Value of API crush test for ceramic proppant evaluation and field studies on productivity in unconventional reservoirs
Outline

• The need to critically review API crush test and misconceptions
• 10 Myths – SPE 119242
  – How to use and misuse crush data!
• Recommendations for proppant evaluation
• What matters when evaluating proppant quality
• Production behavior in fractures completed with different proppants - field studies
The development stages

- External interest
- Volume, price, territory
- Density crush, conductivity, sphericity, inertness
- Distance, availability, cost of ore

1. Request for development
   - (Does the market need it)
   - Internal drive

2. Marketing research
   - Competition, uniqueness

3. Identification of target parameters
   - WHAT to develop
   - How close can we get Trade-offs

4. Identification of ore and process
   - HOW
   - Lab run, followed by Experimental run

5. Commercialization
   - ($)

What test methods in proppant development to use?

- Testing according to ISO 13503-2 (2006)
- Identification of an easy-to-use method to quickly qualify or discard candidate proppants or mineral blends
- Where to test for verification
- External input (e.g., fluid systems compatibility)
CARBORosLite

• In 2010 TNK-BP asked Carbo to develop a «Ryabchek» proppant
• Initial research was done in Carbo’s research center in Houston
• A new product was developed in Russia, launched in 2013, CARBORosLite
How to distinguish a promising blend from a failure

- Crush test, SG and acid solubility for quick answers
- Run full API test on promising blends
- Identify best blend

PROBLEM!
What if Crush test results are misleading?

• From experience and SPE 119242 we know, that crush tests are of limited, or no use to conclude conductivity

• What matters is conductivity as a direct indicator for production rates

• It is technically impossible to run conductivity test on all blends
## TNK-BP QAQC for light weight proppant

<table>
<thead>
<tr>
<th>Fracture Closure Stress (psi/MPa)</th>
<th>Proppant Pack Conductivity (mD/ft)</th>
<th>10/14</th>
<th>12/18 - 12/20</th>
<th>16/20 - 16/30</th>
<th>20/40</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 / 13.79</td>
<td>no data</td>
<td>35708</td>
<td>18270</td>
<td>8352</td>
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<td>4000 / 27.58</td>
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<td>12795</td>
<td>6538</td>
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<tr>
<td>6000 / 41.37</td>
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<td>8442</td>
<td>6445</td>
<td>4055</td>
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<tr>
<td>8000 / 55.16</td>
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<td>2806</td>
<td>2324</td>
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<tr>
<td>10000 / 68.95</td>
<td>no data</td>
<td>1613</td>
<td>1198</td>
<td>1241</td>
<td></td>
</tr>
<tr>
<td>12000 / 82.74</td>
<td>no data</td>
<td>200</td>
<td>225</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>14000 / 96.53</td>
<td>no data</td>
<td>90</td>
<td>154</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Pressure (psi/MPa)</th>
<th>Proppant Crush Test (% Fines)</th>
<th>10/14</th>
<th>12/18 - 12/20</th>
<th>16/20 - 16/30</th>
<th>20/40</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000 / 34.47</td>
<td>8.0</td>
<td>3.0</td>
<td>2.0</td>
<td>1.0</td>
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<tr>
<td>7500 / 51.71</td>
<td>22.0</td>
<td>19.8</td>
<td>13.0</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>10000 / 68.95</td>
<td>38.0</td>
<td>35.0</td>
<td>21.0</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>12500 / 86.18</td>
<td>48.0</td>
<td>43.0</td>
<td>33.0</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>15000 / 103.4</td>
<td>no data</td>
<td>49.0</td>
<td>39.0</td>
<td>31.0</td>
<td></td>
</tr>
</tbody>
</table>
Crush test vs conductivity

• Please take reference to tables provided…
• CARBORosLite 12/18 crush is 2 x higher than specs BUT conductivity is in line or higher
How to Use and Misuse Proppant Crush Tests – Exposing the Top 10 Myths

T. T. Palisch, M. Chapman, R. Duenckel, S. Woolfolk, CARBO Ceramics, Inc.
M. C. Vincent, Insight Consulting
Crush Test Protocols

• Crush tests are cheap, fast, and data available
  – “improve quality…delivered proppants”
  – “enable…to compare physical properties”
  – Original intent to help qualify sand sources
• “Crush results” and proppant selection
  – “qualified engineering analysis….required for their application to a specific situation”
  – SPE 11634 – Conductivity comparisons cannot be made on the basis of crush tests

**Yet many still select proppants based on crush results**
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
ISO 13503-2 Crush Test Procedure

• Proppant is pre-sieved to remove particles outside of stated mesh range.
• Dry proppant placed in steel cell at ~4 lb/sq ft (sand equivalent)
• Room temperature
• Proppant evenly distributed with level surface
• Load applied at uniform rate
• Constant stress maintained for two minutes

• Proppant is sieved post-crush. The weight percent which falls below the primary screen is reported.
  – For 16/20 proppant all material < 20 mesh is reported as “fines”
  – For 30/50 proppant all material < 50 mesh is reported as “fines”
Are test conditions realistic?

- Proppant is pre-sieved.
- Proppant loading (pack width ~ ½”)
  - Sand/RCS/LWC ~ 4 lb/ft²
  - IDC ~ 4.8 lb/ft²
  - Bauxite ~ 5.2 lb/ft²
- Smooth, steel plates – embedment?
- “Carefully loaded”
- Dry, room temperature
- 2000 psi/min, relaxed after 2 minutes
- Only the particles smaller than bottom screen are considered “fines” or “crush”
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
Are the results repeatable?

16/30 Brown Sand Hand Loaded Weight Percent Crush at 4000psi

ISO Subcommittee Results

Lab Number | Test#1 | Test#2 | Test#3 | 14.8% Avg
---|---|---|---|---
1 | 10.95 | 25.21 | 19.06 | 12.27
2 | 10.63 | 24.29 | 16.70 | 11.89
3 | 16.70 | 24.30 | 19.06 | 14.88
4 | 17.86 | 18.45 | 17.52 | 17.09
5 | 10.10 | 24.75 | 17.52 | 17.09
6 | 6.42 | 8.60 | 18.43 | 11.96
7 | 9.10 | 23.29 | 19.88 | 14.88
8 | 5.92 | 8.90 | 9.10 | 8.26
9 | 9.20 | 23.26 | 8.90 | 11.96
10 | 10.1 | 9.50 | 8.40 | 9.18
11 | 9.18 | 25.21 | 17.78 | 11.96

Are the results repeatable?
Are the results repeatable?

16/30 Brown Sand Mechanical Loaded Weight Percent Crush at 4000psi

ISO Subcommittee Results

Lab Number | Test#1 | Test#2 | Test#3 | Percent Crush | No data reported | 10.0% Avg
--- | --- | --- | --- | --- | --- | ---
1 | 9.40 | 11.41 | 10.79 | 9.85 | 9.94 | 10.0% Avg
2 | 9.79 | 16.66 | 12.00 | 8.40 | 10.22 | 10.0% Avg
3 | 11.41 | 12.00 | 9.07 | 7.76 | 9.07 | 10.0% Avg
4 | 12.80 | 10.32 | 8.40 | 9.07 | 9.94 | 10.0% Avg
5 | 12.00 | 10.89 | 7.80 | 9.44 | 9.94 | 10.0% Avg
6 | 10.53 | 9.85 | 7.80 | 9.07 | 9.94 | 10.0% Avg
7 | 10.32 | 10.28 | 9.07 | 9.07 | 9.94 | 10.0% Avg
8 | 9.94 | 8.20 | 7.80 | 9.07 | 9.94 | 10.0% Avg
9 | 10.53 | 7.50 | 8.40 | 9.07 | 9.94 | 10.0% Avg
10 | 9.94 | 8.40 | 7.50 | 9.07 | 9.94 | 10.0% Avg
11 | 10.32 | 7.50 | 8.40 | 9.07 | 9.94 | 10.0% Avg

Are the results repeatable?
Are the results repeatable/reliable?

Crush Cell Loading critical

• “variance in crush results….associated with method of loading…”

• Significant efforts ongoing on ISO Committee and StimLab to alleviate variations in results
  – Loading technique thought to be the cause
  – Lab to lab, technician to technician, equipment to equipment
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
Does Fracture Width Affect Crush?

Various 20/40 Proppants at 6000 psi

Crush Cell Loading, lb/ft²

Crush % 6k

RCS
ELWC
Sand

ISO Crush Test Conditions
Does Fracture Width Affect Crush?

- Interior grains loaded “evenly”
- Exterior grains have fewer load points
- Crush increases significantly as proppant loading decreases

- For a 20/40 proppant, there are approximately 24 layers of proppant in standard 4 lb/ft² crush test.
  - 8% are exterior grains
- 1 lb/ft² is ~6 layers of 20/40 proppant
  - 33% are exterior grains
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
4. Uniform particle arrangement is realistic
Uniform Packing Arrangement?

Is this ribbon laterally extensive and continuous for hundreds or thousands of feet?

Pinch out, proppant pillars, irregular distribution?
Potential Proppant Arrangements

• 45 t of proppant contains ~125 billion particles
• Most every arrangement we can envision likely exists somewhere in a frac
• All arrangements cause higher stress concentration on proppant than our “idealized” testing on uniform wide packs
• In series, the flow capacity limited by poorest arrangement, not the average
Crush at 10,000 psi
20/40 Proppants

0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

# of Layers

% Crush

White Sand
ELWC
RCS
Bauxite Ceramic

1 lb/ft^2
ELWC

1 lb/ft^2
Bauxite

1 lb/ft^2
Sand & RCS

Standard crush tests
~24 layers of 20/40

Partial Monolayer
1000 psi Crush vs # Layers

Crush at 1000 psi
All 20/40 Proppants

# of Layers
% Crush

White Sand
RCS
ELWC
Bauxite Ceramic

1 lb/ft² Sand & RCS
1 lb/ft² ELWC
1 lb/ft² Bauxite Ceramic

Partial Monolayer
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
4. Uniform particle arrangement is realistic
5. Small particles are stronger
Are Large Particles weaker than Small?

SINGLE GRAIN CRUSH
Carbolite

\[ y = 1488.2x - 18.714 \]

\[ R^2 = 0.7765 \]

Pounds of Force to crush one pellet

Bigger particles, more crush

**NO!!**
For all proppant types, larger grains have greater individual strength.

Source: Stim-Lab Consortium, July 2001

Not exactly. However, the addition of curable resin can increase the strength of the overall pack if cured properly in the fracture.

Courtesy Stim-Lab
Smaller mesh sizes distribute the load across more particles compared to larger mesh sizes, and provide more layers for the same mass loading.
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
4. Uniform particle distribution is realistic
5. Small particles are stronger
6. Resin coating improves particle strength
Does the application of resin increase Particle Strength?

Not exactly. However, the addition of curable resin can increase the strength of the overall pack if cured properly in the fracture.

Courtesy Stim-Lab
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
4. Uniform particle distribution is realistic
5. Small particles are stronger
6. Resin coating improves particle strength
7. All proppants fail (crush) in the same way
Do all Proppants Fail in the Same Manner?

When they fail…
- Sands shatter like a glass
- Ceramics cleave like a brick
- Resin Coated products “deform”; fines captured

Brown Sand at 6k psi.
RCS at 8k psi.
IDC at 8k psi.
Remember that 5% crush on a 20/40 proppant could be a 5g of 50 mesh particles or 5g of 200 mesh particles.

Source: CARBO Analyses Nov 1998

Do all Proppants Fail/Crush the Same?

Sieve distribution of fines generated at 6k psi for two proppants

Weight Percent of total crushed material

Source: CARBO Analyses Nov 1998
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
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3. Fracture width doesn’t affect proppant crush
4. Uniform particle distribution is realistic
5. Small particles are stronger
6. Resin coating improves particle strength
7. All proppants fail (crush) in the same way
8. 5% crush damages all proppants similarly
Do fines affect all proppants similarly?

CAUTION: There is little doubt that most fines have the potential to affect the flow capacity of the fracture. However, to use this chart, one must assume:

- All reported crush is in the 60/100 range
- Pore geometry of 20/40 Brady at 3500 psi is identical to the product of interest
- Fines are equally damaging to sand, RCS, ceramic
- Fines will be uniformly distributed as in test

Coulter and Wells:
Measured effect of 60/100 fines dry mixed into sand. Fines were too large to migrate. This is not a fines migration test, it is a fines contamination measurement.

Authors noted the reduction would depend on proppant roundness, conductivity, and concentration.

Source: SPE 3298, Coulter and Wells
Uniformly mixed 60/100 mesh fines into pack before measuring conductivity

Conductivity testing can account for crushed material/fines in a hot, wet environment, and demonstrate that this correlation doesn’t work for all proppants!
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
4. Uniform particle distribution is realistic
5. Small particles are stronger
6. Resin coating improves particle strength
7. All proppants fail (crush) in the same way
8. 5% crush damages all proppants similarly
9. Hot/wet crush tests provide adequate understanding
**Fluid Effects**

- Crush testing is performed dry. What if the proppant is saturated?

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**Modified Crush Test Results**

ELWC at 6000 psi

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Source: CARBO Tech Brochure 3/4/96
Is one set of Test Conditions superior to another?

Dry, wet, hot, room temperature, water or oil… is one method more realistic than another?

Source: SPE 119242
Ten Myths to Investigate

1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable
3. Fracture width doesn’t affect proppant crush
4. Uniform particle distribution is realistic
5. Small particles are stronger
6. Resin coating improves particle strength
7. All proppants fail (crush) in the same way
8. 5% crush damages all proppants similarly
9. Hot/wet crush tests provide adequate understanding
10. Crush tests correlate with conductivity
Can Crush results be Correlated to Conductivity?

**Test Differences**

<table>
<thead>
<tr>
<th>Conductivity Test</th>
<th>Crush Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proppants evaluated as received</td>
<td>Remove out of spec particles</td>
</tr>
<tr>
<td>Equivalent <em>mass</em> loading</td>
<td>Equivalent <em>volume</em> loading</td>
</tr>
<tr>
<td>2 lb/ft$^2$</td>
<td>~4 – 5.2 lb/ft$^2$</td>
</tr>
<tr>
<td>Sandstone shims</td>
<td>Steel pistons</td>
</tr>
<tr>
<td>Flow brine through pack</td>
<td>Dry</td>
</tr>
<tr>
<td>Elevated temperature</td>
<td>Room temperature</td>
</tr>
<tr>
<td>(150° to 350° F)</td>
<td></td>
</tr>
<tr>
<td>Stress held for at least 50 hours</td>
<td>Stress held for 2 <em>minutes</em></td>
</tr>
</tbody>
</table>
Does proppant damage in the conductivity cell correlate to damage with other loading procedures?

More proppant damage occurs in a conductivity test than in the crush cell.

Horizontal lines denote crushed proppant recovered from conductivity cell after 50 hour testing.

All tests at 2 lb/ft² loading
Can Crush results be Correlated to Flow Capacity?

Permeability vs ISO Crush Results at Comparable Concentration

No direct correlation between ISO Perm and ISO Crush, even at comparable proppant concentrations
Can Crush results be Correlated to Conductivity?

Comparison of Two Different 20/40 IDC Proppants

**Proppant Blue**
- 20/40 Mesh
- MPD 731 μm
- ASG 3.34 g/cc
- 10k Crush - 3.7%

**Proppant Red**
- 20/40 Mesh
- MPD 685 μm
- ASG 3.32 g/cc
- 10k Crush - 8.6%

By traditional measurements, Blue has superior proppant sizing and superior crush resistance!
Are Crush results Useful?

• In Manufacturing
  – CARBO performs >70,000 crush tests per year!
  – With automated sampling and crush equipment, can achieve extremely repeatable data
  – Excellent QC gauge for ensuring a consistent quality product is being produced
  – But results are not predictive of conductivity (CARBO has ~ dozen conductivity cells running 24/7/365)

• For Proppant Selection
  – By itself, CAUTION should be used.
  – May be used for qualitative observations.
  – Conductivity testing a much better way to determine proppant value
From API test to practice

• We understand that API test is giving misleading, or at best incomplete answers
• Conductivity tests are closer to reality and a better tool to select a proppant
• Now lab meets reality: How much conductivity is really there and how proppant quality impact productivity
The Challenge of Tight/Unconventional reservoirs:

- EXTREMELY low permeability formations

Applying key technologies driving UCR development:

- Advanced horizontal drilling and completion
- Multi stage fracturing to dramatically increase reservoir contact
Permeability (pore throat) visualization

Neptune (conventional)
Pluto (tight)
Earth

Territory of Moscow represents shale!
Fracture Optimization

• Wellbore placement and lateral length
• Completion hardware and isolation techniques
• Fracture spacing and number of fracs
• Fracture geometry and conductivity
How can we increase fracture conductivity?

• Larger proppant volumes
• Higher proppant concentration
• Larger diameter proppant (depending on quality)
• Cleaner fluids
• Higher tier/Quality proppant

In most cases, increase in conductivity will lead to an increased investment
Proppant selection process

- Predict the fracture Conductivity at Realistic Conditions
  - Several sophisticated Frac Models will do this
- Run sensitivities to determine optimal Conductivity
  - Provides the highest return on investment
- Validate with field results
  - Do the results match the model? Recalibrate?
Eagle Ford Shale

Webb County operator

- Evaluated Tier 1 vs Tier 3 proppants
- Compared to internal wells, as well as offset operators
Conductivity at Eagle Ford Conditions

Baseline Conductivity, mD-ft

Realistic Conductivity, mD-ft

93% reduction

94% reduction

97% reduction

SPE 155779
Eagle Ford Production Match/Modeling

Cumulative Production vs Time

<table>
<thead>
<tr>
<th>Transverse Fractures</th>
<th>xf (ft)</th>
<th>kfwf (mD-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>113.00</td>
<td>0.16</td>
</tr>
<tr>
<td>20</td>
<td>175.00</td>
<td>0.66</td>
</tr>
<tr>
<td>20</td>
<td>250.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

- +50%
- +100%
Production impact of conductivity

Rosetta Resources Gates Ranch
12 Month Cumulative Gas Production, MMCFE
Well Completion Between Sand and Ceramic Proppant
Normalized to Number of Stages

Ordered By 6 Month BOE - 6 Month Cum BOE

- 180,000
- 160,000
- 140,000
- 120,000
- 100,000
- 80,000
- 60,000
- 40,000
- 20,000

12 Month Cumulative Gas Production per Stage, MMCFE/stage
Haynesville Shale

- *Desoto/Caddo Parish* by one operator
- 55 Wells – 20 utilized Tier 1 proppant, 35 utilized Tier 2
- All drilled/completed similarly in similar time frame
Actual production after 2.5 years

Cumulative Gas Production at Month 32

Incremental 30% production (0.5 BCF per well avg) in ~2.5 Years

$1.8 million incremental PV per well after 2.5 years, for a $250k investment

Tier 1

Tier 2

$3.50/mcf
Bakken Trial

22 Month Cumulative Production per Well Average

- Tier 1 LW Ceramic Wells
- Tier 3 Offset Wells
What impacts proppant pack conductivity from a proppant perspective

- Improved roundness equals to improved “space to flow”
- Shape and form of fines
- Ability of fines to migrate
- Proppant uniformity and strength
- Resistance to cyclic loads, chemicals and temperature
Key Take Away Messaging

• The HF process provides two things – reservoir contact and conductive pathway.
  - *It is the critical (only) link between the reservoir and the wellbore*
• Proppant is the conductivity pathway.
• Hydraulic fractures are Conductivity Limited…period.
  - *The more you have, the more you make*
  - *One must estimate the conductivity of the fracture at realistic conditions*
• Proppant Selection cannot be made based on depth, stress, mean particle diameter or what the last engineer did.
  - *It must be designed specifically to the deliverability of a given well*
• Proppant Selection is a Cost vs Benefit decision
  - *You must determine the economic benefit of increasing the conductivity via frac modeling and field validation*
Summary

• Availability and cost impacting proppant selection
• Unconventional reservoir developments, when taking off, will require massive volumes
• Fluid selection and Conductivity should drive proppant selection
• Best completion practice require a realistic estimate of conductivity
• The economical impact can be tremendous
Questions?

- Presentation based on SPE 119242 and 160206