SPE 119242

How to Use and Misuse Proppant Crush Tests – Exposing the Top 10 Myths

John Kullman, CARBO Ceramics

M. C. Vincent, Insight Consulting
Outline

• Introduction/Motivation
• Crush Test Procedure
• Myths
  – Misuse/misapplication
• Summary
The Big Picture

- Fracs must provide:
  - Reservoir contact (length, height) to contact and collect oil and gas
    - Related to volume of proppant
  - Flow capacity to carry oil and gas to the wellbore
    - Related to proppant permeability and frac width – described as conductivity

- Other Important Proppant Characteristics
  - Durability
  - Temperature Resistance
  - Transportability
  - Fluid Compatibility
  - Flowback Control
  - Environmentally Benign
Question…

• Gas Well
  – 7500 psi stress
  – You can successfully place a 16/20 or 16/30 sized proppant

• Two choices of proppant
  – Proppant A – 16/20 Ceramic, 14% Crush (7.5k)
  – Proppant B – 16/30 Ceramic, 7.5% Crush (7.5k)
  – Which proppant would you choose?
  – What if I told you that they had the same MPD?
  – What would you be willing to pay for your choice?
Introduction/Motivation

  - “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 choose their proppants based on crush results**
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. 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”
ISO 13503-2 Crush Test Procedure

Do these reflect realistic conditions?

- Proppant is pre-sieved.
- Proppant Loading – 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”
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
Are the results repeatable?

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

Test#1  Test#2  Test#3
10.63  10.63  10.63
9.18  9.18  9.18
24.29  24.29  24.29
22.60  22.60  22.60
25.21  25.21  25.21
16.70  16.70  16.70
14.60  14.60  14.60
16.70  16.70  16.70
17.86  17.86  17.86
14.71  14.71  14.71
24.52  24.52  24.52
17.52  17.52  17.52
9.80  9.80  9.80
10.10  10.10  10.10
9.20  9.20  9.20
22.75  22.75  22.75
22.28  22.28  22.28
23.26  23.26  23.26
24.77  24.77  24.77
6.42  6.42  6.42
2.95  2.95  2.95
8.04  8.04  8.04
9.04  9.04  9.04
18.88  18.88  18.88
8.77  8.77  8.77
6.09  6.09  6.09
8.40  8.40  8.40
18.43  18.43  18.43
19.98  19.98  19.98
9.38  9.38  9.38
9.10  9.10  9.10

14.8% Avg
16/30 Brown Sand Mechanical Loaded Weight Percent Crush at 4000psi

Are the results repeatable?

Lab Number

ISO Subcommittee Results

Test#1
Test#2
Test#3
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 crush test.
  - 8% are exterior grains
- 1 lb/ft² is ~6 layers of 20/40 proppant
  - 33% are exterior grains
Crush Depends Upon Frac Width!

Monolayer ~ 0.2 lb/sq ft
Crush vs # Layers

Crush at 10,000 psi
20/40 Proppants

- White Sand
- ELWC
- RCS
- Bauxite Ceramic

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

% Crush vs # of Layers
Crush vs # Layers

Crush at 1000 psi
All 20/40 Proppants

White Sand
RCS
ELWC
Bauxite Ceramic

Partial Monolayer
RANGE OF FRACTURE COMPLEXITY
SPE 77441

Simple Fracture

Complex Fracture

Very Complex Fracture Network

Complex fracs are believed to provide less cumulative conductivity than simple, wider fractures
Vertical Complexity Due To Joints

Physical evidence of fractures nearly always complex

NEVADA TEST SITE
HYDRAULIC FRACTURE MINEBACK
Uniform Packing Arrangement?

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

Pinch out, proppant pillars, irregular distribution?
Are Large Particles weaker than Small?

Single Pellet Crush

NO!!

Proppant Size inches  Courtesy Stim-Lab

Pounds of Force to crush one pellet

Percent Crush

30/50 LWC  20/40 LWC  16/20 LWC  12/18 LWC
For all proppant types, larger grains have greater individual strength.

Source: Stim-Lab Consortium, July 2001
Note that application of resin does not improve grain strength, but rather improves distribution of stress between grains and encapsulates fines.
So why does crush increase with large proppants?

• Strength in numbers?
Smaller mesh sizes distribute the load to across more particles compared to larger mesh sizes.
Proppant Type

- Natural quartz crystals (sand), manufactured ceramics, and resin-coated proppants crush differently

- Sand
  - Quartz crystals tend to result in a greater number of fine shards

- Ceramics
  - Tend to cleave or part into relatively few, larger pieces

- Resin Coated Products
  - Resin does not significantly change single grain strength, but improves distribution of stress. If the particles can be encapsulated, they will not be measured as “crush” regardless of whether the substrate fails

SPE 11634 - conductivity comparisons cannot be made on the basis of crush tests.
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.
Do fines affect all proppants similarly?

Remember…

- All proppants do not fail in the same manner
  - The fines generated by one proppant may look drastically different than those generated by another.

- The packing arrangement for similarly sized proppants are not the same for all types of proppants.
  - i.e. the packing arrangement for a 20/40 ceramic, 20/40 RCS and 20/40 Sand will be different even at comparable stresses.
After crushing 20/40 EconoProp at 6000 psi Standard API technique

Source: CARBO Analyses Nov 1998
"2% fines" reported with standard testing could mean 2 cleaved grains per 100 (4 immobile pieces), or it could represent 400 mobile fragments in the 100-mesh range.

It makes a difference!

Source: CARBO Analyses Nov 1998
Fluid Effects

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

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?

6k Crush @ 2#/ft2
Can Crush results be Correlated to Conductivity?

More Realistic Conditions in a Conductivity Test
What’s the Difference?

- Proppants evaluated as received
- Tests equivalent mass loading, and 2 lb/ft²
- Utilizes Sandstone shims
- Flow water through pack
- Elevated temperatures (150° or 250° F)
- Stress held for at least 50 hours
Disassembled API Proppant Cell

- Ports for Measuring Differential Pressure
- Temperature Port
- Proppant Bed
- Sandstone Cores
- Flow Through Proppant Bed
Long Term Conductivity Cells
Can Crush results be Correlated to Conductivity?

The “crush” measured after a Conductivity test significantly higher than Crush test.

6k Crush Results vs Crush after Conductivity Testing at 6k psi

All tests at 2 lb/ft² loading
Embedment

More width retained, but lower perm
Spalling
Example of Conductivity Loss

CONDUCTIVITY VS. CLOSURE STRESS

Source: Stim-Lab Consortium, Feb 2002 1.6-46
Proppant Durability

In the real world:

- Fractures are subjected to high stresses (increasing) for extended periods of time
- Stress levels fluctuate (cyclic stress) with wellwork and changes in line pressure

Therefore:

- All proppants appear to lose conductivity over time
- Traditional resins do not appear to protect proppants from degradation.
- Many data suggest degradation is a mechanical failure, not chemical attack.
Proppant Durability

• Traditional “long term” conductivity tests maintain stress on proppant for 50 hours
  – It is known that proppants continue to degrade beyond 50 hours, but this was a practical compromise between laboratory expense and accuracy.

![Graph showing conductivity decline over hours at constant stress.]

Longer test captures a portion of the time-dependent decline. We know degradation continues beyond this, but modern “50 hour” tests include correction for initial repacking/etc.

This phenomenon occurs even with silica saturation.

Reference: SPE 16415 Norton and Stim-Lab
Extended duration tests:

1984
(75 & 250F)
API “short term” cell: Metal plates, continuous flowing 2% KCl,
Non-silica saturated

Fig 19, SPE 12616 between metal plates

% Original Conductivity

0 30 60 90 120 150 180 210 240 270 300

Days at Constant Stress, 5000 psi

Reference: SPE 12616 by Montgomery, Steanson, Schlumberger
Published extended duration tests:

- 1986
  - 93C (200F)
  - All non-corrodible surfaces, prop in Teflon tube, continuous flowing 2% KCl

- 1986
  - (300F)
  - Teflon tube, continuous flowing 2% KCl, Non-silica saturated

Fig 4, SPE 14133

- CarboPROP at 10,000 psi (69 MPa)
- CarboLITE at 10,000 psi (69 MPa)
- Sand at 5000 psi (35 MPa)

SPE Drilling, April 1986, page 5

- Interprop
- Proflow
- RCS
- Ottawa Sand

Days at Constant Stress, 8500 psi

Conductivity (md-ft)

References: SPE 14133 by CARBO, SPE Drilling article by Norton-Alcoa Proppants and TerraTek Research
At 6500 psi and 250°F, 20/40 White Sand loses 40% of its conductivity compared to 150°F.
Cyclic Loading of Proppant Packs

- All proppants appear to be damaged by continued stress cycling

Effect of Stress Cycling on Proppants

Three cycles, 6000 to 1000 psi

- RCS #1: 50 hrs at 6000 psi, 23% loss
- RCS #2: 3 cycles, 6000 to 1000 psi, 32% loss
- EconoProp: 3 cycles, 6000 to 1000 psi, 15% loss

Source: CARBO Tech Rpt 99-062
Effect of Stress Cycling on Proppant Conductivity
(Stim-Lab July 2000 data)

- Ceramic loses 26%
- RCS loses 35% due to 25 cycles
Effect of Stress Cycling on Proppant Crush (6000 psi)

- Single Crush at 6000 psi
- Triple Cycle Dry Crush
- Triple Cycle Crush in Long Term Cell

Percent Crush (wt% smaller than 40 mesh)

<table>
<thead>
<tr>
<th>Proppant Type (all 20/40)</th>
<th>RCS #1</th>
<th>RCS #2</th>
<th>EconoProp</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS #1</td>
<td>1.37</td>
<td>3.33</td>
<td>1.92</td>
</tr>
<tr>
<td>RCS #2</td>
<td>1.52</td>
<td>3.83</td>
<td>3.02</td>
</tr>
<tr>
<td>EconoProp</td>
<td>10.44</td>
<td>15.79</td>
<td>8.47</td>
</tr>
</tbody>
</table>

CARBO Tech Rpt 99-062
Options to reduce crush:

<table>
<thead>
<tr>
<th>Action</th>
<th>Crush</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rename 16/20 to 16/30</td>
<td>↓ ~50%</td>
<td>No change</td>
</tr>
<tr>
<td>Add 30 mesh material to 16/20 and rename to 16/30</td>
<td>↓ ~60%</td>
<td>↓ ~30%</td>
</tr>
<tr>
<td>Reduce average proppant size or produce broader distribution</td>
<td>↓</td>
<td></td>
</tr>
<tr>
<td>Sticky additive to agglomerate fines</td>
<td>↓ ~100%</td>
<td>↓</td>
</tr>
<tr>
<td>Pre-cured or curable resins</td>
<td>↓</td>
<td>often ↓ at low stress,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>↑ at high stress</td>
</tr>
<tr>
<td>Include deformable “cushioning” agents</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>
The Correct Way to Test Proppant

• Remember, proppant must achieve two goals:
  – Reservoir contact (proppant volume)
  – Ability to conduct hydrocarbons with minimal pressure loss

• These characteristics can be *directly measured* with a conductivity test
  – Proppant confined between sandstone core
  – Realistic temperatures
  – Flowing brine, oil, and/or gas
  – 50 hour duration (or longer)
  – Cyclic stress, embedment, fines migration, non-Darcy and other issues can be investigated in specialized tests
  – *Directly measures parameters of interest* [frac width and flow capacity]
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Questions?
Darcy’s Law vs. Forchheimer Equation

- $\Delta P/L = \mu \frac{v}{k}$
  - Pressure drop is proportional to fluid velocity
  - Applicable only at low flowrates

- $\Delta P/L = \mu \frac{v}{k} + \beta \rho v^2$
  - Pressure drop is proportional to square of fluid velocity
  - Applicable at realistic fracture flowrates
Does Fracture Width Affect Crush?

- Crush increases significantly in narrow fractures.

  Interior grains are loaded “evenly” on 6 sides.

  Exterior grains are not stressed uniformly.
**Long Term Conductivity Test Procedure**

- Load 63 g (equivalent to 2 lbs/sq ft) of proppant in each cell.
- Install cells in the press.
- Purge 2% KCl solution with oxygen-free nitrogen.
- Apply a vacuum for 45 minutes to remove air in cells.
- Flow 2% KCl solution through heated silica sand, and cells.
- Ramp to an initial stress of 1000 psi and to a 500 psi fluid pressure.
- After checking equipment is working properly, heat cells to 250°F.
Long Term Conductivity Test Procedure

- Increase stress to 2,000 psi.
- Flow fluid at rates of 3, 4 and 6 ml/min. Measure $\Delta p$ 30 minutes after each step change in flow rate.
- Measure frac width and temperature. Maintain stress for 50 hr.
- Increase stress in 2,000 psi increments for 50 hours each.
- Continue measuring $\Delta p$ at 3, 4 and 6 ml/min of fluid flow, frac width and temperature until 12,000 psi stress is reached.
A Better Test to Select Proppant

- Long term conductivity testing
- Direct measurement of flow capacity of proppant pack
- Can account for:
  - Embedment
  - Temperature
  - Fluid Effects
  - Fines Migration (with appropriate flowrates)
Is complexity solely attributed to “rock fabric”?

Chudnovsky, Univ of Ill, Chicago

Unconsolidated 200 mesh sand, 35 lb XLG, Flow ← SPE 63233

Many other examples! [TerraTek, Baker, Weijers, CSM FAST consortium]
Frac Width – with CrossLinked Gel

Diffuse slurry
Modest concentration

TSO + high concentration

Diffuse slurry
Low concentration

We don’t envision thick filtercakes in very tight rock, but it doesn’t take much to damage a narrow frac!

2 ppa [240 kg/m³] sand slurry is about 1 part solids to 7 parts liquid.
Final frac width could be ~1/7th the pumping width!

\( W_f \)