, a K-Value of 8K suggests considerable strength, considering it surpasses the 90% threshold set forth in the standard. But A closer examination of Fig. 1 reveals that the initial distribution of the 140-mesh size, prior to crushing, is a mere 2%. After application of 8,000 psi, the finer mesh sizes' percentages increase. This indicates that coarser particles have broken down, but they have not broken down small enough to impact the API score (must become smaller than the 140).

Therefore, it is clear the API result can easily be manipulated to achieve a higher result by coarsening the sample. To increase the perceived strength of this sample under the API Test, the following adjustments can be made:

- Lower the distribution of smaller mesh sizes. The biggest impact will be made by reducing the smallest size, in this case the 140-mesh.
- Increase the distribution of larger sizes. For example, increase the amount of 45 and 50-mesh.

- Increase the number of mesh sizes. For example, add 45 and 50-mesh to convert the sample from a 50/140 to a 40/140. This both lowers the finer mesh sizes and increases the coarser sizes at the same time.

All three of these adjustments will yield a higher API K-Factor even though none of them increases the actual strength. In fact, since these adjustments coarsen the samples, they, by the very nature of physics, weaken the proppant.

Further exposing the inconsistencies of the API Crush test, the sand sample was sieved and categorized into four groups: 70/140, 60/80, 40/140, and 40/70. A comparison of the strengths of these groups clearly demonstrates that the 40/70 sample is the weakest due to its coarseness, whereas the 70/140 sample emerges as the strongest owing to its fineness. Subsequent API crush tests were conducted on these four samples to obtain K-values, as detailed in Table 1.

Table 1: Results of the API Crush Test for the Four Isolated Samples

Fine level	Resistance	Mesh size	API K-value, psi
1	Very strong	70/140	6,000
2	Strong	60/80	4,000
3	Weak	40/140	8,000
4	Very weak	40/70	5,000

Table 1 presents the API crush results for the four isolated samples, showcasing that the strongest sample (70/140) yields a K-value of 6,000 psi, while the weaker sample (40/140) exhibits a K-value of 8,000 psi. Notably, the results indicate no correlation between sample strength and K-value. Essentially, the K-value derived from the API crush fails to accurately capture a sample's true strength, as evidenced by Fig. 1, where the K-value heavily relies on the initial distribution in relation to the smallest size.

In conclusion, the manipulability of the API Crush test to achieve desired K-values renders it unsuitable for effectively comparing and evaluating the strength of proppant samples. In addition, particle size distribution must be taken into consideration to evaluate proppants' strength and performance. The API Test does not consider distribution as it relies on the smallest size to determine strength of the entire proppant.

3. TrueCrush Test

The TrueCrush test is a new, patented testing procedure for determining the actual performance of a proppant sample. In contrast to the API Crush Test (which uses only the smallest grain size to determine strength of the entire proppant), the TrueCrush Test analyzes each size in isolation to determine its ability to maintain its original size. Additionally, it accounts for each size's distribution in the total product. Each product receives an "EWS" or "Effective Weight Score," which is the % of the total proppant that maintains its original size under pressure. This final score is calculated from each individual size's strength and each size's distribution (impact factor). In other words, the EWS value from the TrueCrush Test reveals the strength of each individual proppant mesh size (i.e. 45, 50, 60, etc.) and the strength of the entire sample (i.e. 40/140) after a specific pressure (i.e. 8000 psi) is applied.

$$EWS = \sum_{sizes} WS = \sum_{sizes} \%sieve \times \%remained\ original\ size$$

The TrueCrush test procedure for 40/140 sand can be summarized as follows:

1. Sieve Analysis: A sieve analysis is conducted to obtain a precise size range of 40/140 mesh for the proppant sample.
2. Distribution of Individual Sizes: Each mesh size, ranging from 45 mesh to 140-mesh, is captured and isolated.
3. Crush: Each mesh size is individually subjected to pressure
4. Post-Pressure Analysis: After each mesh size is subjected to pressure, an analysis is conducted to determine the Remaining Original Size %.
5. Weight Scores: The Remaining Original Size % is multiplied by its distribution (impact factor) which yields a weight score.
6. Calculation of Effective Weight Score (EWS): The summation of all weight scores obtained from step 5 is defined as the effective weight score or EWS.

An example of the TrueCrush test result is shown in Table 2.

Table 2. Calculation of EWS at 8K Based on Proppant Size Distribution and Remained Original Proppant % of Each Size.

Mesh size	Distribution, %	Remained original proppant, %	Weight Score, %
45	20.13	59.94	12.07
50	19.55	56.82	11.11
60	26.08	58.58	15.28
70	12.76	59.26	7.56
80	9.85	66.72	6.57
100	6.59	74.35	4.90
120	0.27	65.83	0.18
140	4.76	74.85	3.56
Sum	100.00	-	61.23

In this example, the EWS score of 61.23 indicates that 61.23% of the entire proppant sample is expected to maintain its original size at 8,000 psi.

Benefits of using EWS from TrueCrush test:

- Improving the quantification of the strength and the performance of proppant compared to the API Crush Test.

- EWS values provide an "apples to apples" comparison when choosing proppant.
- There is a connection between the EWS and the downhole hydraulic propped-fracture conductivity or permeability.
- There is a connection between the EWS and the declined curves for hydraulic propped-fracture wells.

4. Permeability Test Procedure

The primary objective of the permeability test is to assess the performance of the proppant, a crucial factor influencing fluid flow, and hence productivity, in oil/gas wells. By evaluating permeability, we directly gauge the impact of crushed proppant on fluid flow within the fracture. As such, permeability tests were conducted both before and after the crushing test, employing various applied crush pressures.

Fig. 3 illustrates the permeability test apparatus utilized in this experiment. Pure water is pumped through the proppant sample using an ISCO pump, while data such as injection pressure, outlet pressure, and injection rate are recorded to measure permeability. The injection rate is systematically varied to obtain different permeability values, and the permeability of the proppant is determined by calculating the average of these values across different injection rates.

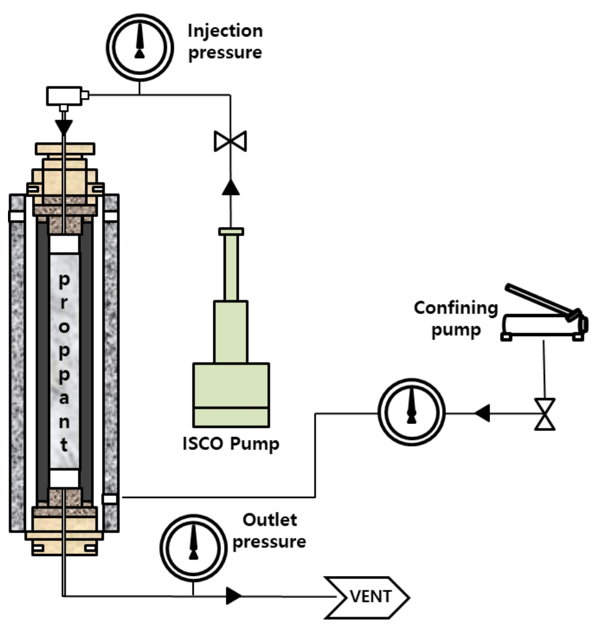

Figure 3: The Permeability Test Apparatus

5. TrueCrush Test Results

This section outlines the results obtained from the TrueCrush Test conducted on sand from Oklahoma, one of the four samples examined in this study. According to the API Crush test, this sample is categorized as an 8K sand, passing at 8,000 psi but failing at 9,000 psi.

For the TrueCrush Test, a particle size distribution analysis was conducted, as depicted in Fig. 4.

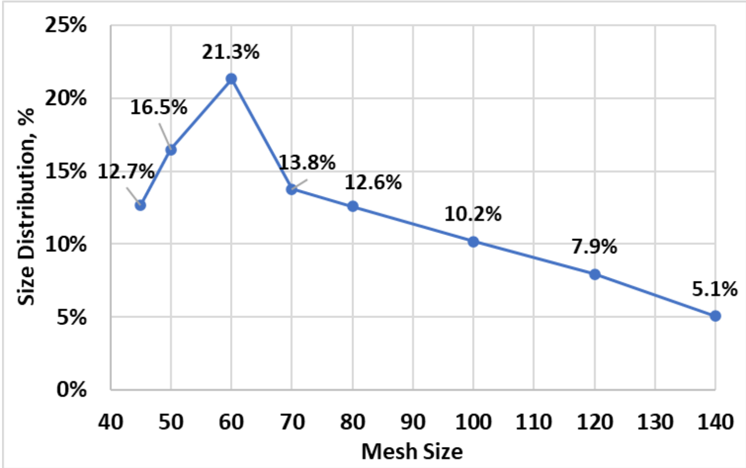

Figure 4. Particle Size Distribution of OK 40/140

Subsequently, individual sizes were subjected to different pressures: 4,000 psi, 6,000 psi, 8,000 psi, and 10,000 psi, and post-crush analysis was performed to determine Remained Original Size %. Results in Fig. 5 indicate that smaller particles can withstand pressure better than larger ones.

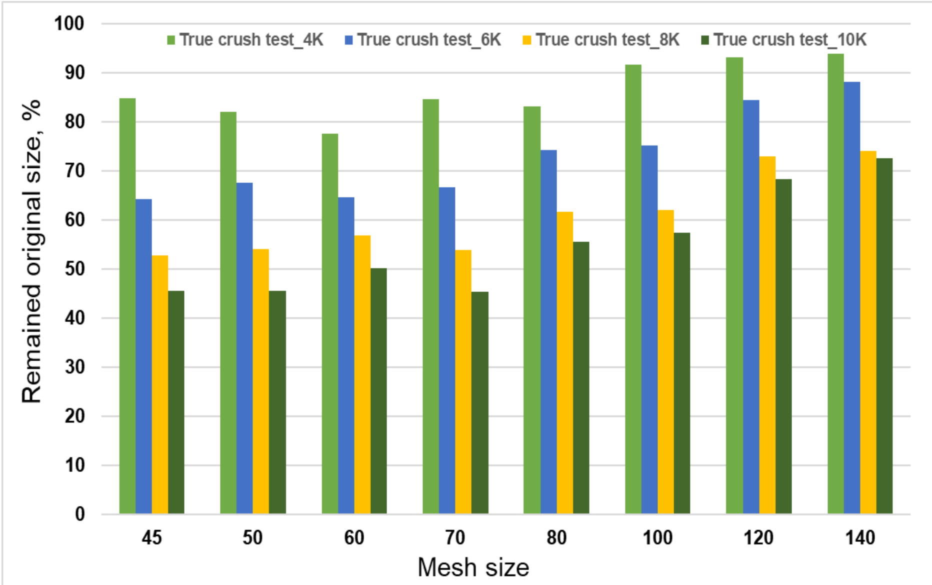

Figure 5. TrueCrush Ind. Mesh Results for the OK 40/140

It is evident from Fig. 5 that smaller mesh-sized proppants maintain their integrity under pressure better than larger mesh-sized proppants, as indicated by higher values for Remained Original Size. For instance, the Remained Original Size at 8K for the 140-mesh and 60-mesh sizes are approximately 74% and 56% respectively. However, these figures do not account yet for their respective representation (distribution) in the sample, and therefore a weight score is calculated.

To demonstrate the weight score calculation, the 140-mesh Maintained Original Size of 74% is multiplied by its distribution of 5.1% (impact factor). This yields a weight score for the 140-mesh of only 3.8%. In the same way, when the 60-mesh Maintained Original Size of 56% is multiplied by its distribution of 21.3% (impact factor), the weight score for the 60-mesh size is 12%. So, even though the 60-mesh is clearly weaker than the 140-mesh, because of the distribution, its impact on the overall proppant is 3 times greater. Distribution is very important, and it is clear from Fig. 6 below, that the 140-mesh size does not exert significant control over this sand's performance. Instead, larger mesh-sized proppants (45, 50, 60, and 70-mesh) are likely to govern this sand's performance, given their higher weight scores and distribution values.

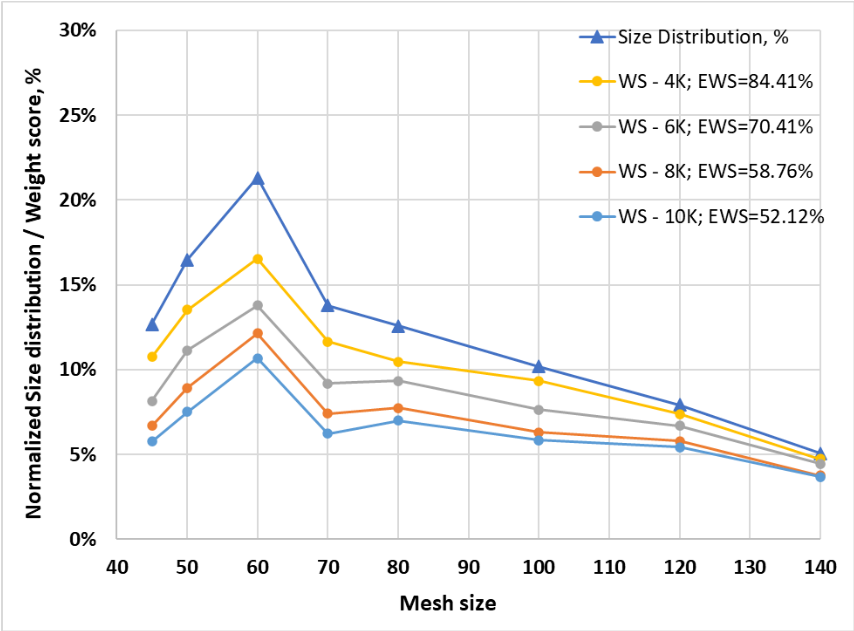

Figure 6. TrueCrush Ind. Weight Scores for the OK 40/140

The final step of the TrueCrush test is to calculate the Effective Weight Score (EWS). EWS represents the % of the total proppant that maintains its original size. This final score reveals the strength of each individual proppant mesh size and the strength of the entire sample. When we add up the weight scores for this Oklahoma sand at 8,000 psi, we get a final EWS of 58.8%. This means that 58.8% of the total proppant is expected to maintain its original size at 8,000 psi.

While the 40/140 OK sand passed the API test at 8,000 psi, with over 90% of the proppant remaining above the 140-mesh sieve, the TrueCrush Test revealed that only 58.8% of the entire proppant remained its original size at 8,000 psi. This discrepancy could significantly impact the estimation/forecasting on the cumulative productions, decline curve, and economics analysis of oil wells employing hydraulic fracturing.

6. Summary Analysis

Permeability tests and subsequent permeability reduction analyses, presented alongside the EWS in Fig. 7, demonstrate a very strong correlation. This further supports the efficacy of the TrueCrush Test for evaluating proppant performance.

As applied pressure increases, leading to decreased EWS values, permeability reduction also increases, signifying greater sand crushing. These findings facilitate the prediction of permeability reduction based on known EWS values relative to applied pressure.

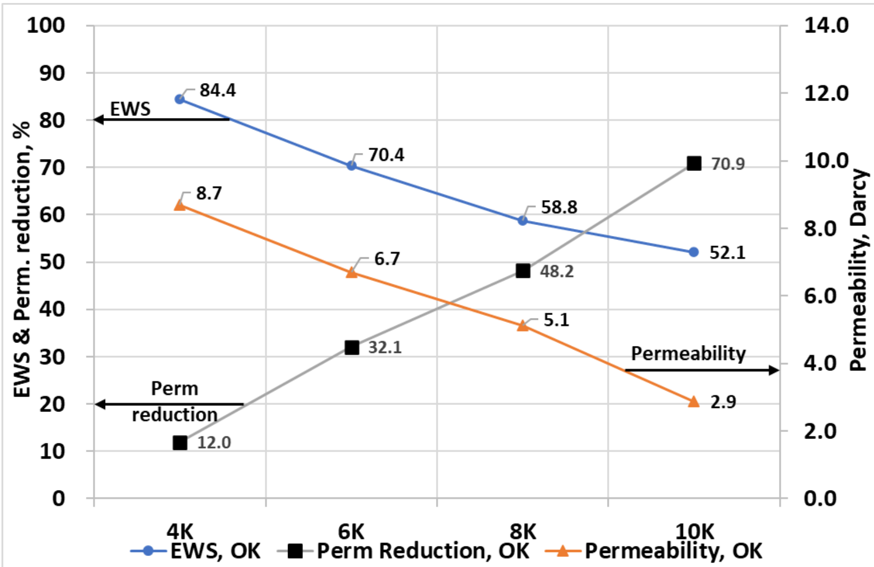

Figure 7. Correlation Between EWS and Permeability Reduction of OK 40/140

7. Conclusions

This study carefully reviewed the procedure and the true physical meaning of the API Crush Test and presented in detail the procedure and the applications of the TrueCrush Test. We also pointed out a few weaknesses in the API Crush Test and ways that it can be misleading. To prove the TrueCrush test is more reliable than the API Crush Test in terms of evaluating proppant performance, we conducted four samples: OK sand, South TX sand, White sand #1, and White sand #2. The results from all four sands yielded the same conclusions, which can be summarized as follows:

(1) Since the API Crush Test uses the smallest mesh size as a main driving force to determine a proppant's strength, the K-value might not always represent well the actual strength and actual performance of the sample. Higher K-values might not always indicate better proppant performance in terms of downhole permeability.

(2) The size distribution is one of the key factors that controls the proppant's performance. The API test does not account for size distribution. Instead, it uses the smallest size alone, which is not enough to evaluate the performance of the entire proppant. In most cases, larger sizes are dominated and sometimes exceed 90%. This group, in fact, controls the performance of the sample when stress is applied.

(3) API Crush Test can be easily manipulated to achieve higher K-Values (samples look stronger) by coarsening the proppant. This can be done by decreasing the distribution of the smallest sizes (i.e. decrease % of 140) and/or increasing the distributions of the larger sizes (i.e. increase % of 45 mesh). Mesh sizes can also be added (i.e. change from 50/140 to 40/140). Although these methods provide opportunity for increasing the K-Value, they do not increase the strength. Since these methods coarsen the sample, they actually weaken the proppant.

(4) the API test should be replaced by the TrueCrush test to precisely analyze and compare the capabilities of proppants. The TrueCrush test shows better results and implication than the API test when evaluating the performance of the proppant. The TrueCrush EWS value represents the overall strength of the entire proppant by taking into consideration particle size distribution and each individual size's strength.

(5) Since the EWS values from the TrueCrush Test quantify a proppant's actual strength, EWS values allow for "apples to apples" proppant comparisons for cost/benefit analysis.

(6) The TrueCrush Test data from the OK, South TX, White Sand #1, and White Sand #2 reveals that the permeability reduction % (and permeability) due to the applied crushing pressure and the TrueCrush EWS are strongly correlated. Practically, it is proposed using the EWS to estimate permeability values under downhole conditions if zero-pressure permeability values are known. Because of this strong connection, EWS values will assist with decline curve and future reservoir performance forecasting.

(7) The implementation of the TrueCrush Test promises to maximize well performance, improve cumulative well output, and enhance decline curve forecasting.

8. References

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