Task 3 Cement Barriers: Assessment of Foamed Cement Systems used in Deep Offshore Wells (GOM)

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Improving Science-Base to Understand Wellbore Integrity & Performance of Foamed Cements

Behavior & performance of foam cements is unknown under in situ conditions

This study has sparked significant interest from both industry & BSEE (DOI)

Bridging significant knowledge gaps, providing information about behavior of foam cements at in situ conditions

3D CT Scan of a 10.4 mm³ digital subsection of 10% foam quality cement

Lab-based Pressure Vessel (on loan from Schlumberger)

Slip Stream at Wellhead (with BP/Schlumberger & BP/Baker Hughes)

3D CT Scan of field-generated foamed cement. Foam quality 47.8%; collected at a pressure of ~290 psi

Development of new imaging and analysis protocols
Evaluation over range of mix-design parameters
Evaluation of mix designs under field conditions
CFD to simulate mesostructure

For more information and products from the UDW Portfolio see https://edx.netl.doe.gov/udw
Physical Properties of Foamed Cement

- Atmospheric-Generated; 2 sets – part 1 (ongoing)
- Field-Generated; 2 sets – part 2 (depressurizing)
- Laboratory Pressure-Generated – part 3
  - How does gas distribution/BSD effect strength and permeability?

Ultrasonic velocity – quantitative physics based model of cement

Helium Porosimeter

N₂ Constant Flow Permeameter

Compressive Strength Modified ASTM C109

10% air
20% air
30% air
40% air
Permeability of 10% and 20% FCS1 foam quality does not appreciably change compared to the neat cement. This is a good indication that no coalescence takes place and the permeability is still determined mostly by the matrix.

Starting from 30% FCS1, permeability appreciably increases (more than three times) compared to 10% and 20% FCS1 foam quality. This likely indicates the beginning of bubble coalescing (although it is not dramatic yet).

Finally, for 40% FCS1 foam quality, the change in permeability is more than an order of magnitude. This may mean that permeability is predominantly determined by coalesced bubbles.
- The addition of air (as a lightweight additive) resulted in lower Young's modulus and compressive strength (with increasing foam quality).
  - Remarkable linear fit of strength and Young's modulus with foam quality (including the neat cement).
  - The entrained air in the cement creates a foamed network within the matrix of the cement which in turn exhibited a more elastic response. The lower Young's moduli values are consistent with a more ductile cement.
• FCS2 measurements show a slightly different behavior compared to FCS1. In particular, permeability growth starts already for 20% FCS2 foam quality.
• The 30% FCS2 foam quality continues the same trend and exceeds permeability of neat cement by about an order of magnitude.
• Difference in permeability between FCS1 and FCS2 of the same quality gives birth to the hypothesis about different BSD (bubble size distribution).
  • This is because the only difference between, say, 20% FCS1 and 20% FCS2 is the addition of a stabilizer.
• The addition of air (as a light-weight additive) resulted in lower Young's modulus and compressive strength (with increasing foam quality).
  • Remarkable linear fit of strength with foam quality (including the neat cement)
  • The entrained air in the cement creates a foamed network within the matrix of the cement which in turn exhibited a more elastic response the lower Young's moduli values are consistent with a more ductile cement.
Findings

• Good correlation between foam quality and mechanical properties
• The primary goal of foaming is to decrease the density of cement, while leaving the permeability unchanged.
• From this prospective, 10% and to some extent 20% foam cements fit the goal.
  – Measurements of the cements cured under pressure may give dramatically different results. Therefore, the above conclusions should be considered only as a base line for future investigations.

Significant Finding:
• Lower/Upper limit to foam quality:
  – Lower limit is strength related
    • Don’t want foam quality too low because you don’t get the mechanical benefits
  – Upper limit is permeability related
    • Need to provide zonal isolation
Gas Distribution of Foamed Cement

- Atmospheric-Generated; 2 sets – part 1 (complete)
- Field-Generated; 2 sets – part 2 (mostly complete)
- Laboratory Pressure-Generated – part 3
  - Comparisons of atmospheric- and field-generated samples continues.
Density Distribution of Field Generated Foamed Cement

D1 41.2%, ~310 psi
D2 47.8%, ~290 psi
E1 33.8%, ~290 psi
Density Distribution of Field Generated Foamed Cement D1

- Average CT number of a 13.8 cm² (2.1 in²) area through the center of pressurized vessel D1 along the vessel length.
  - Lower CT number indicates a lower density (higher gas fraction)
- The number of higher porosity zones in the CT images appears to increase with distance from the injection port to the retracting piston on the top.
Density Distribution of Field Generated Foamed Cement D1

High resolution industrial CT scans enable researchers to perform more detailed analysis of the structure of this pressurized foamed cement.
Density Distribution of Field Generated Foamed Cement D2

- Average CT number of a 12.0 cm² (1.9 in²) area through the center of pressurized vessel D2 along the vessel length.
  - Lower CT number indicates a lower density (higher gas fraction)
  - This sample appears to be more homogeneous with less variation than D1
Density Distribution of Field Generated Foamed Cement D2

*Foam Quality 47.8%, ~290 psi*

3D reconstruction of D2. Injection port is in the bottom of the core. Green is a higher porosity zone than the surrounding cement.
Density Distribution of Field Generated Foamed Cement E1

- Average CT number of a 14.0 cm² (2.2 in²) area through the center of pressurized vessel E1 along the vessel length.
  - Lower CT number indicates a lower density (higher gas fraction)
- This sample is distinctly different than the other 2 samples.
- Large “void” at the top filled primarily with a lower density liquid
Density Distribution of Field Generated Foamed Cement E1

Dense regions of cement (white) where the cement is less porous

The connected and localized nature of the low porosity zones suggest they were influenced by flow through the sample vessel.

Bands are parallel and on one side of the core. Linear bands may be indicative of shear bands in the foam.

Low density zone near the top. Left-most image show the isolated structure within the pressure vessel. Right-most image is the isolated structure with a 1 mm³ cube included for scale reference.

Adjacent to the inlet both gas and fluid filled voids were observed.

- These regions likely formed as the cement was entering the pressurized vessel.
- The abrupt change in geometry may have resulted in this unique distribution of irregularities.

Low Energy Technology Laboratory
Sub-cored Samples: steel vessel A2

- Starting with 3 foot long, 3 inch diameter vessel
  - Cut into 4 inch sections, sub-cored to 1.5 inch diameter
    - Because of gas at top of vessel a total of six sub-cores were obtained
    - Taped regions are where sub-core fractured
2 or 3 scans per subsection

• Original scans of the cement inside the steel vessels were not high quality
  – Too many artifacts

• To obtain highest resolution while imaging all of the sub-cores, subsections of the sub-cores were scanned.

• By scanning a ≈1.5” tall section we fill the CT detector and obtain scans with a resolution of 22.9 μm
Sub-core A2 - closest to injection port

- Sub-core A2 8-9 was used to explore the void distribution of the field generated foamed cement.

- **Purpose**: examine the void distributions in detail to determine how best to analyze all data.

Adjacent to inlet port
250 slices for analysis (originally 1000)

- **Region identified**
  - no unusual features
  - approximately 50 mm from injection port

- **Sub-cropped to remove edge effects**
  - Length = 5.7 mm
  - Diameter = 3.22 cm
  - Volume = 4.67 cc

**NOTE:** Total volume in vessel ≈ 4170 cc. Analysis on 0.1% of vessel volume!
Threshold to Isolate Voids

- Conservative threshold value used to minimize void interconnectivity
  - Voids less than 10 voxels large disregarded
  - See 2013 TRS for details on thresholding
- 85,669 individual voids segmented from scans
Bubble Void Size Distribution

- **85,669 total voids**
  - Largest void is 5.1 mm³ in total size, or 5.82% of the total isolated volume
  - Five largest voids are 10% of the total isolated volume
    - Of these 5, three are interconnected clusters of bubbles
  - Equivalent radius of voids calculated as well
The largest void – interconnected clusters

- The largest void is actually a connected cluster of individual bubbles.
- Connected through all 250 XY slices.
- Initial segmentation of this cluster identified more than 1000 bubbles, separated by throats.
  - John working on relationship between clusters and bubble counts.
Separating Voids

- Voids separated to determine where large voids are located
  - 10% of the total volume in each set
  - largest to smallest individual void volumes in each set
Separating Voids

Largest 10% - Red
2nd 10% - Orange
3rd 10% - Yellow
4th 10% - Green

Largest 10% - Red
2nd 10% - Orange
3rd 10% - Yellow
4th 10% - Green

Largest 10% - Red
2nd 10% - Orange
3rd 10% - Yellow
4th 10% - Green
5th 10% - Blue
6th 10% - Cyan
Separating Voids

Largest 10% - Red
2nd 10% - Orange
3rd 10% - Yellow
4th 10% - Green
5th 10% - Blue
6th 10% - Cyan
7th 10% - Violet

Largest 10% - Red
2nd 10% - Orange
3rd 10% - Yellow
4th 10% - Green
5th 10% - Blue
6th 10% - Cyan
7th 10% - Violet
8th 10% - Magenta
Separating Voids

- The smallest voids that comprise the final 20% make the 3D image difficult to render.

- Larger voids tend to be located in low density ‘swirls’.

- Smaller voids tend to be dispersed throughout the cement.
So, next steps

• Detailed analysis not possible on the entire volume
  – Not a matter of computer resources, but of practicality.
    • In 4.67 cc sub-sample there are $389(10^6)$ voxels … or roughly $3.24(10^{11})$ voxels in each vessel …
  – Downscaling to determine pertinent features and rapid/automated procedures to determine bubble size distributions are needed.
Clusters should be dealt with

• **Bubbles vs voids**
  – The large connected clusters skew the bubble size distribution.
  – Debatable whether or not truly connected, or an artifact of segmentation procedure.
  • But probably not a debate worth having. If not truly connected the amount of cement matrix between the bubbles is very small; \( \approx 20 \mu m \).

• **Possible solution path**
  – Imorph to determine how many bubbles in clusters of volume \( X \) relationship.
  – Equivalent radii to volume threshold to automate cluster identification.
**Downscaling**

- **Features (i.e. swirls) are still readily apparent when images are downscaled.**
- **Proposed methodology:**
  - Develop Freemat macro to read in original 16bit data as text, downscale within Freemat to get volumes & locations of high porosity zones. More control than image processing…
  - Won’t be as accurate to # of bubbles or exact porosities, but will give macroscopic picture of where these localized zones are forming.

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![Images showing original and downscaled versions](image_url)
Findings

• We have developed an imaging and analysis methodology

• We see a clear correlation between the gas distribution and the physical properties (atm)
  • Upper/lower foam quality limit dictated by permeability and strength

• Foamed cements generated using atmospheric methods do not look like those generated in the field

• Variations in cement structure within field-generated samples appear to indicate a relationship between the flow of the cement and the final porosity and properties of the hardened cement

• Work is continuing to isolate flow, distribution, and other relevant properties that can be engineered into safer and more efficient placement of foamed cement

All of our data is made available through the NETL website and EDX [https://edx.netl.doe.gov](https://edx.netl.doe.gov).
Extra slides
<table>
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<tr>
<th></th>
<th>Neat</th>
<th>10% FCS1</th>
<th>20% FCS1</th>
<th>30% FCS1</th>
<th>40% FCS1</th>
<th>10% FCS2</th>
<th>20% FCS2</th>
<th>30% FCS2</th>
<th>40% FCS2</th>
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<tbody>
<tr>
<td><strong>Permeability (mD)</strong></td>
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<td></td>
<td>0.3</td>
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<td>±0.1</td>
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<td><strong>Porosity</strong></td>
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<td>44.4</td>
<td>53.8</td>
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<td>40.3</td>
<td>45.1</td>
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<td><strong>Compressive Strength (psi)</strong></td>
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<td>3459</td>
<td>2211</td>
<td>1284</td>
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<td><strong>Young’s Modulus (psi)</strong></td>
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<td>310089</td>
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<td>463178</td>
<td>432482</td>
<td>431482</td>
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<td><strong>Poisson’s Ratio</strong></td>
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<td>0.125</td>
<td>0.101</td>
<td>0.108</td>
<td>0.106</td>
<td>0.110</td>
<td>0.106</td>
<td>0.108</td>
<td>0.107</td>
</tr>
</tbody>
</table>
Separating Voids

- The 10% volume void sets can be isolated from the overall distribution as well.