Measuring air void distribution in fresh concrete

Braden Tabb, Robert Felice, John Michael Freeman, Robert Frazier, David Welchel, Morteza Khatibmasjedi, Jake LeFlore

Tyler Ley, P.E., Ph. D

Acknowledgements

- Ken Hover
- Kevin Folliard
- Portland Cement Association
- Oklahoma Transportation Center
- Concrete Pavement Technology Center

Acknowledgements

- Oklahoma DOT
- FHWA
- Kansas DOT
- Nebraska DOT
- Iowa DOT
- Minnesota DOT
- Idaho DOT
- North Dakota DOT
- Pennsylvania DOT
- Connecticut DOT
- Illinois DOT
- Indiana DOT
- Michigan DOT
- Wisconsin DOT
- RMC Foundation

Summary

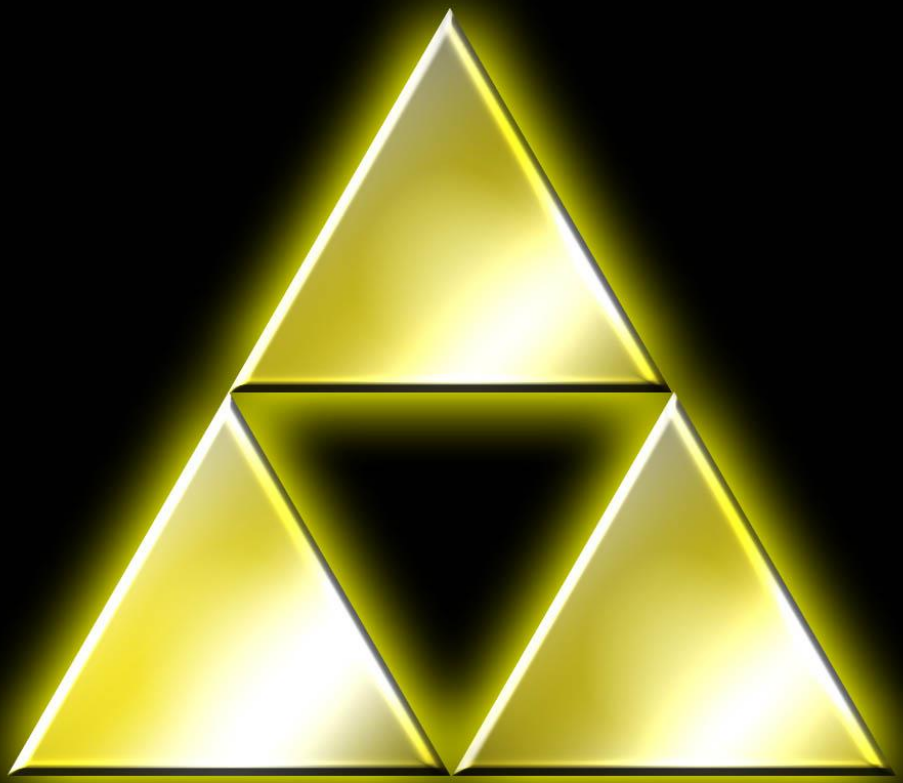
- Some basics of air entrained concrete…
- The Super Air Meter
- The future

Deicer salts

- The use of deicer salts are critical for the safety of the traveling public
- Highway agencies are becoming more aggressive in the types and uses of deicers
- Deicer salts can exasperate freeze thaw damage of concrete

The Freeze Thaw Triforce!!!

Air void System Quality

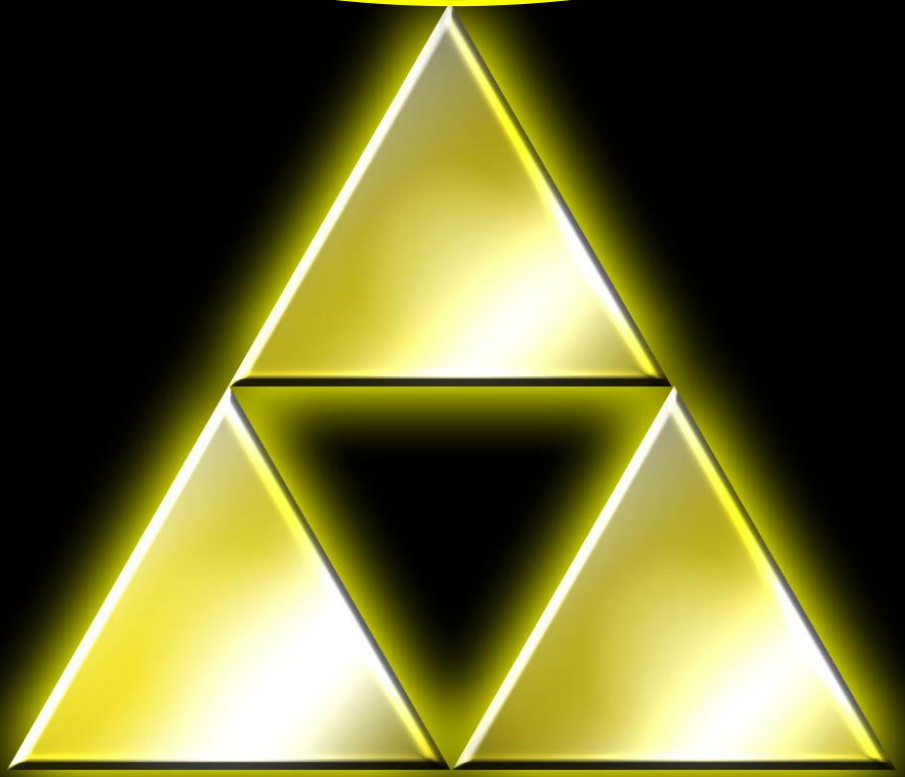


Durable Aggregate

Paste Quality

The Freeze Thaw Triforce!!!

Air void System Quality



Durable Aggregate

Paste Quality

Why Do We Add Air to Concrete?

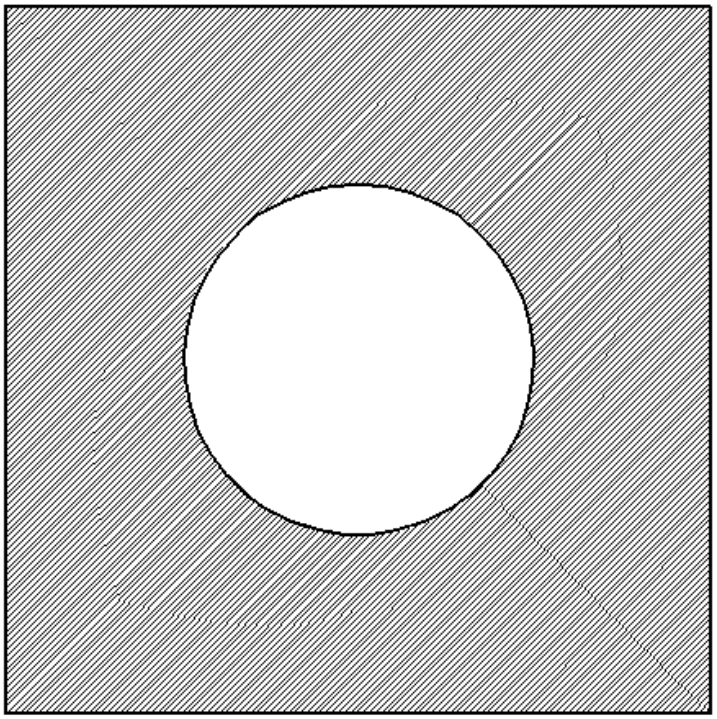
- Air-entrained bubbles are the key to the freeze-thaw resistance of concrete

Air volume ≠ freeze-thaw performance

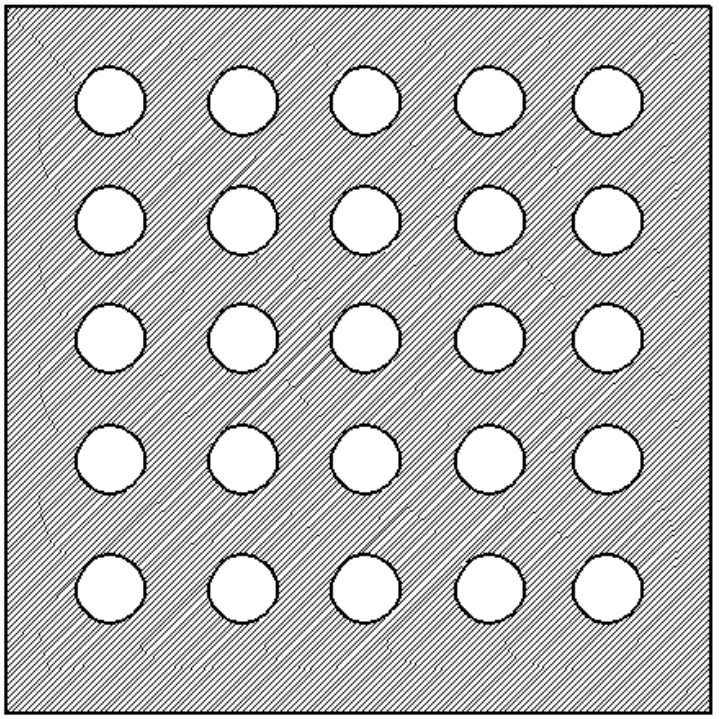
- Smaller bubbles are more effective in providing freeze-thaw resistance than larger bubbles

What Do You Want in an Air-Void System?

A



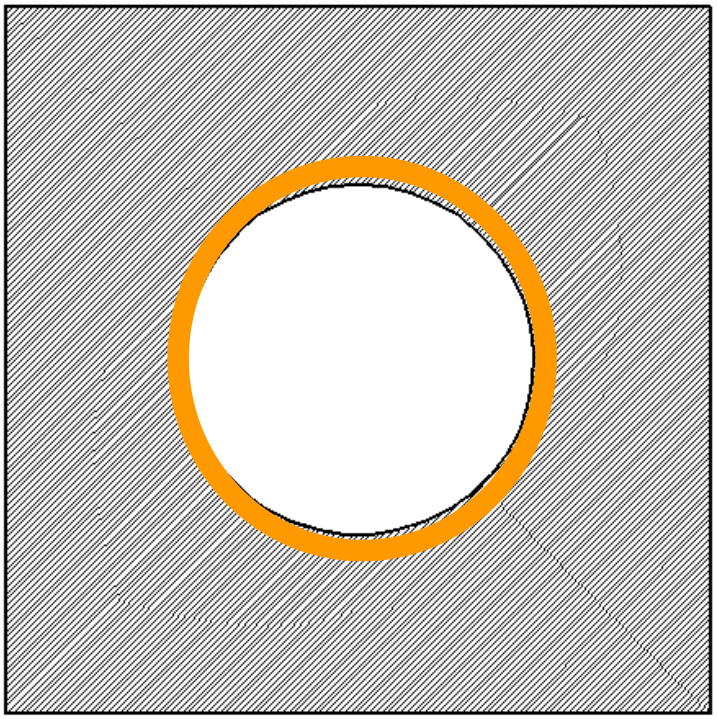
B



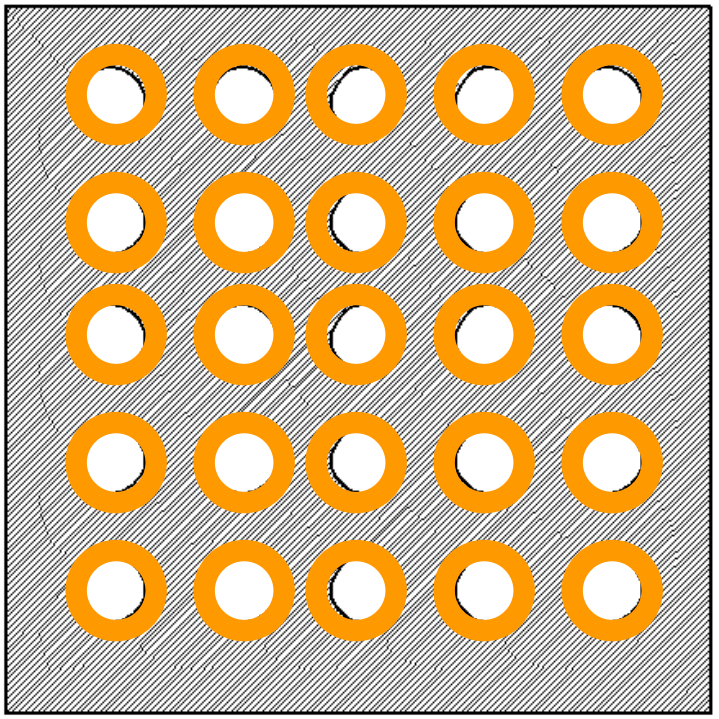
- Volume of air provided is the same for both circumstances.
- Case B has a lower spacing factor and a higher specific surface.

What Do You Want in an Air-Void System?

A



B



- Volume of air provided is the same for both circumstances.
- Case B has a lower spacing factor and a higher specific surface.

Hardened Air Void Analysis

Image From Hover

Hardened Air Void Analysis

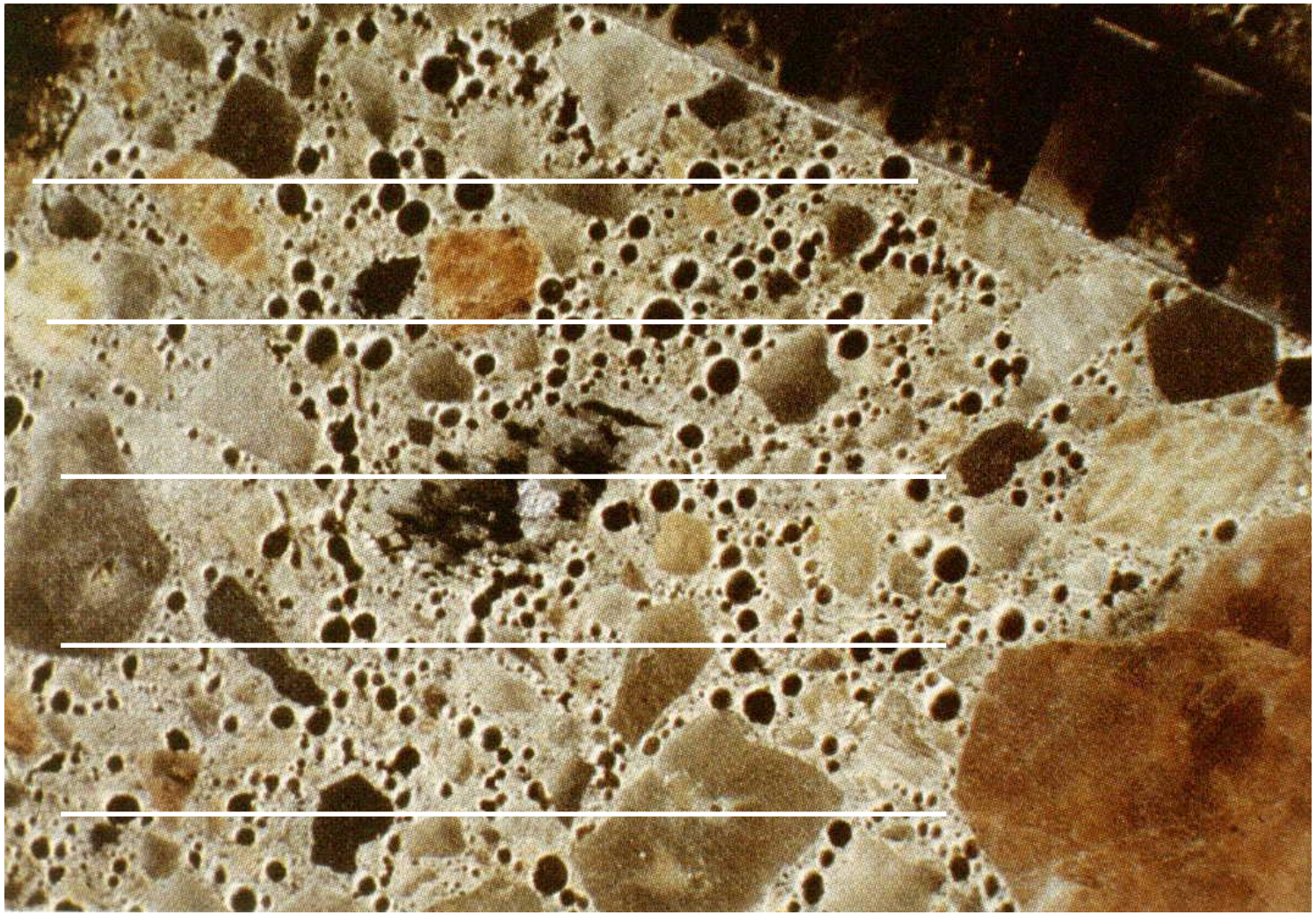


Image From Hover

- Spacing Factor – ½ of the average distance of an average sized void uniformly distributed in the paste
- **<u>Desired Value < 0.008 in (ACI 201)</u>**

real concrete

idealized concrete

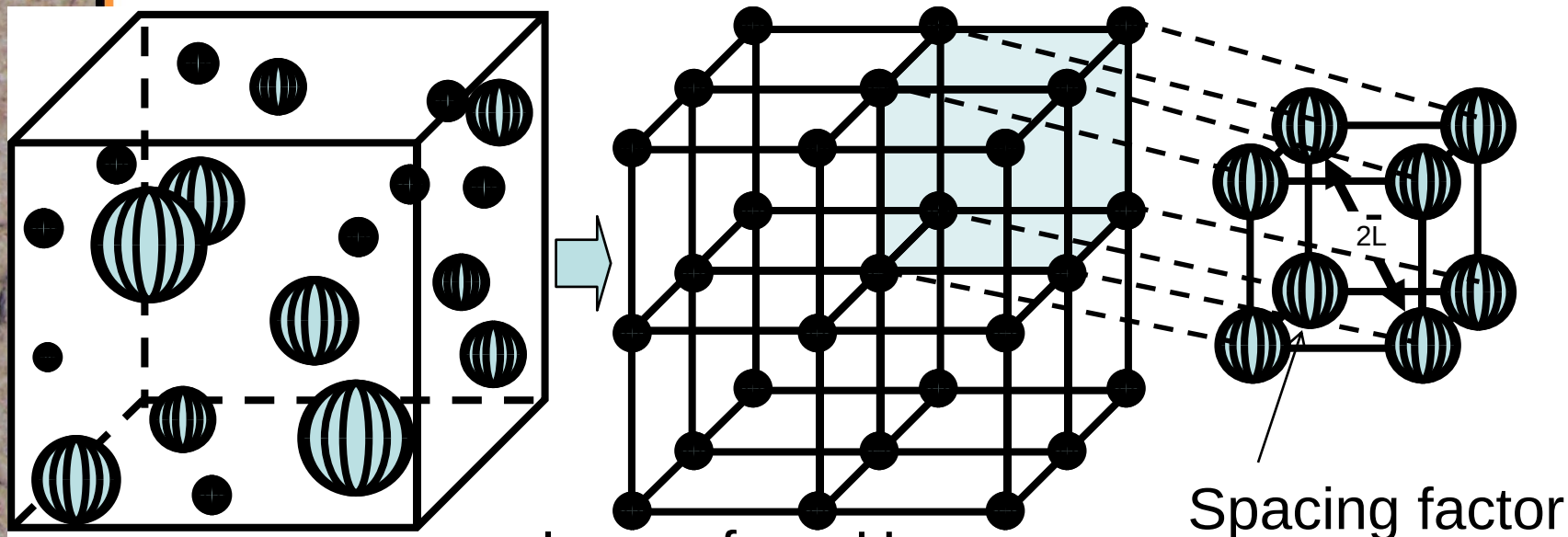
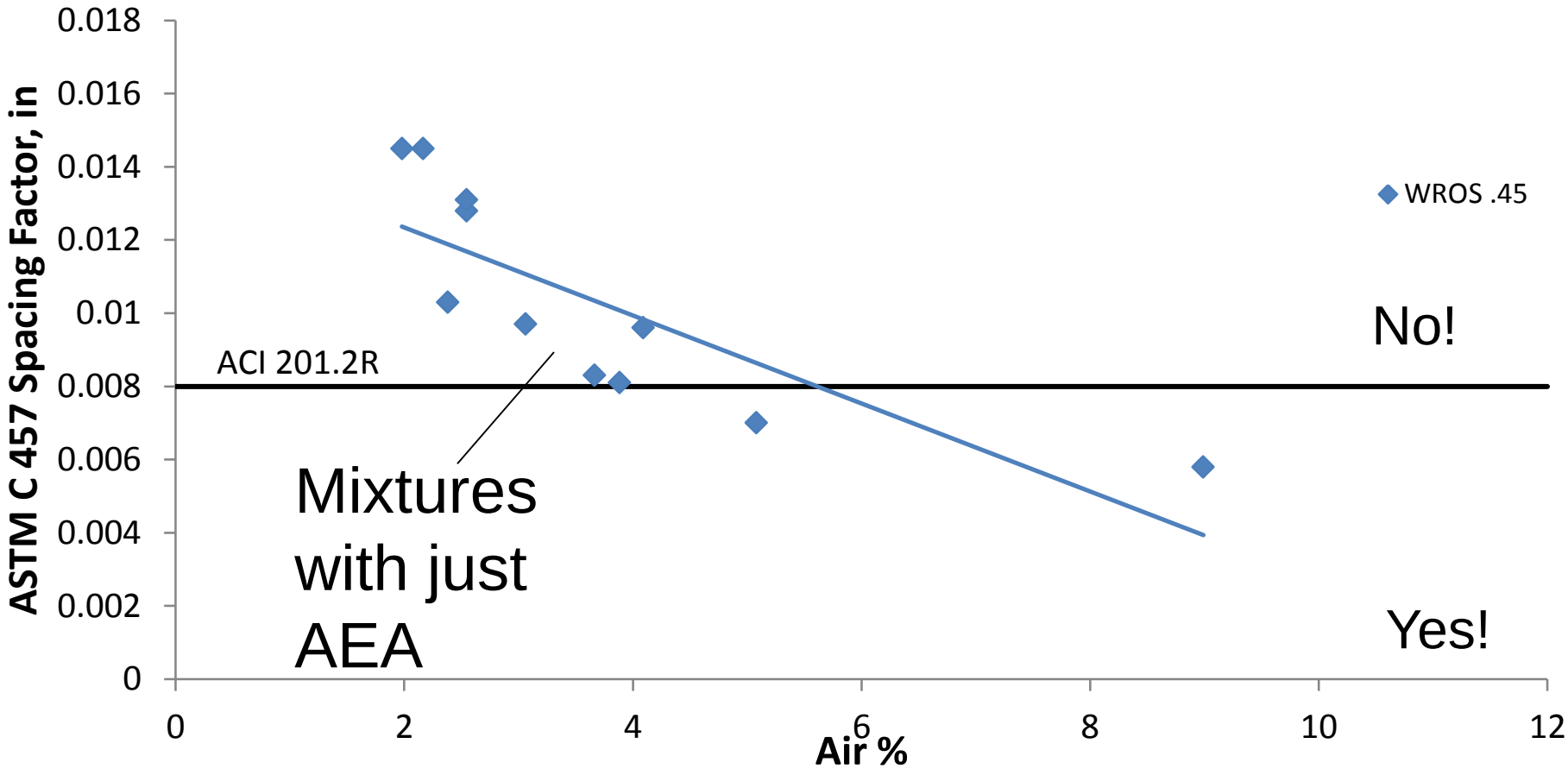
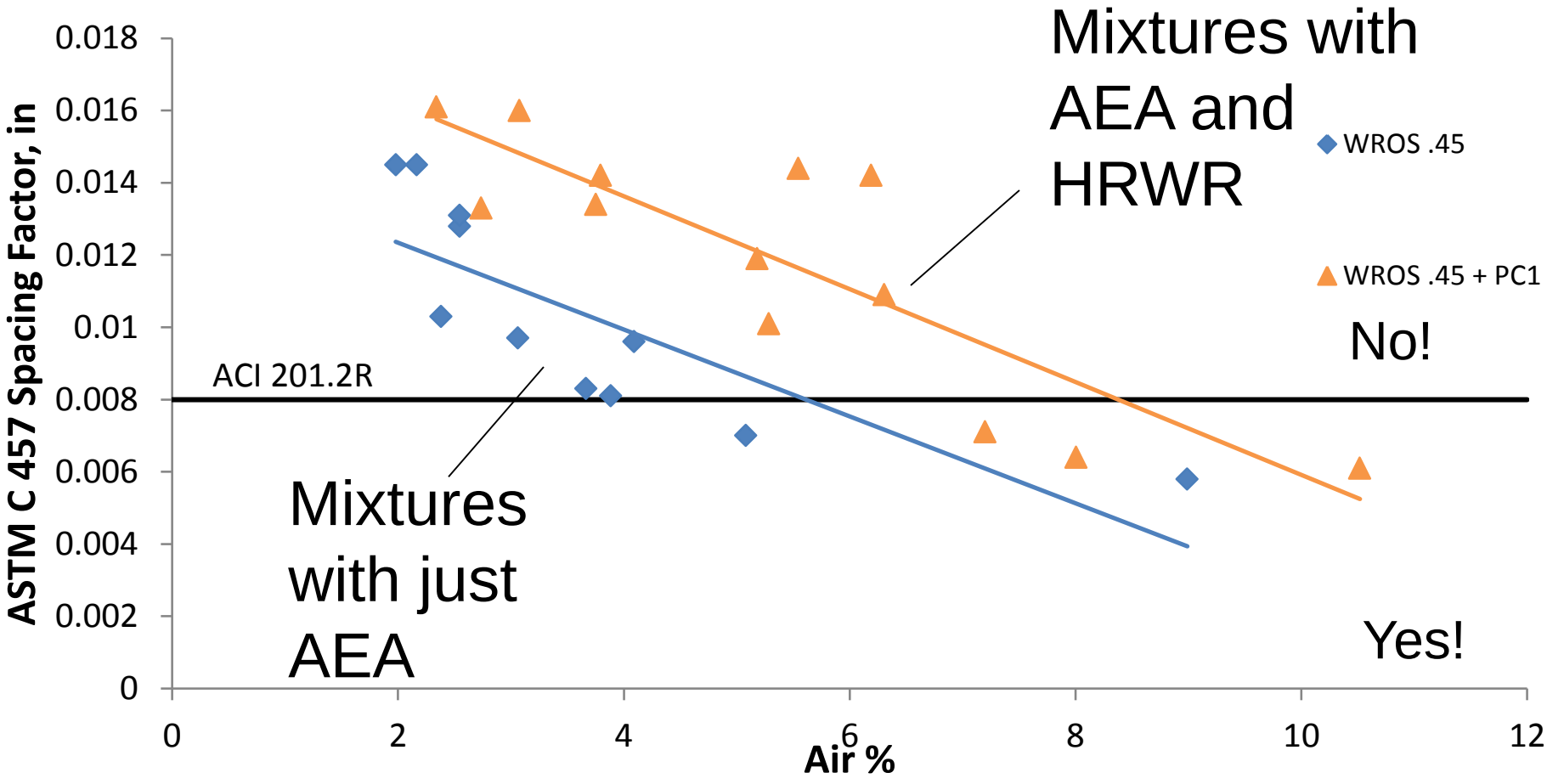


Image from Hover

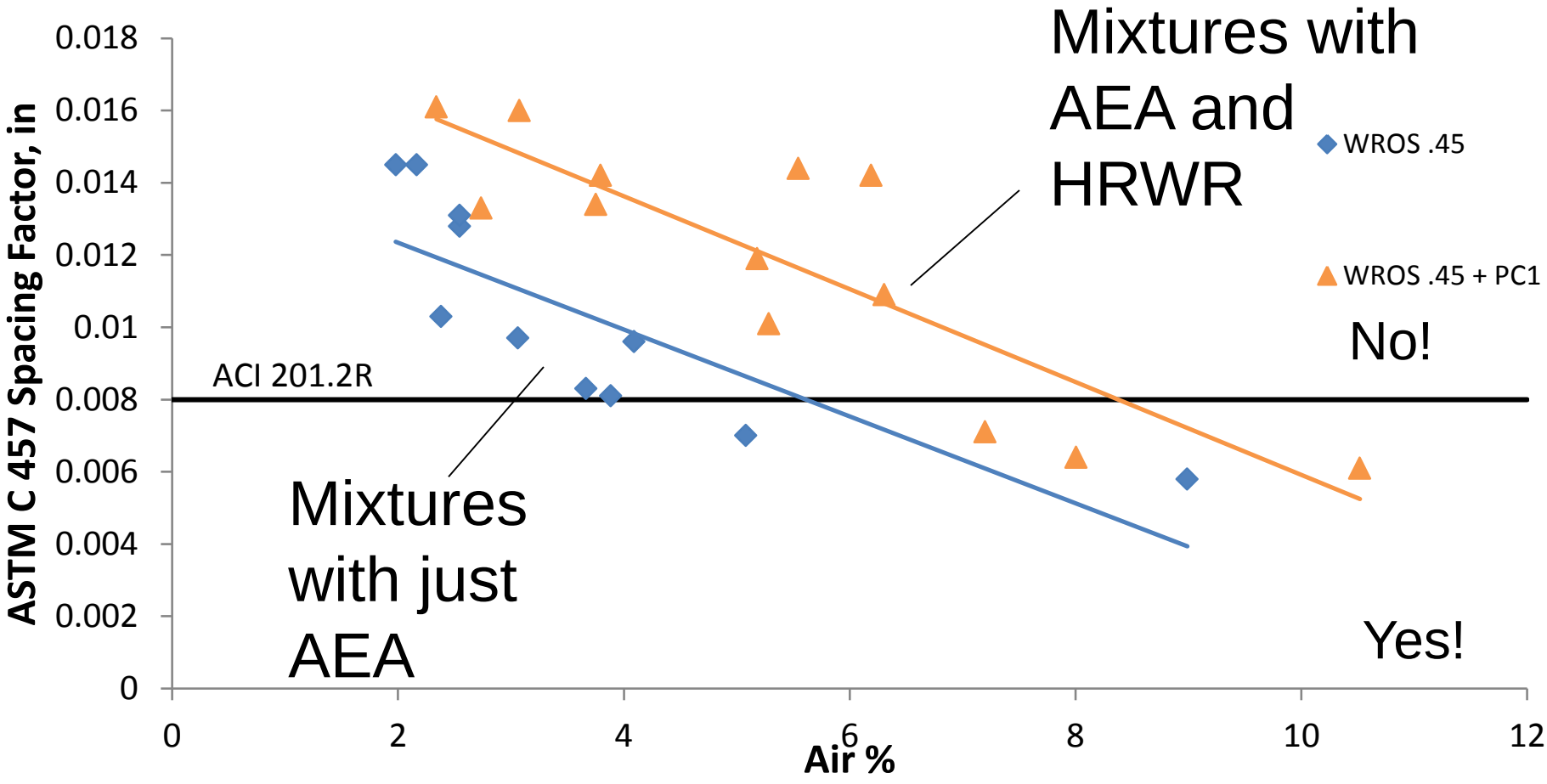
Spacing factor

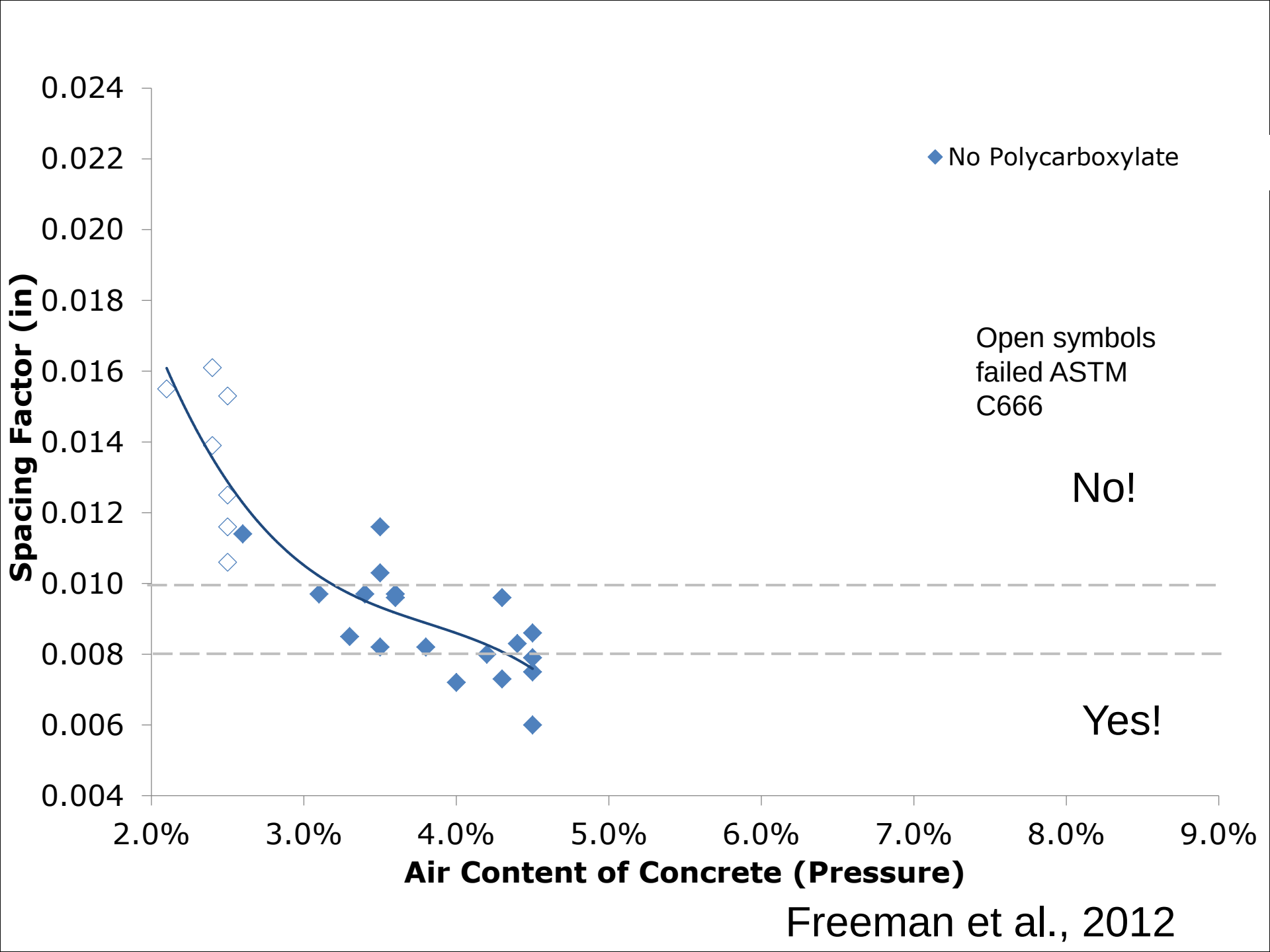
Why Can’t We Just Use Air Volume?


ASTM C 457 Spacing Factor, in
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
2
4
6
8
10
12
Air %
WROS .45
ACI 201.2R
No!
Yes!
Mixtures with just AEA

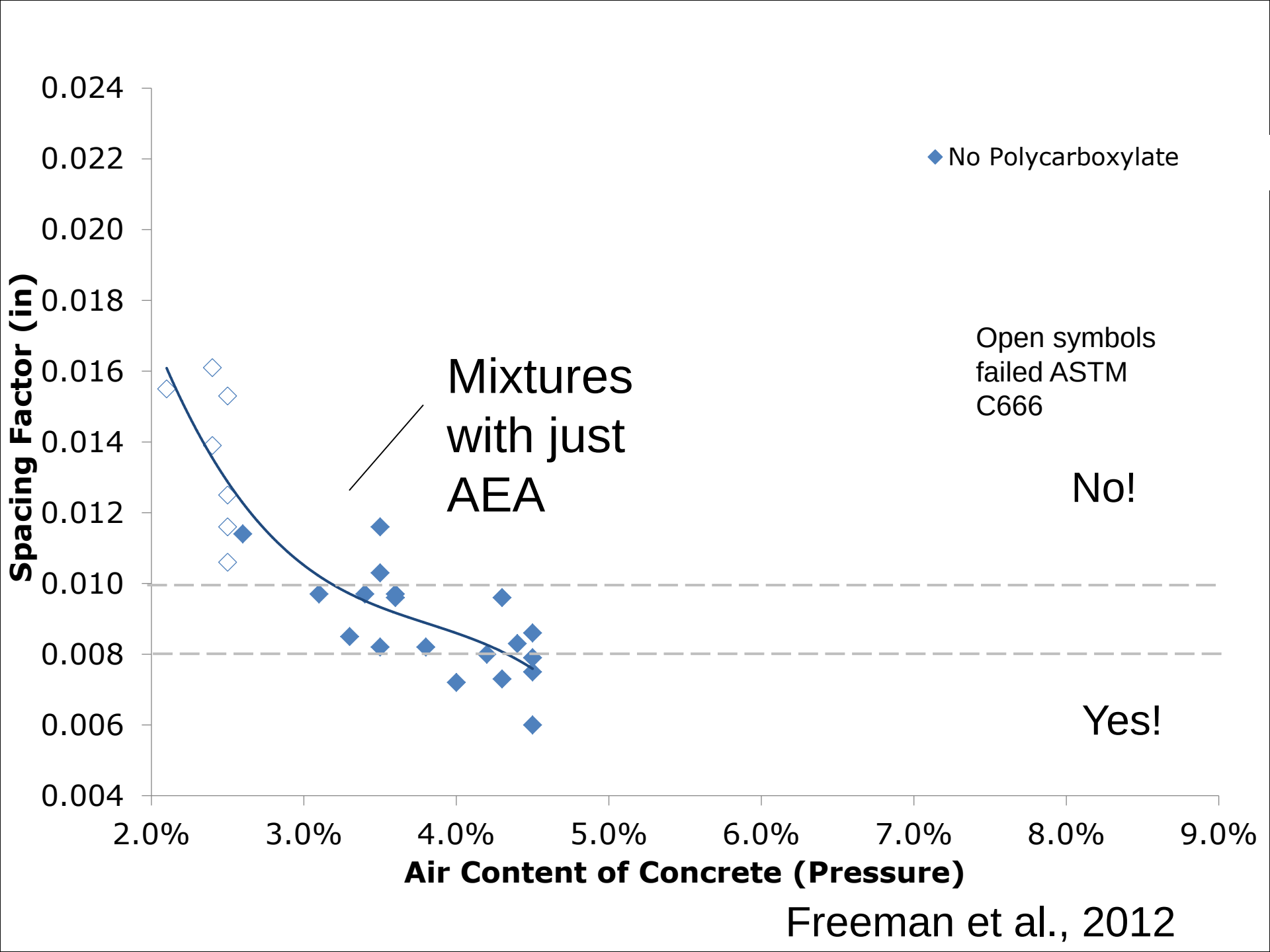

Mixtures with AEA and HRWR
WROS .45
WROS .45 + PC1
No!
ACI 201.2R
Mixtures with just AEA
Yes!
ASTM C 457 Spacing Factor, in
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
2
4
6
8
10
12
Air %

Yikes!

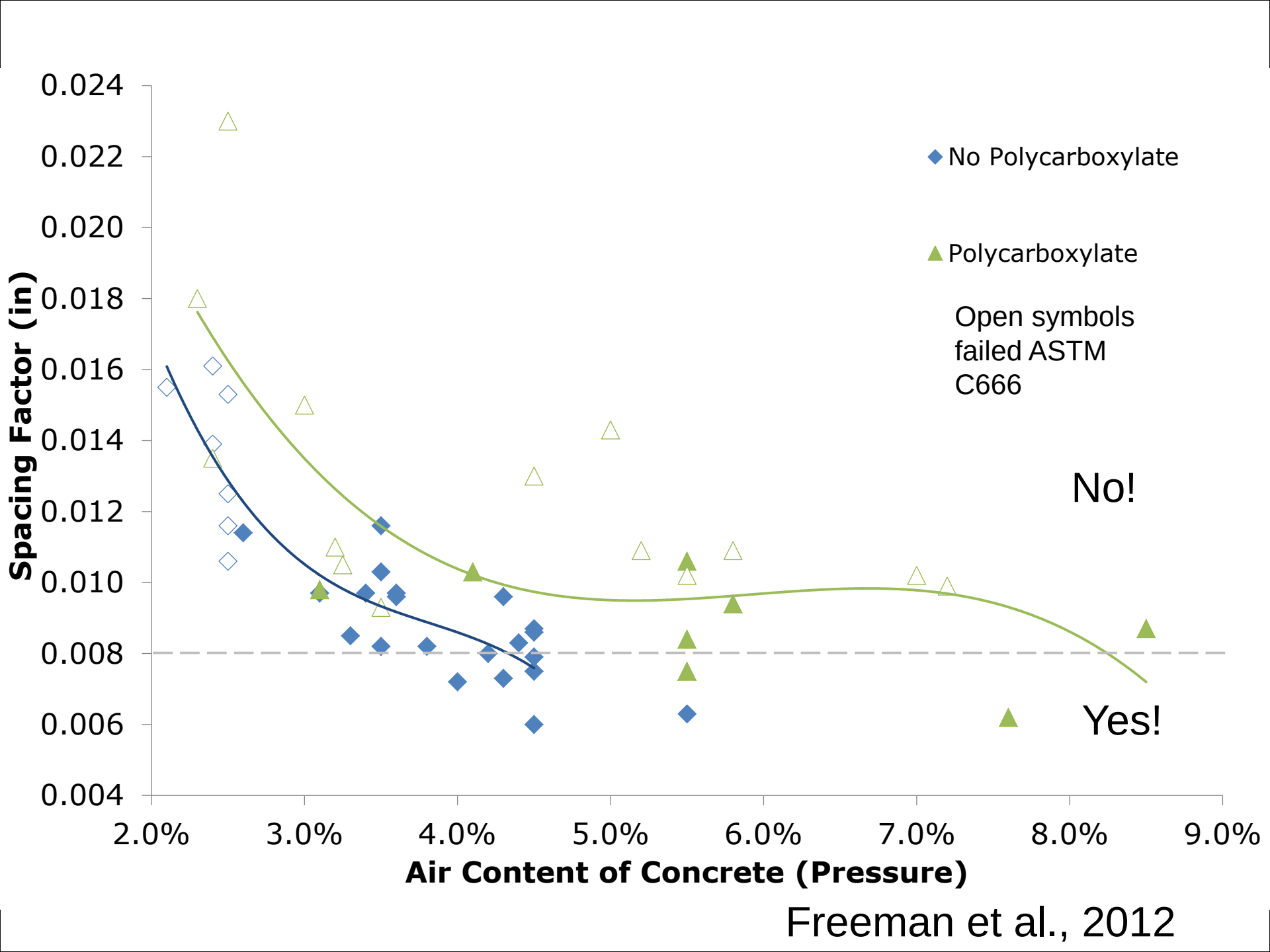

Mixtures with AEA and HRWR
WROS .45
WROS .45 + PC1
No!
ACI 201.2R
Mixtures with just AEA
Yes!
ASTM C 457 Spacing Factor, in
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
2
4
6
8
10
12
Air %



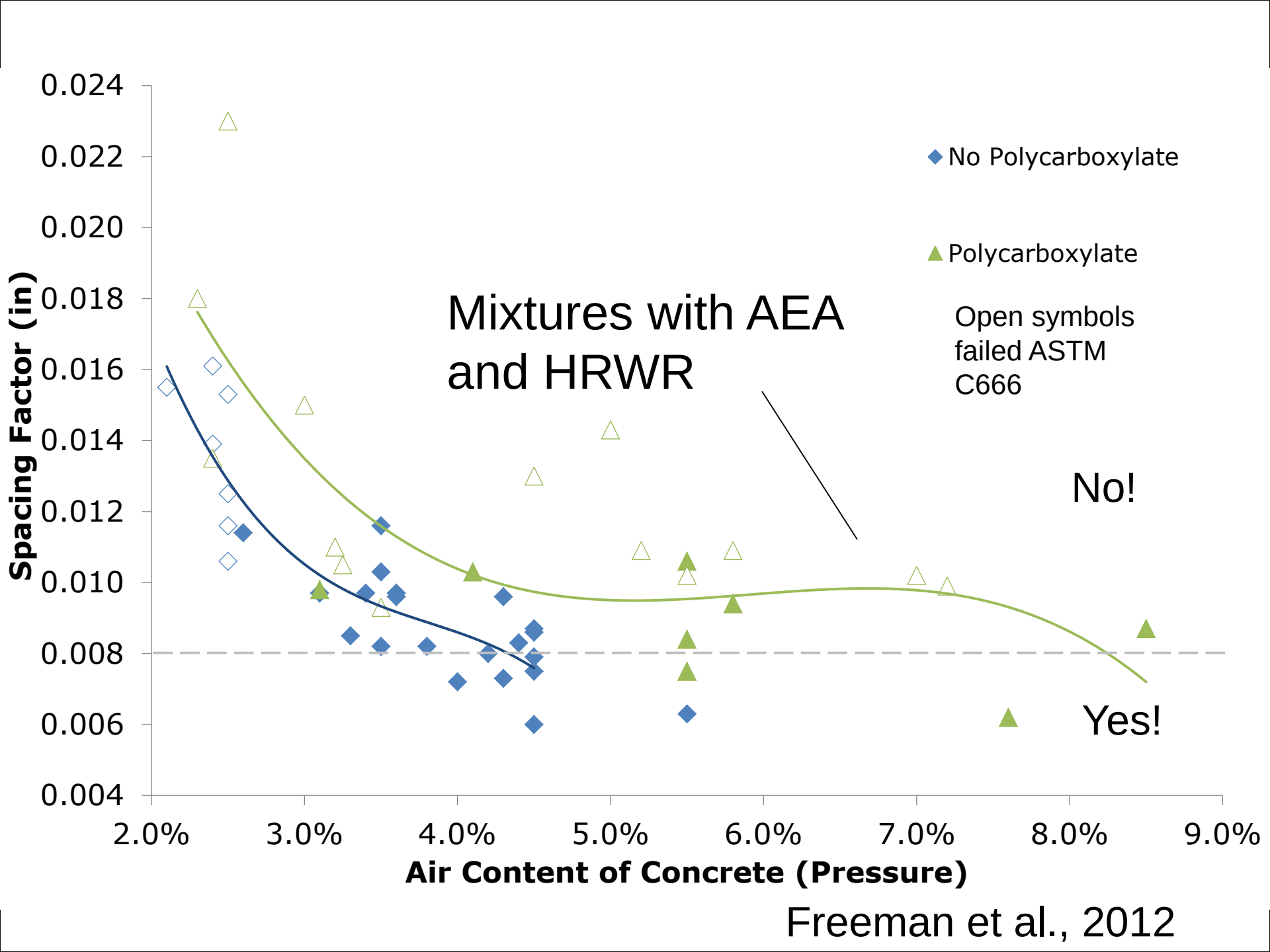
Freeman et al., 2012



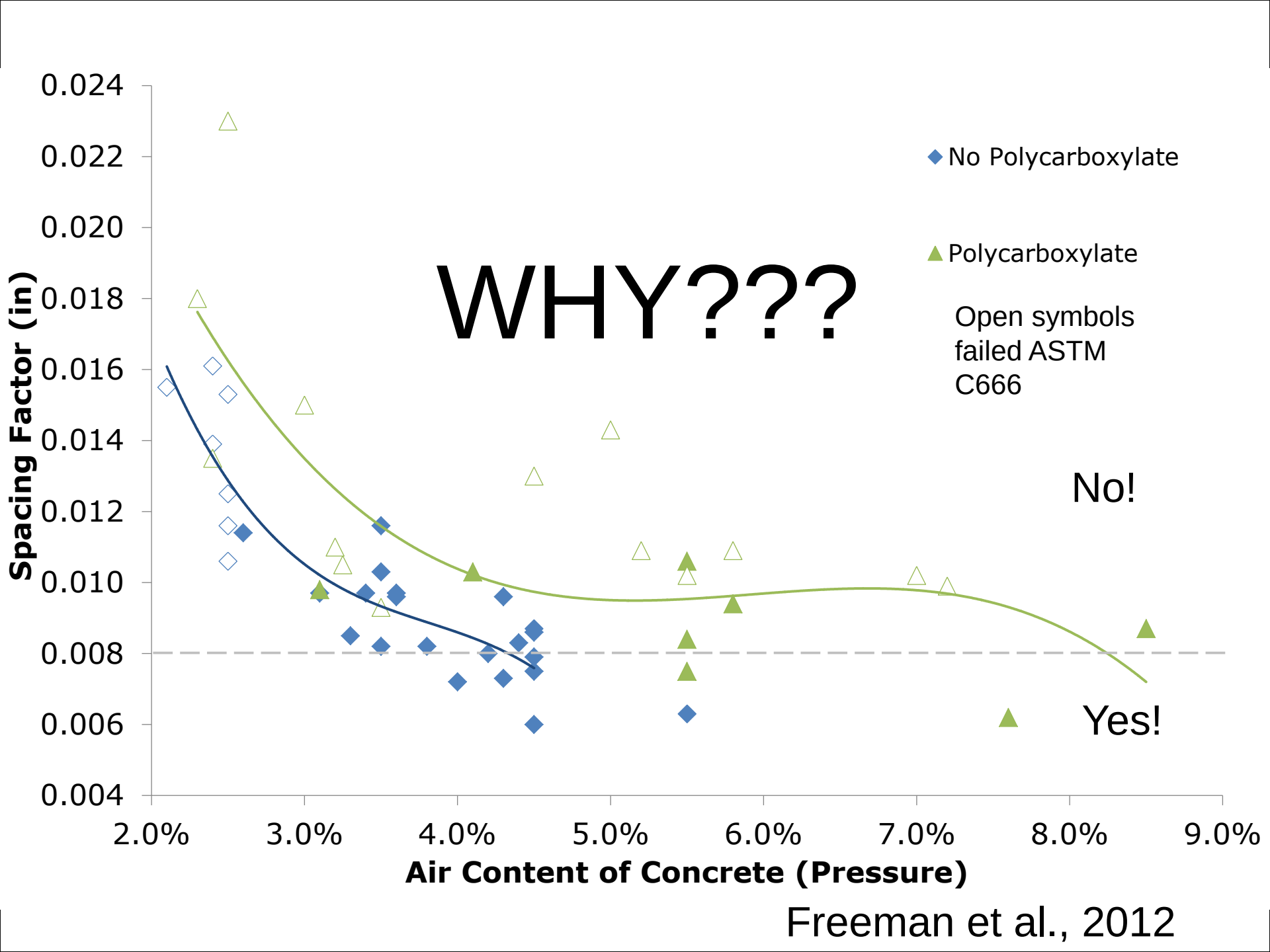
Freeman et al., 2012



Freeman et al., 2012



Freeman et al., 2012



Freeman et al., 2012

Hardened Air Void Analysis

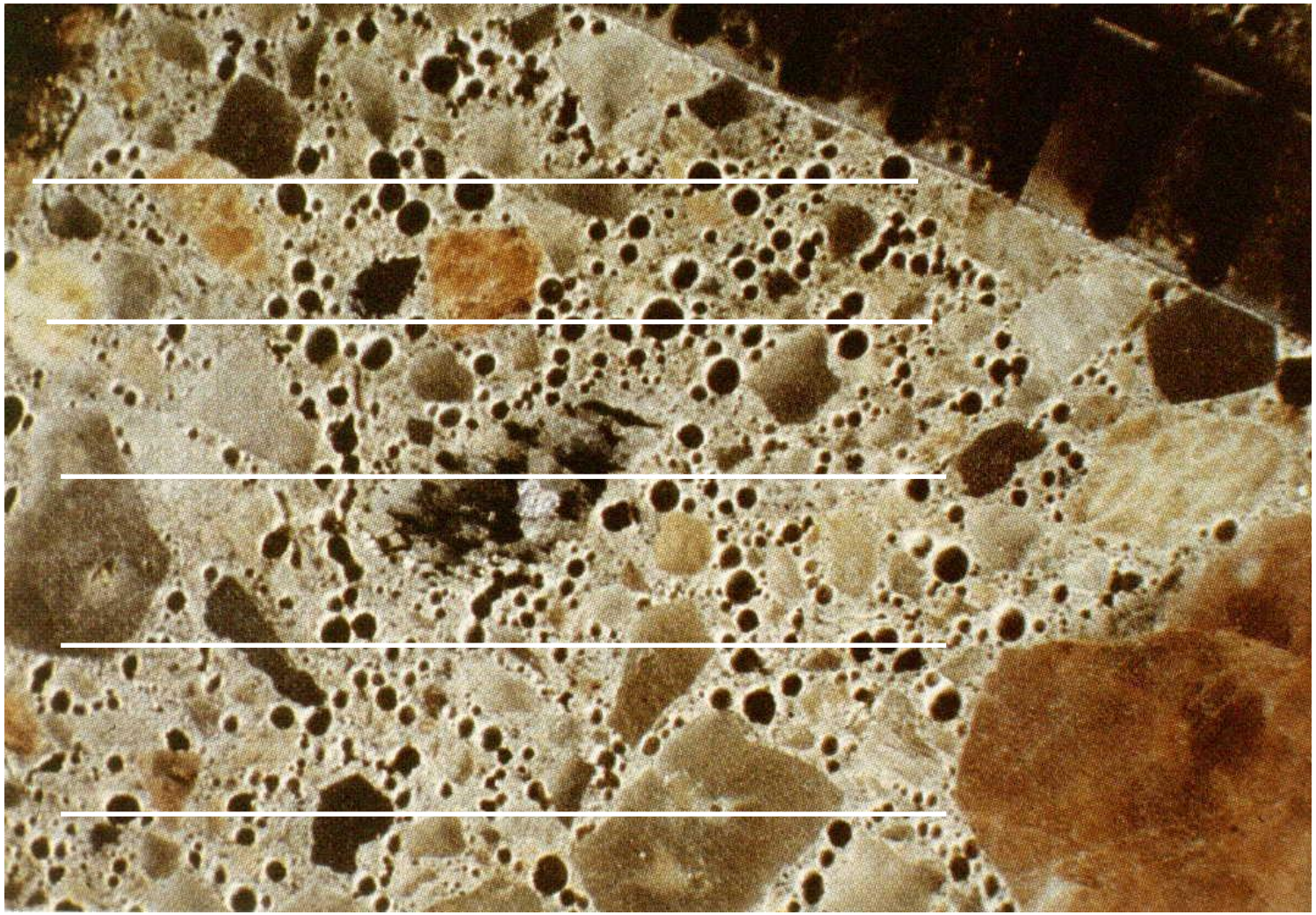
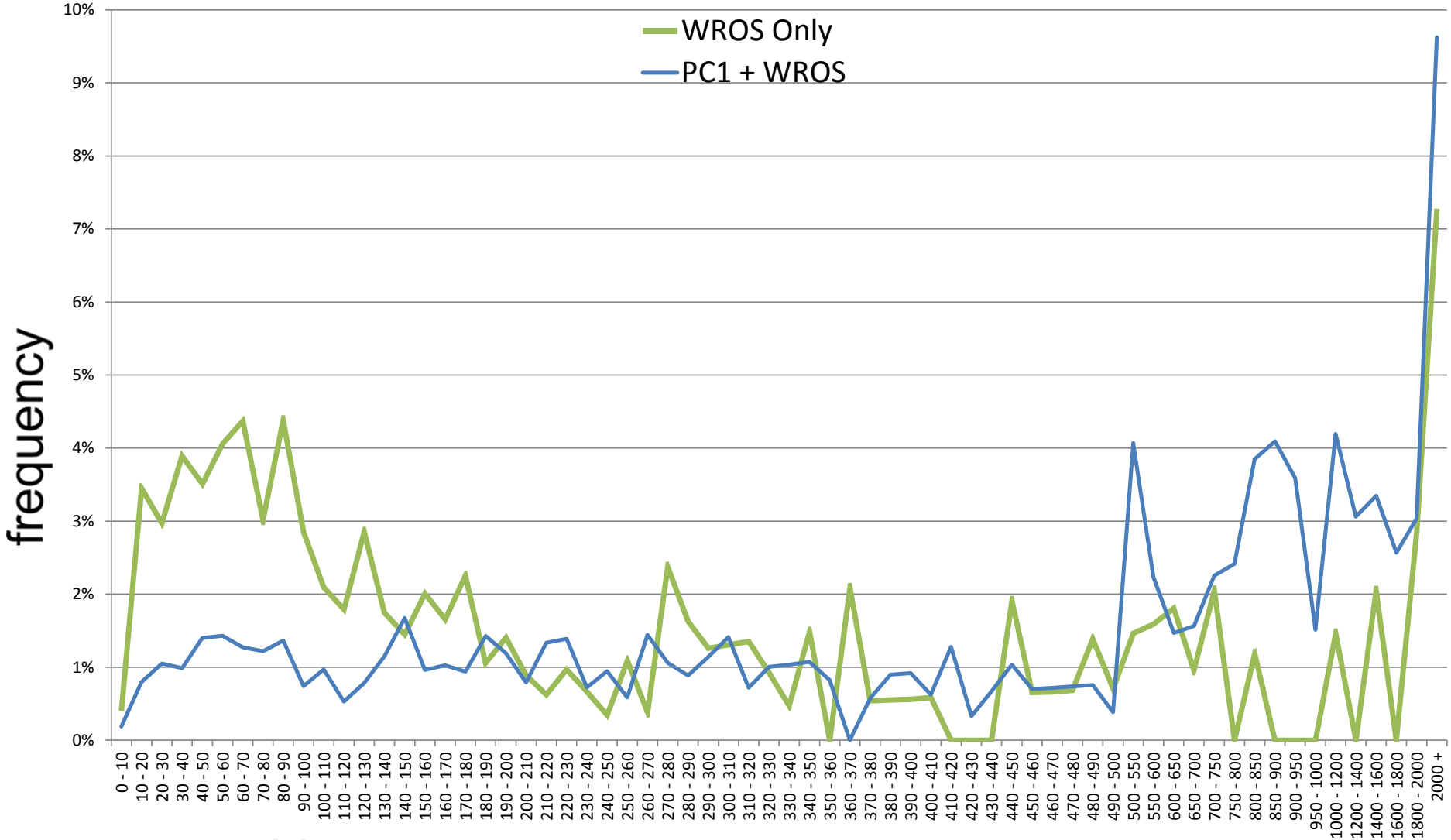


Image From Hover

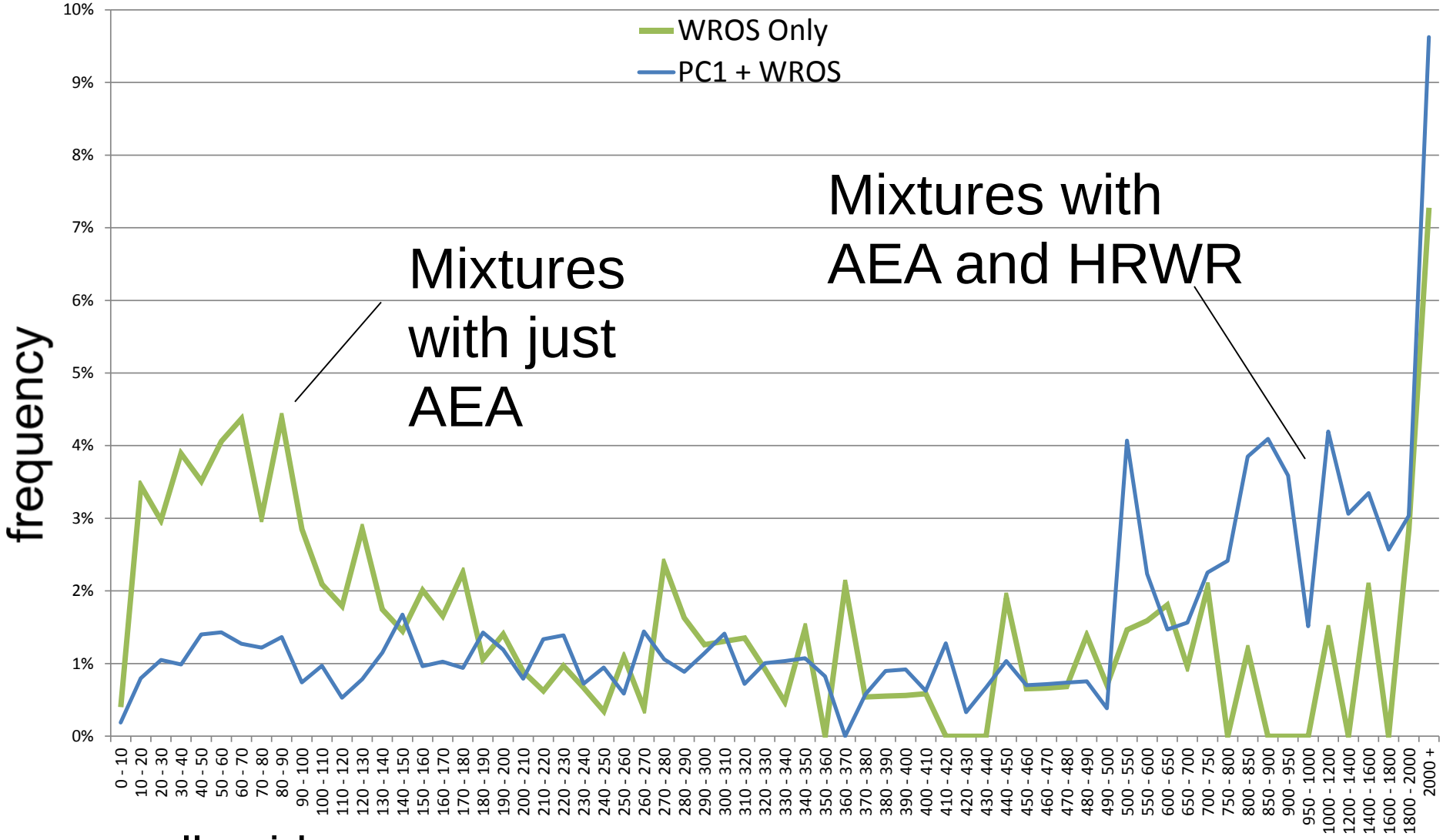


small voids

Chord Size, microns

large voids

Freeman et al., 2012



Freeman et al., 2012

Summary

- It is common to require a certain volume of air in concrete in order to obtain freeze thaw durability
- *The volume of air does not equal air void system quality*
- Although a hardened air void analysis (ASTM C457) can measure the air-void quality it is not practical to run regularly

What do we need?

- We need a test that can quantify air-void systems quickly in fresh concrete
- Investigate a sample of significant size
- Economical
- Field ready

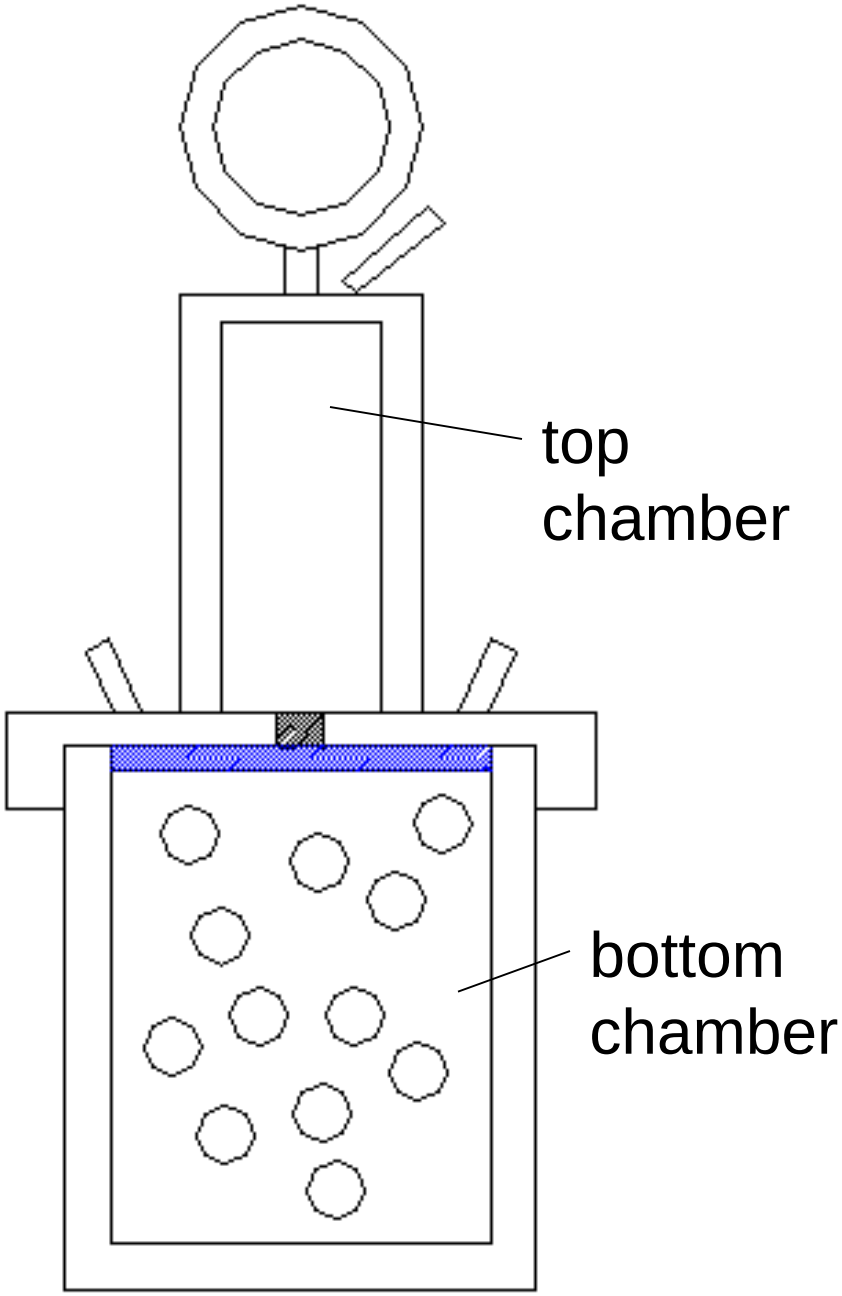
Super Air Meter (SAM)

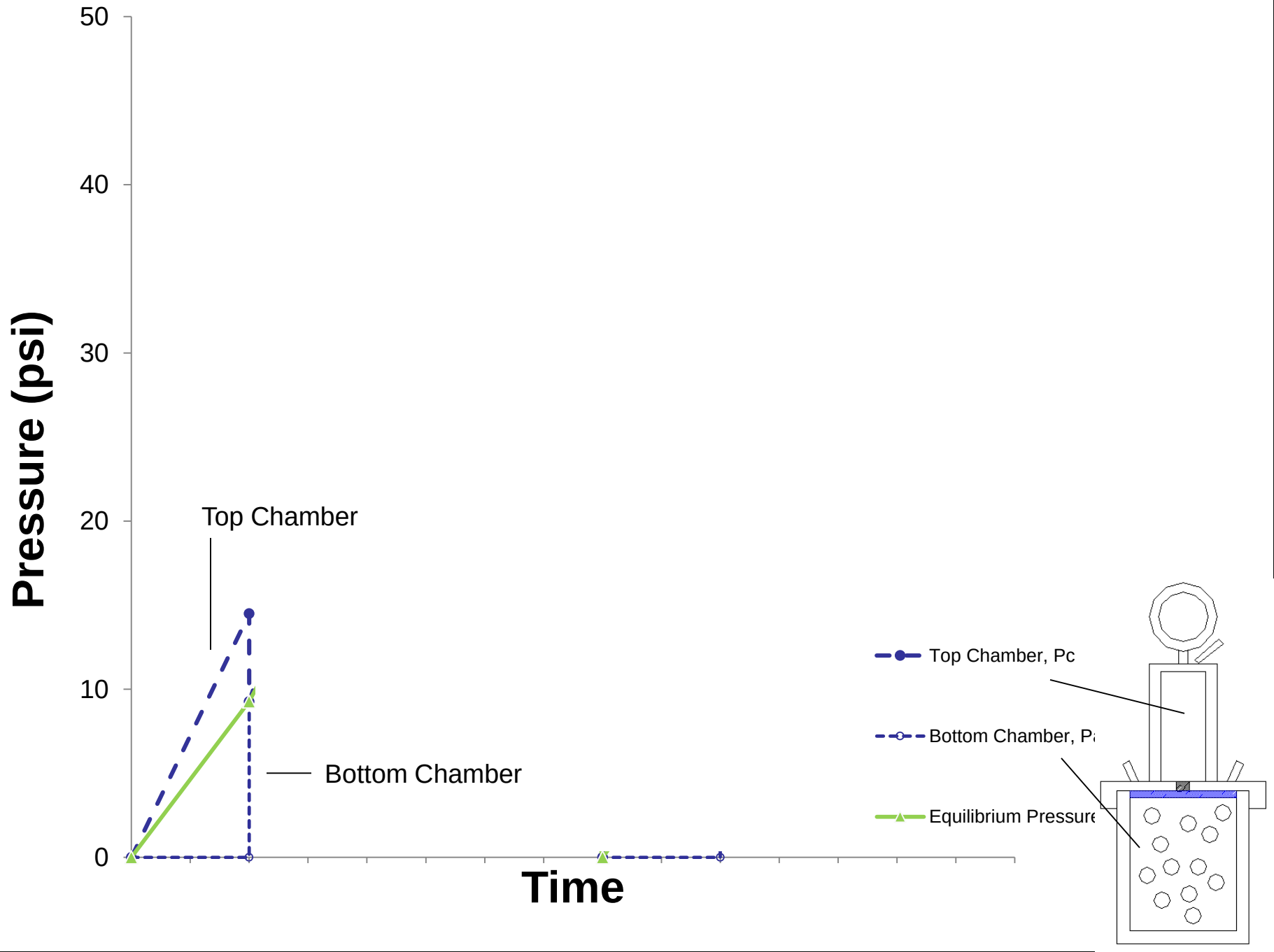
- We have modified a typical ASTM C 231 pressure meter so that it can hold larger pressures
- We have replaced the typical gage with a digital one
- The test takes 8 - 10 minutes

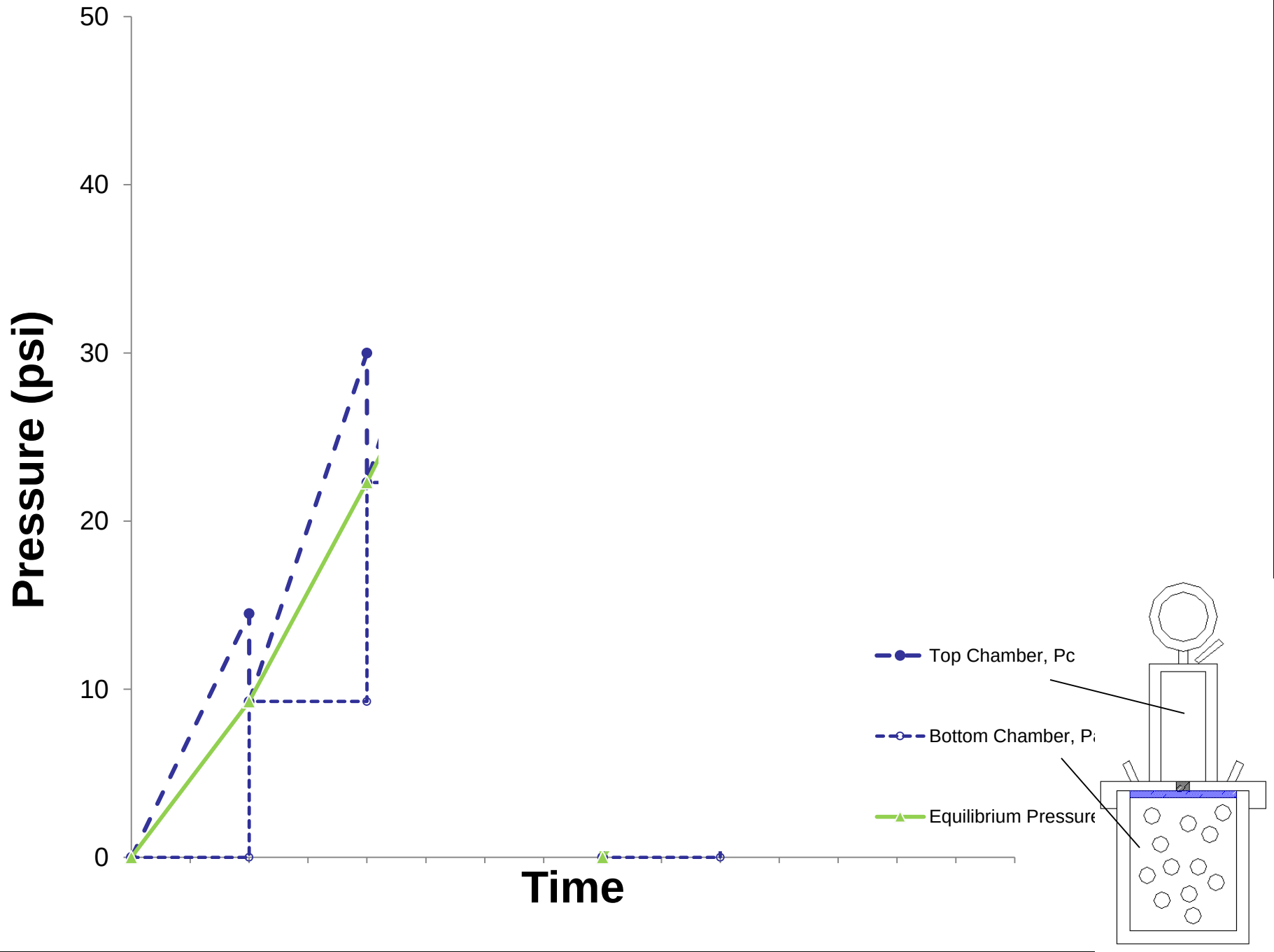

digital
gauge
Six
clamps!

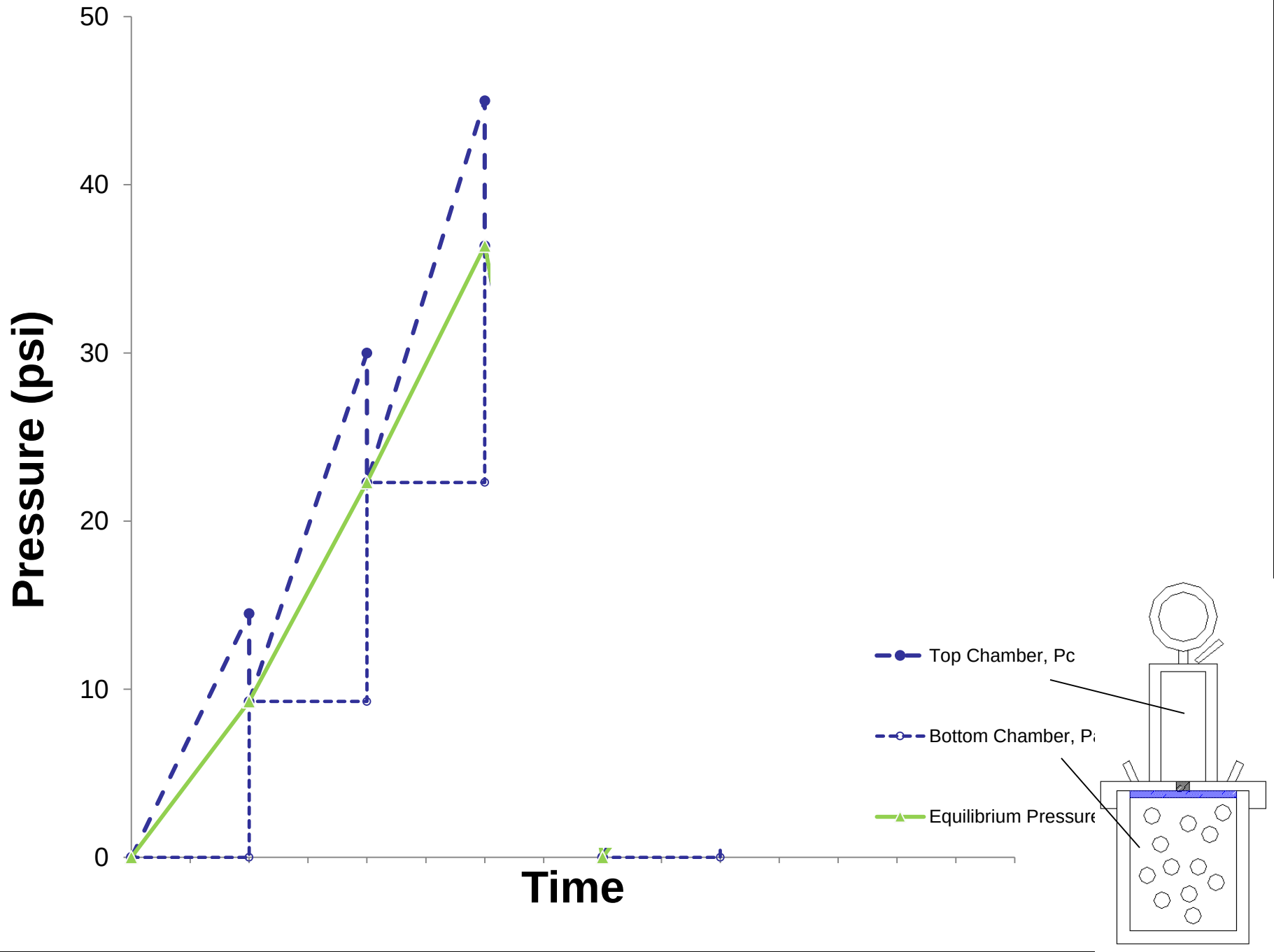
How does it work?

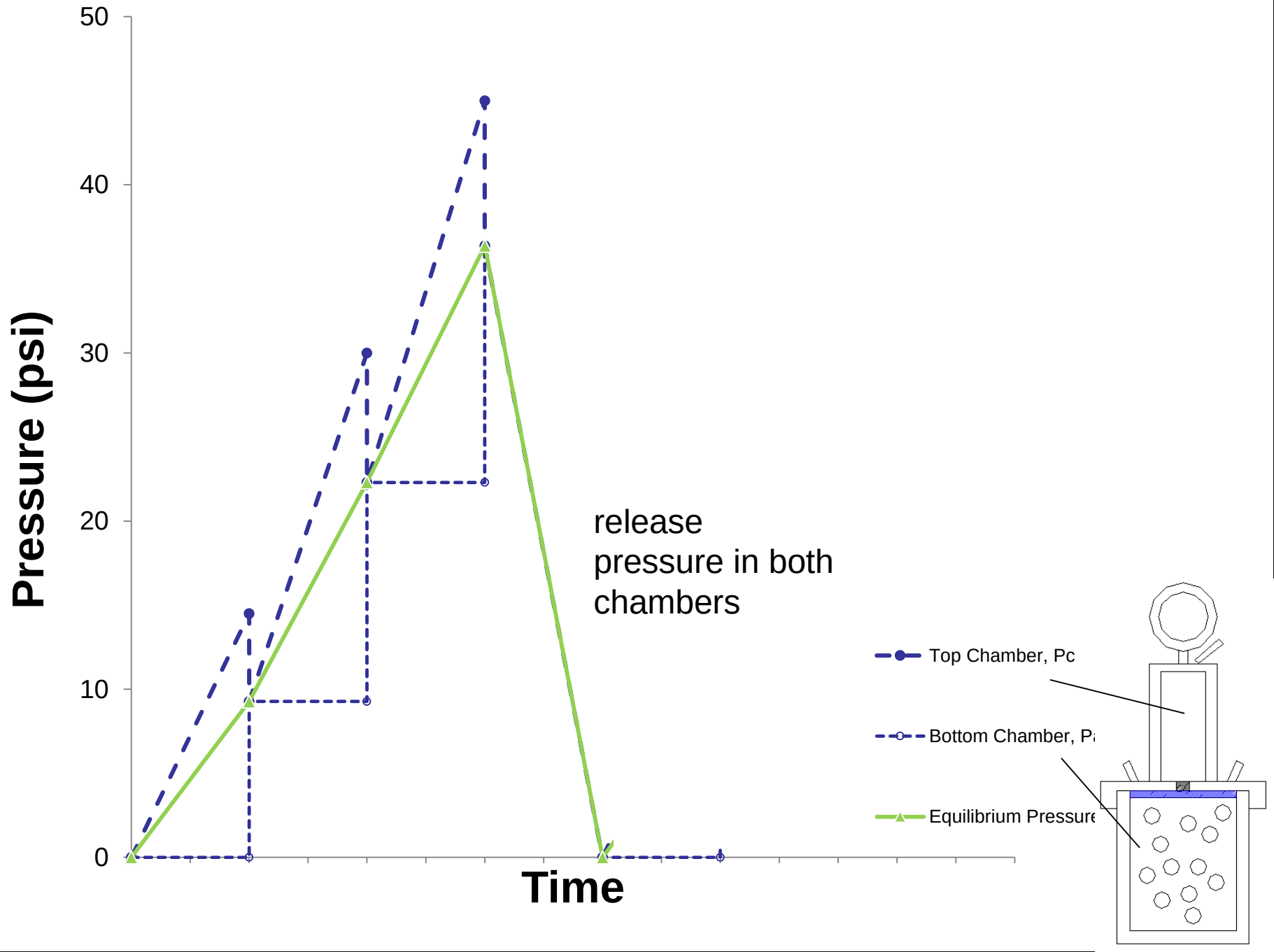
- Use ASTM C 231 procedures to fill the measurement bowl
- Secure the lid
- Add water through the petcocks

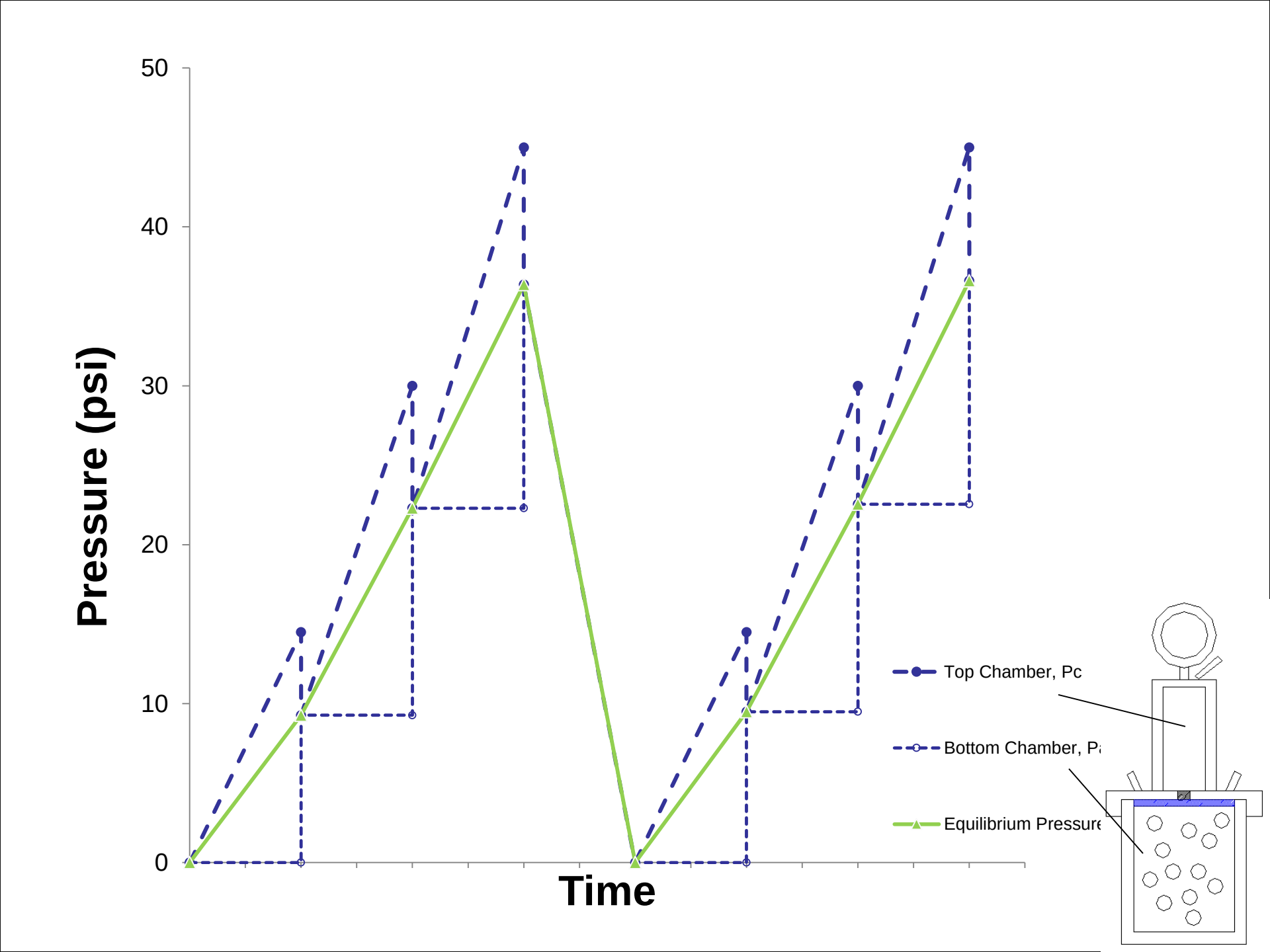

top
chamber
bottom
chamber

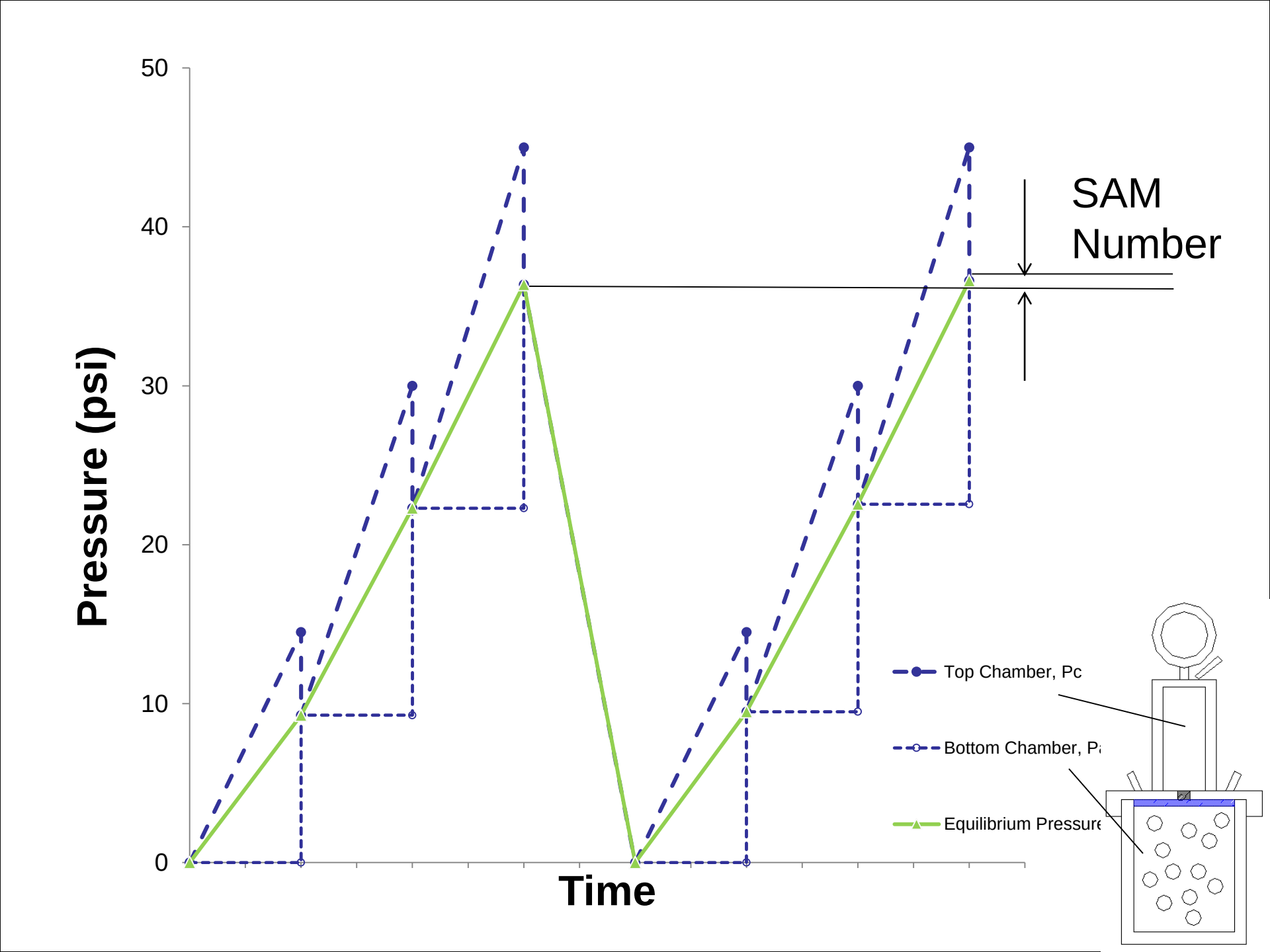

50
40
30
20
10
0
Pressure (psi)
Top Chamber
Bottom Chamber
Time
Top Chamber, Pc
Bottom Chamber, Pi
Equilibrium Pressure


50
40
30
20
10
0
Pressure (psi)
Time
Top Chamber, Pc
Bottom Chamber, Pi
Equilibrium Pressure


50
40
30
20
10
0
Pressure (psi)
Time
Top Chamber, Pc
Bottom Chamber, Pi
Equilibrium Pressure


50
40
30
20
10
0
Pressure (psi)
Time
release
pressure in both
chambers
Top Chamber, Pc
Bottom Chamber, Pi
Equilibrium Pressure


50
40
30
20
10
0
Pressure (psi)
Time
Top Chamber, Pc
Bottom Chamber, Pi
Equilibrium Pressure


50
40
30
20
10
0
Pressure (psi)
Time
SAM
Number
Top Chamber, Pc
Bottom Chamber, Pi
Equilibrium Pressure

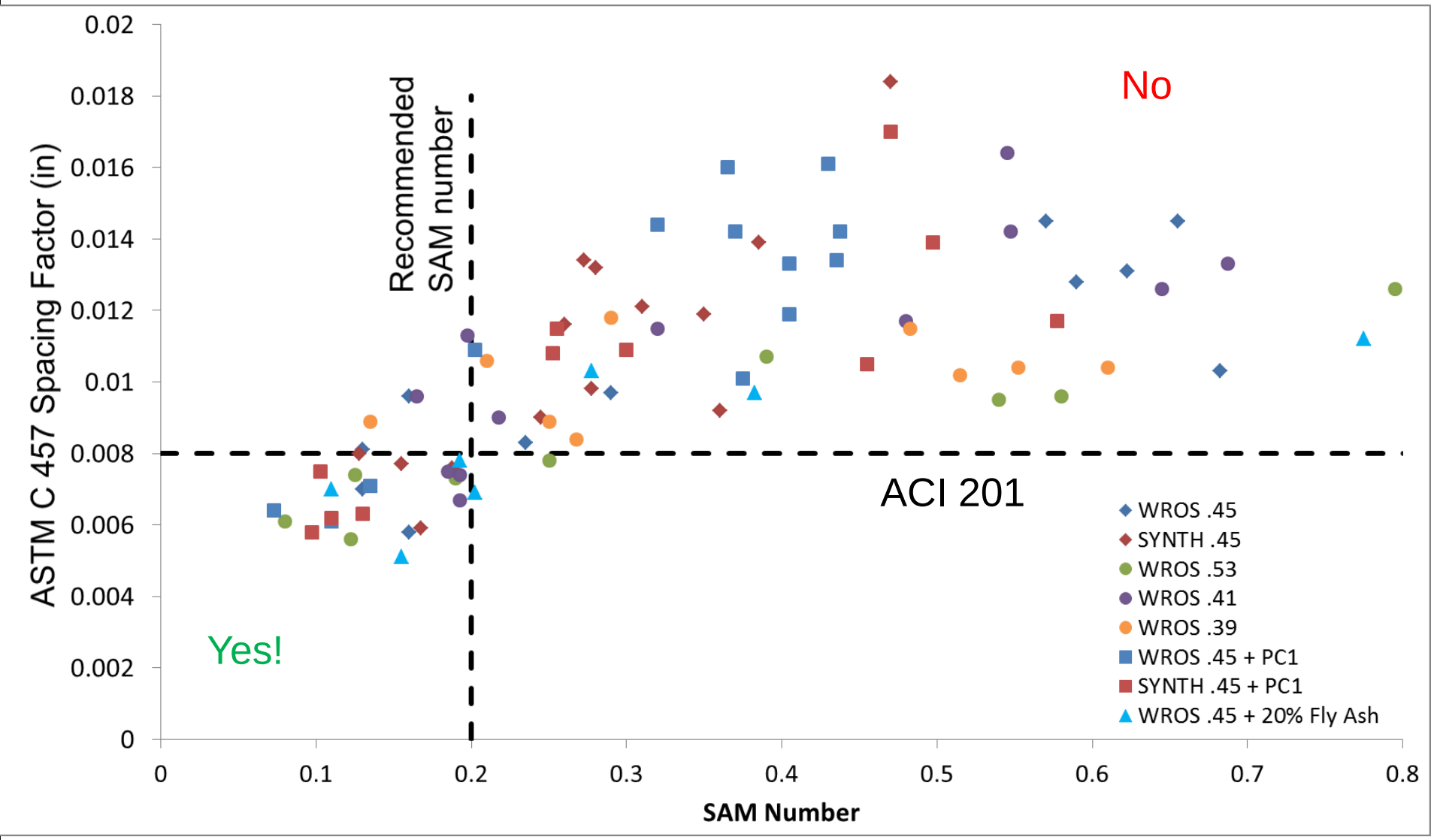
How does it work?

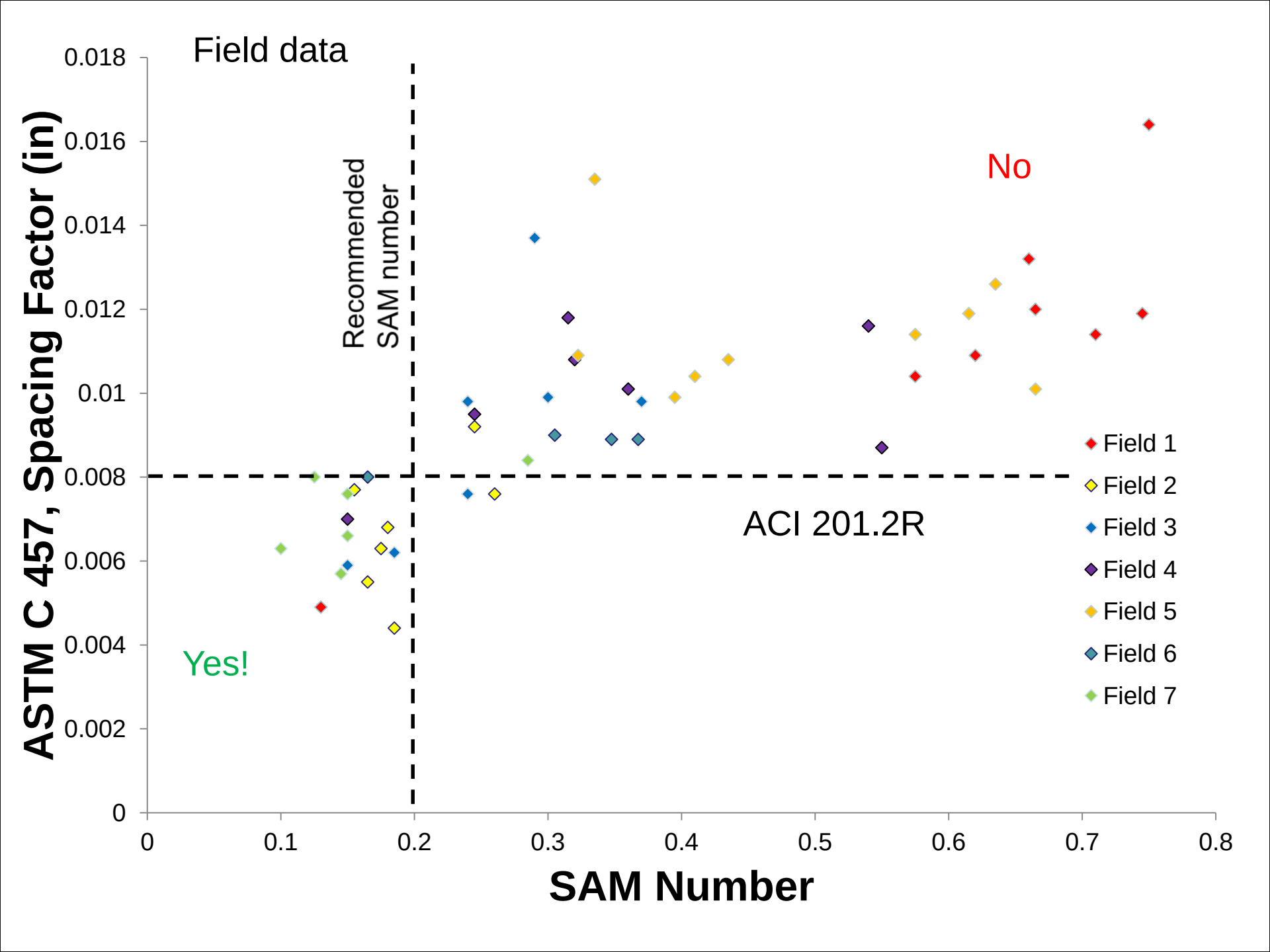
- The SAM number correlates to air void size distribution
- The meter also measures air volume

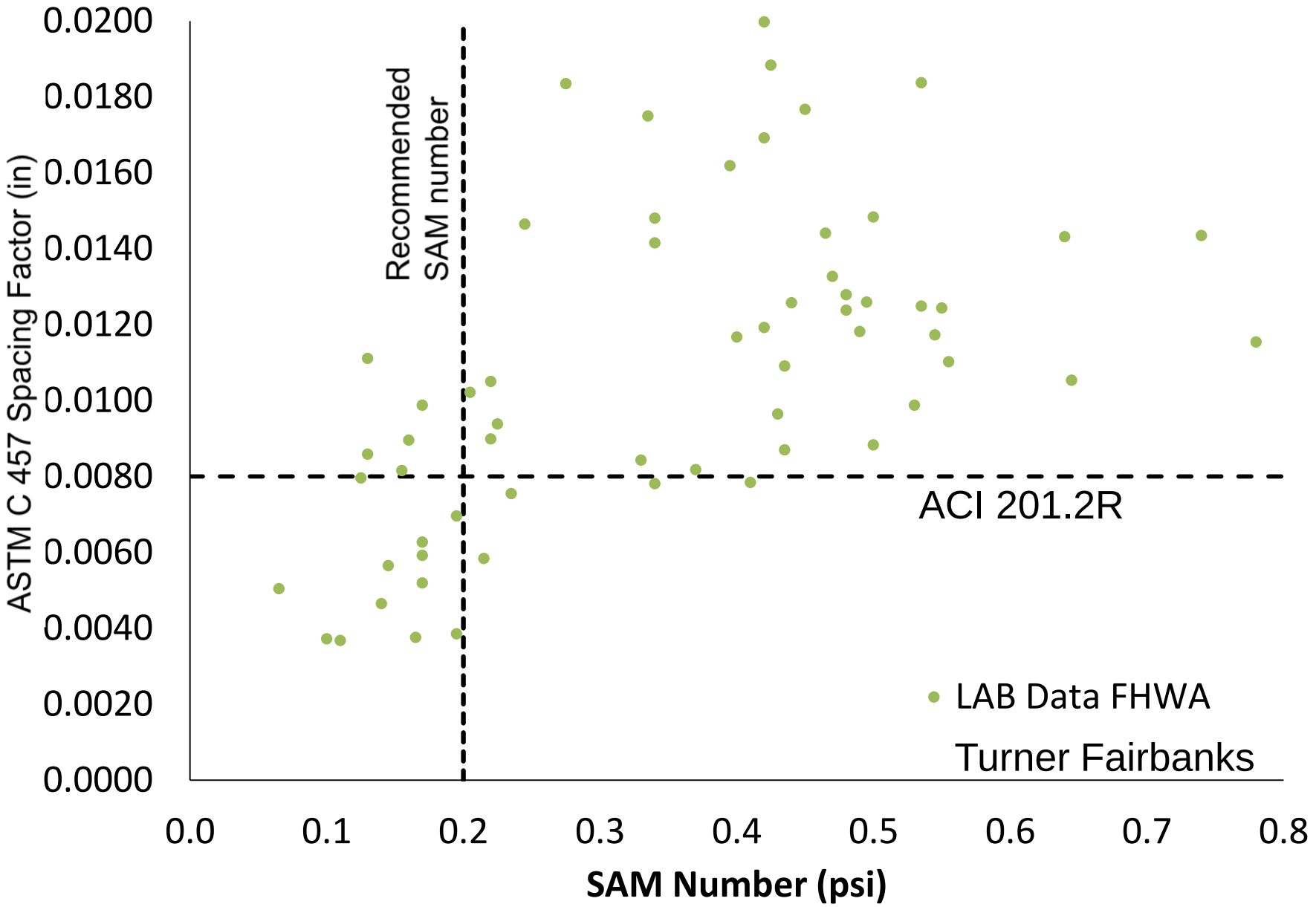
How can we prove it?

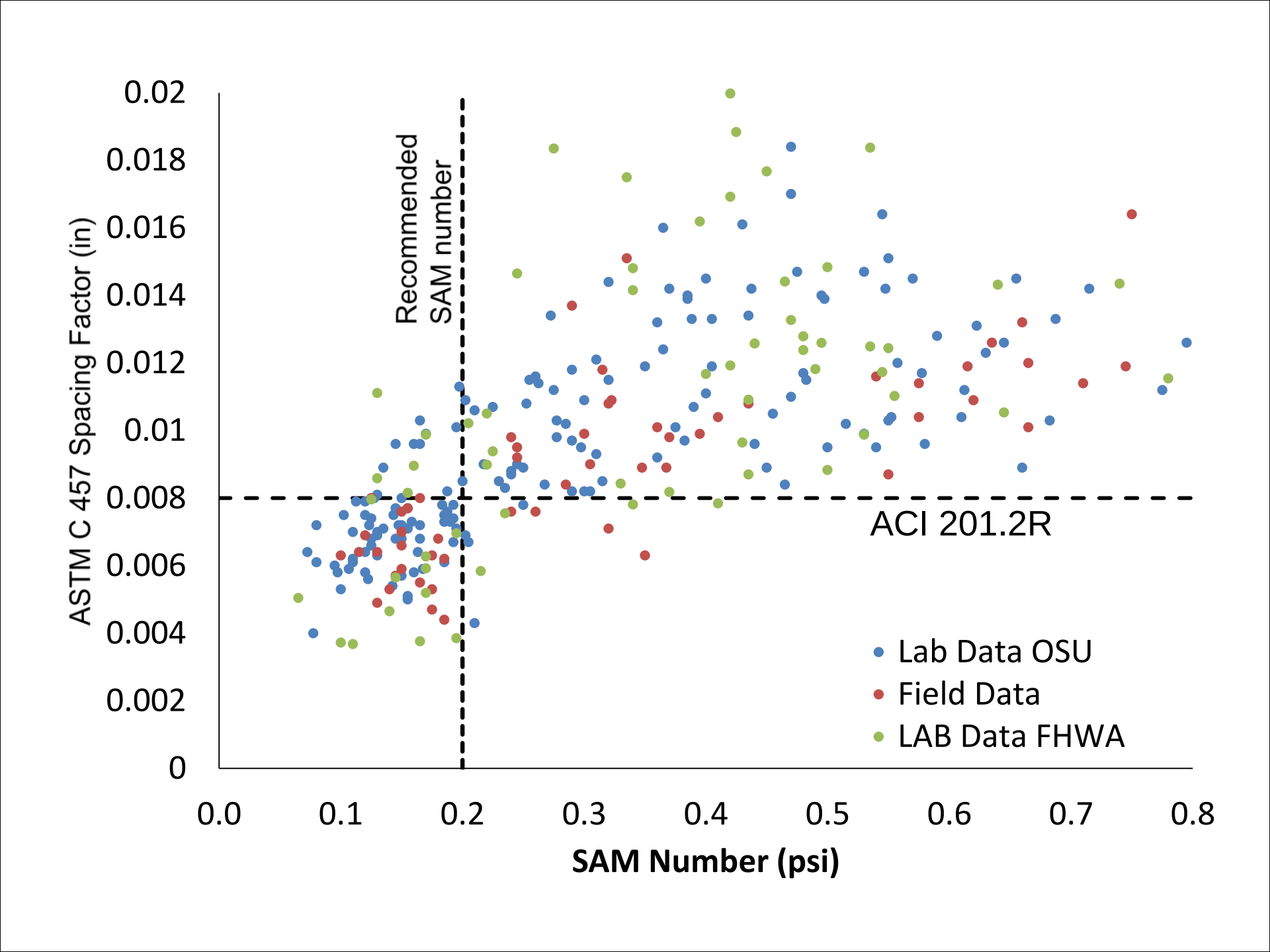
- We made a lot of concrete mixtures
- Different AEAs
- Combinations of AEAs and HRWRs
- Different w/cm (0.39 - 0.53)
- Slumps from 0.25” to 10”
- Air contents from 1.25% to 10%
- ***Hardened air void analysis (ASTM C 457) was completed on each mixture***
- Values were compared to the SAM number

Lab data

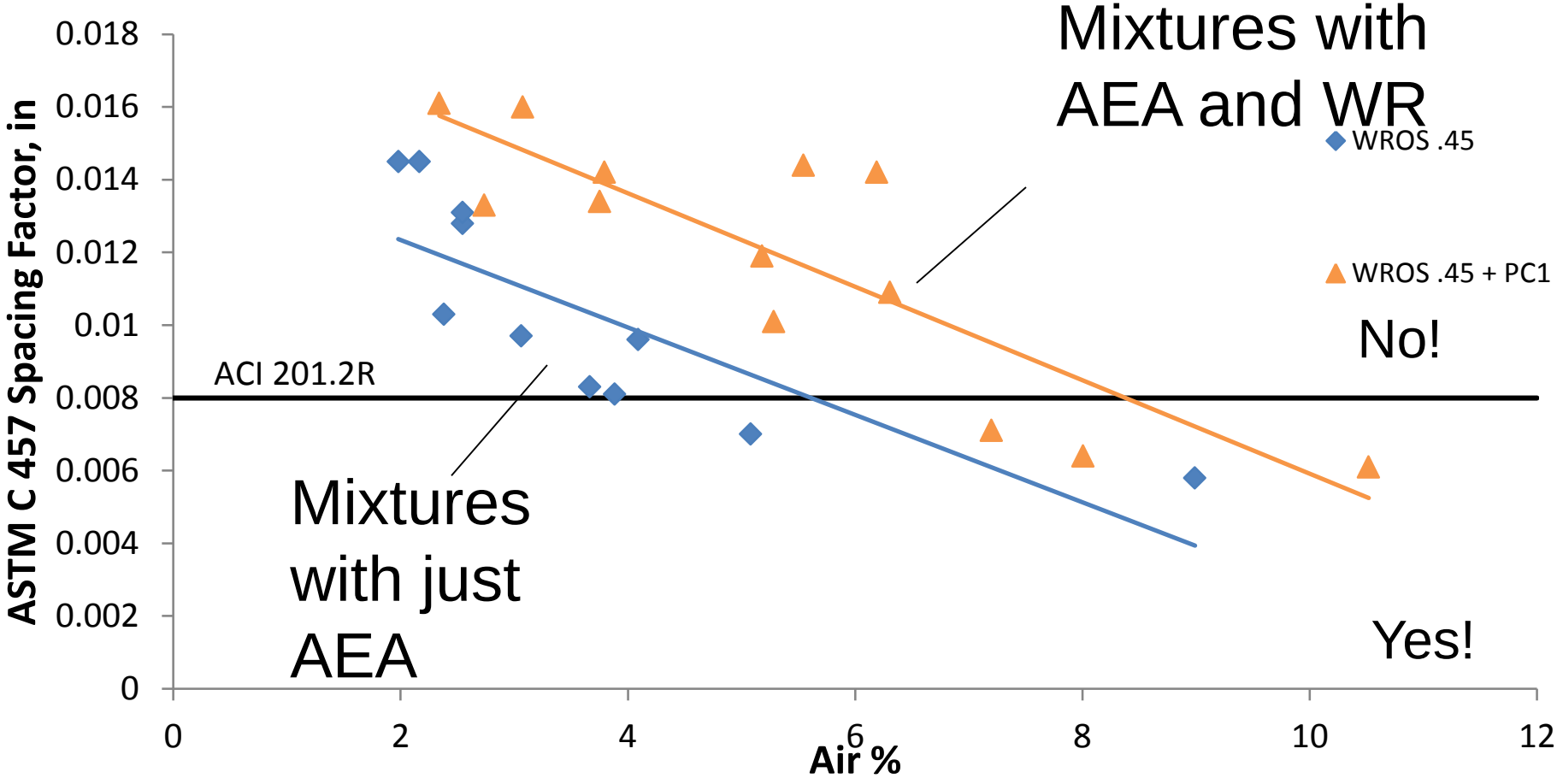

ASTM C 457 Spacing Factor (in)
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
SAM Number
Recommended SAM number
No
ACI 201
Yes!
WROS .45
SYNTH .45
WROS .53
WROS .41
WROS .39
WROS .45 + PC1
SYNTH .45 + PC1
WROS .45 + 20% Fly Ash

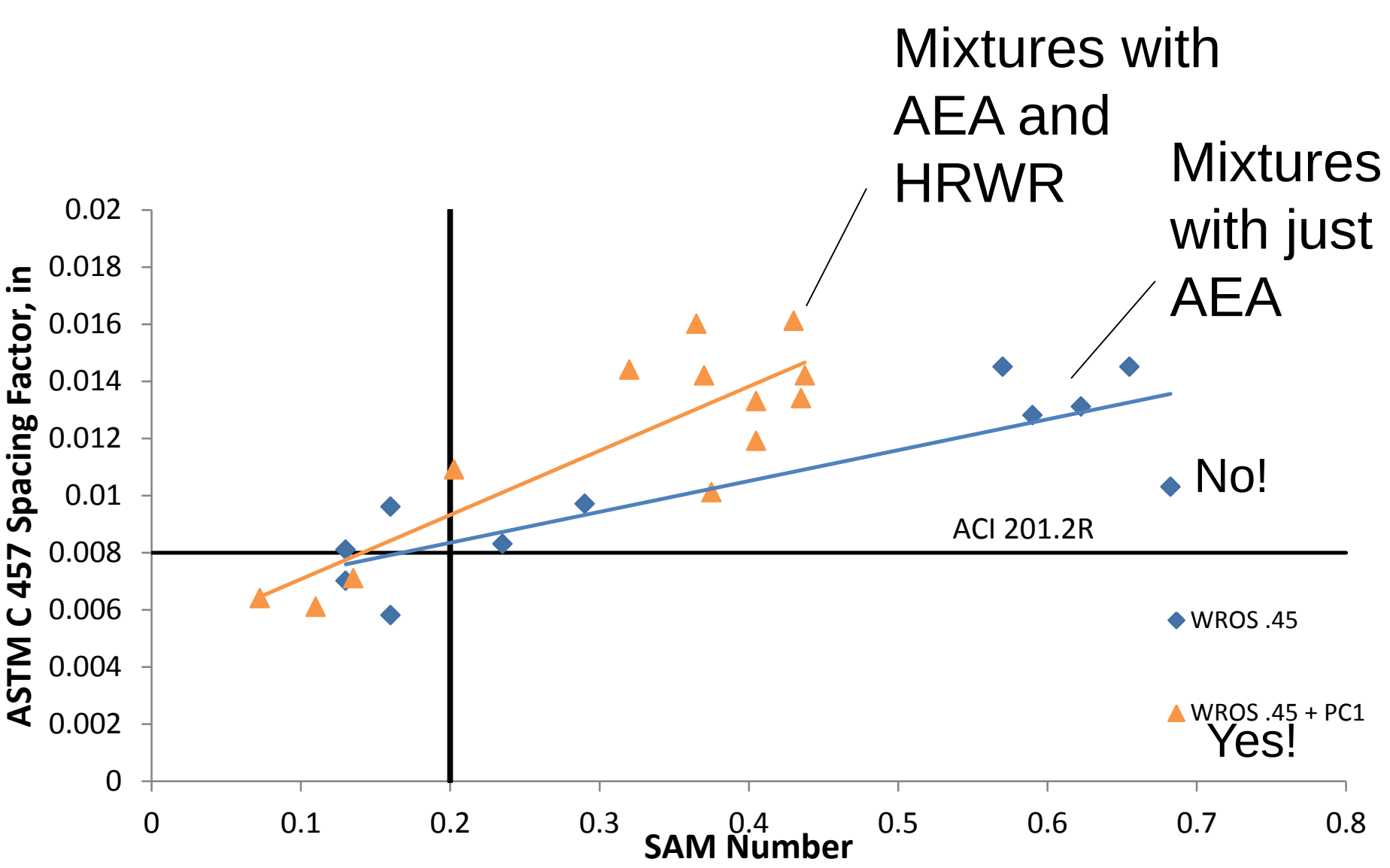

Field data
ASTM C 457, Spacing Factor (in)
SAM Number
Recommended SAM number
ACI 201.2R
No
Yes!
Field 1
Field 2
Field 3
Field 4
Field 5
Field 6
Field 7
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

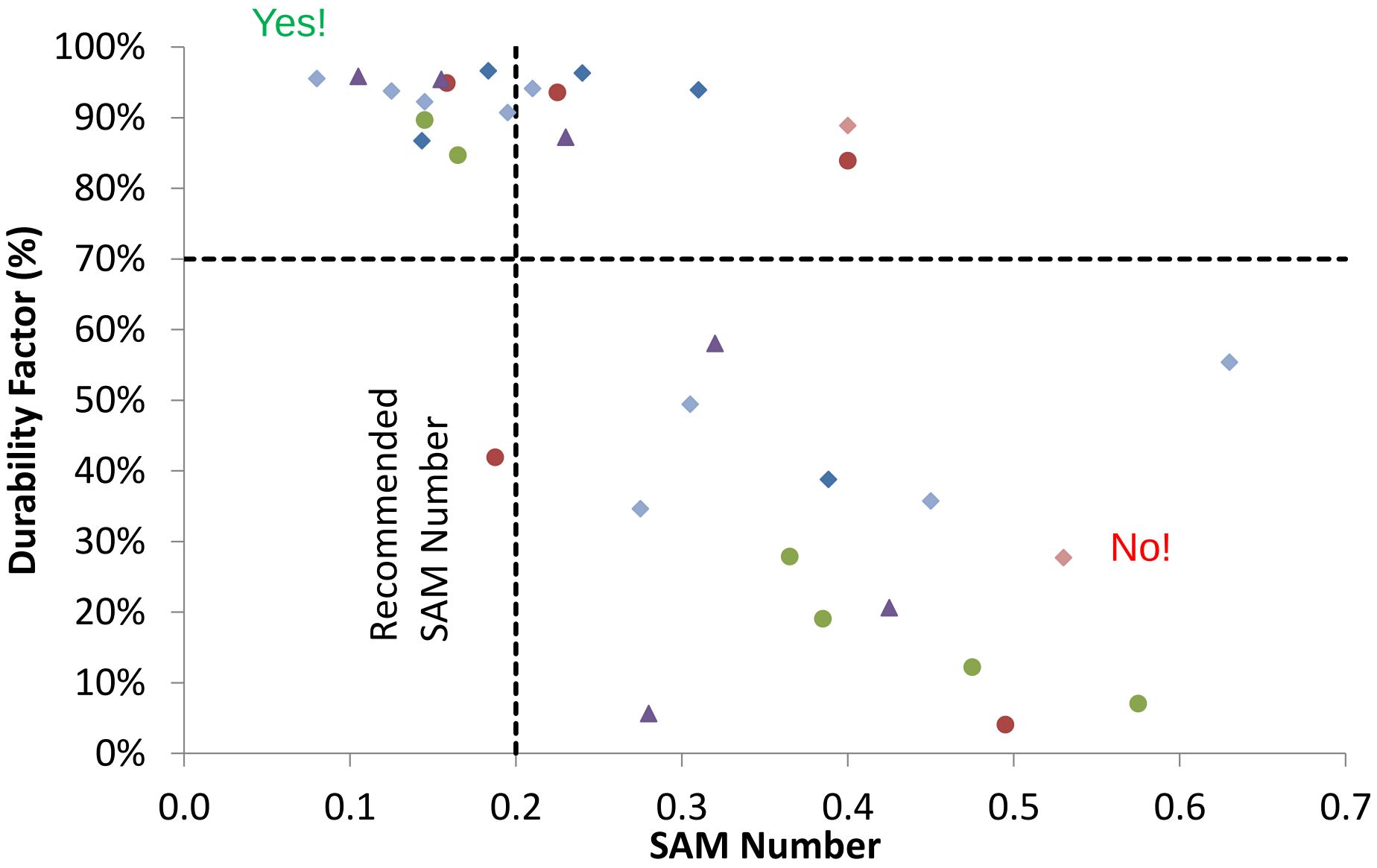

0.0200
0.0180
0.0160
0.0140
0.0120
0.0100
0.0080
0.0060
0.0040
0.0020
0.0000
ASTM C 457 Spacing Factor (in)
Recommended SAM number
ACI 201.2R
LAB Data FHWA
Turner Fairbanks
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
SAM Number (psi)


0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
ASTM C 457 Spacing Factor (in)
Recommended SAM number
ACI 201.2R
Lab Data OSU
Field Data
LAB Data FHWA
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
SAM Number (psi)

Yikes!


Mixtures with AEA and WR
WROS .45
WROS .45 + PC1
No!
ACI 201.2R
Mixtures with just AEA
Yes!
ASTM C 457 Spacing Factor, in
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
2
4
6
8
10
12
Air %


Mixtures with AEA and HRWR
Mixtures with just AEA
No!
ACI 201.2R
WROS .45
WROS .45 + PC1
Yes!
ASTM C 457 Spacing Factor, in
SAM Number
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8



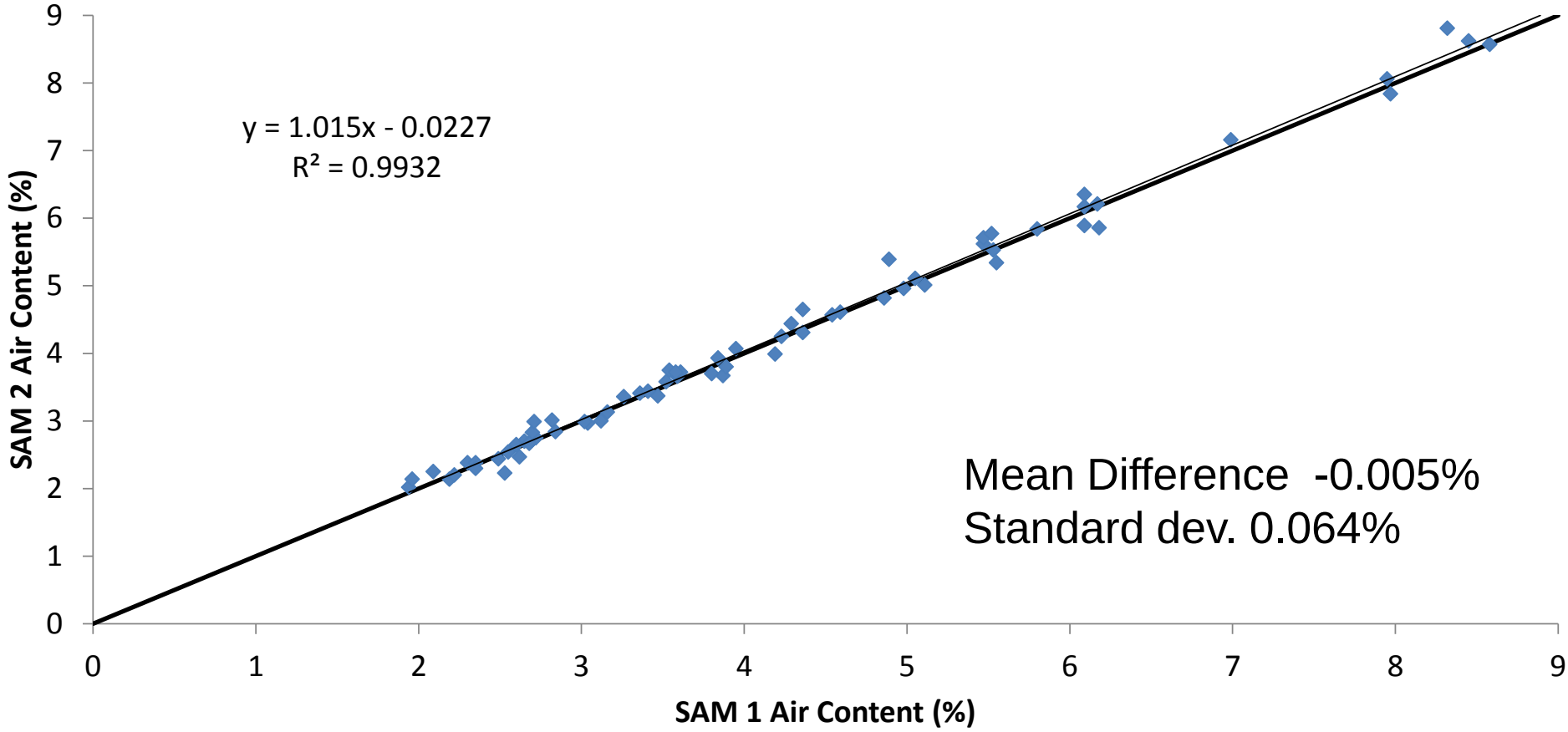
*All mixtures have free-thaw durable aggregates

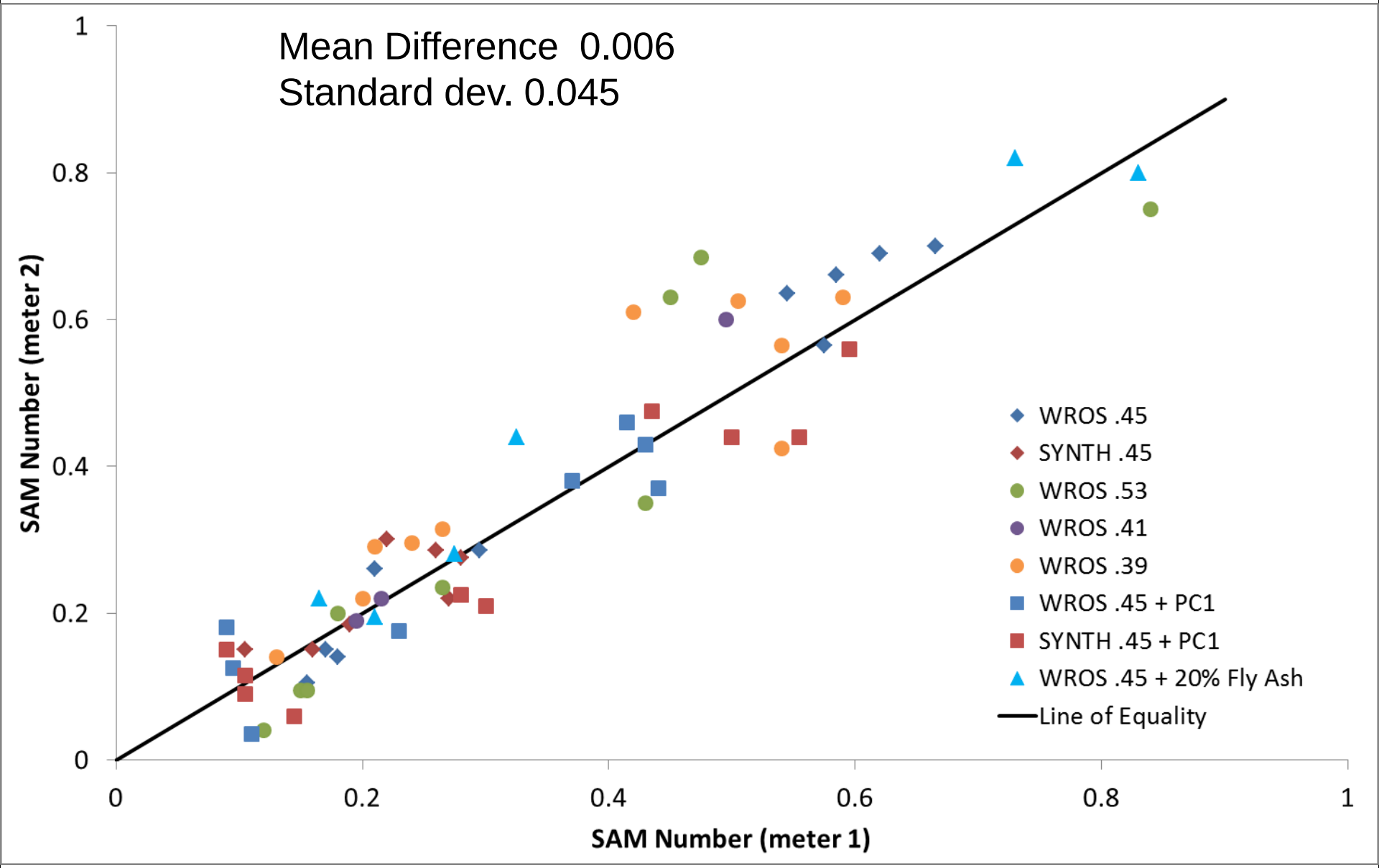
Observations

- A SAM number of 0.20 seems to correspond to a spacing factor of 0.008”
- Over 90% of the data is correctly separated with this limit
- The SAM number seems to correlate with ASTM C666 testing

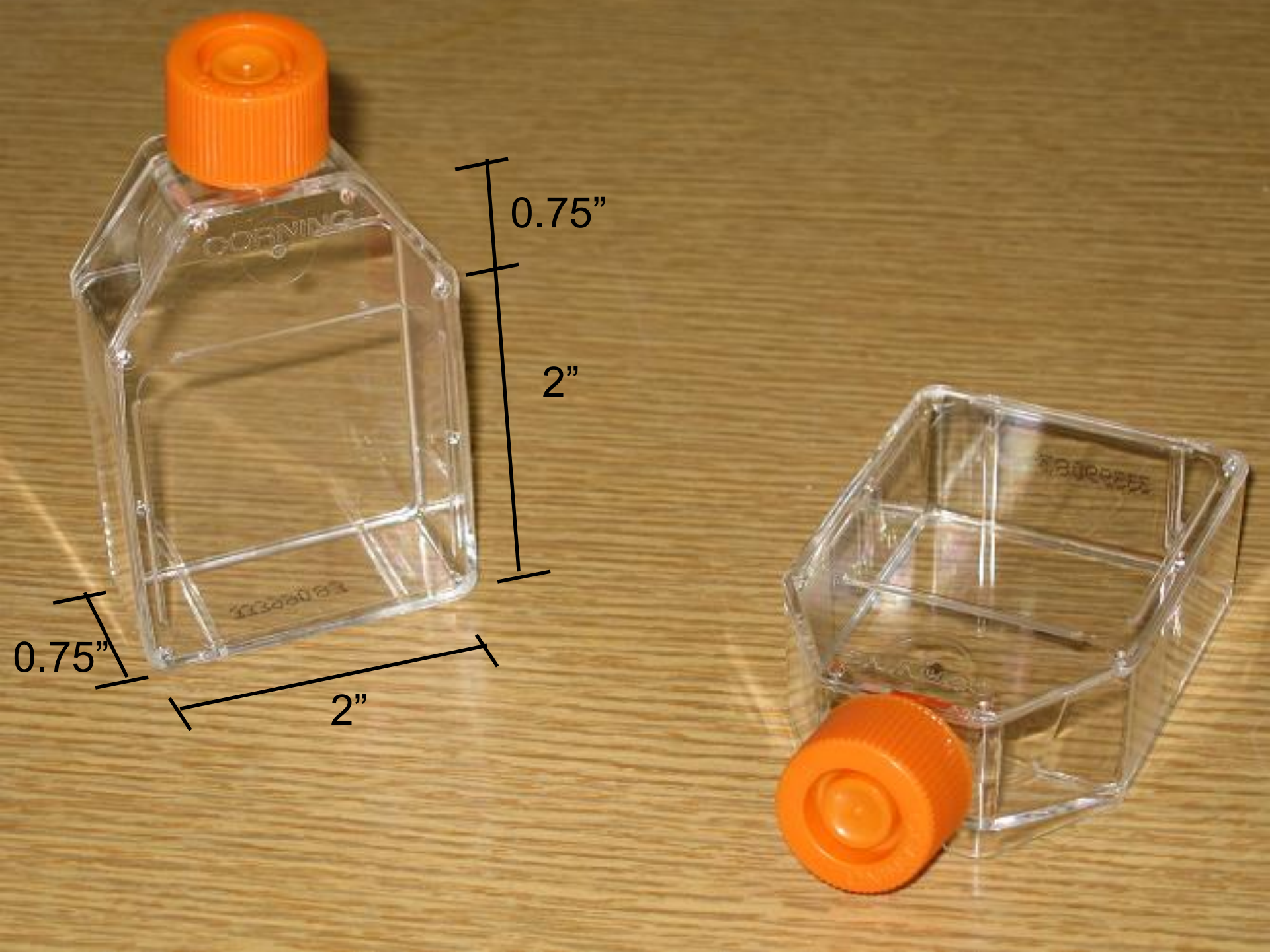
How Consistent Is It?

- We ran the following on each of the 95 mixtures with two separate SAMs:
  - Air contents
  - SAM numbers


y = 1.015x - 0.0227
R² = 0.9932
Mean Difference -0.005%
Standard dev. 0.064%
SAM 2 Air Content (%)
SAM 1 Air Content (%)
0
1
2
3
4
5
6
7
8
9

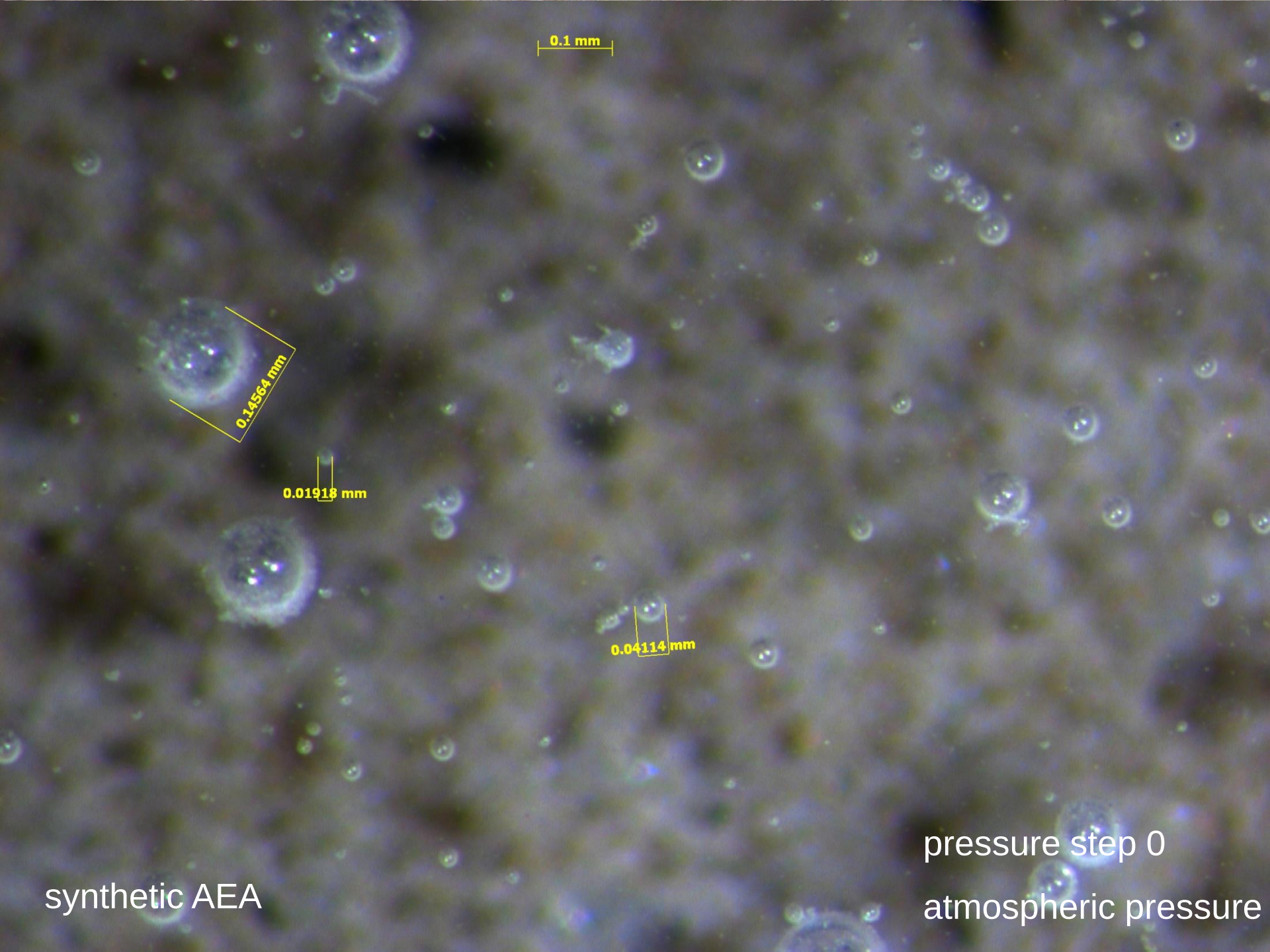

Mean Difference 0.006
Standard dev. 0.045
SAM Number (meter 2)
SAM Number (meter 1)
0
0.2
0.4
0.6
0.8
1
WROS .45
SYNTH .45
WROS .53
WROS .41
WROS .39
WROS .45 + PC1
SYNTH .45 + PC1
WROS .45 + 20% Fly Ash
Line of Equality

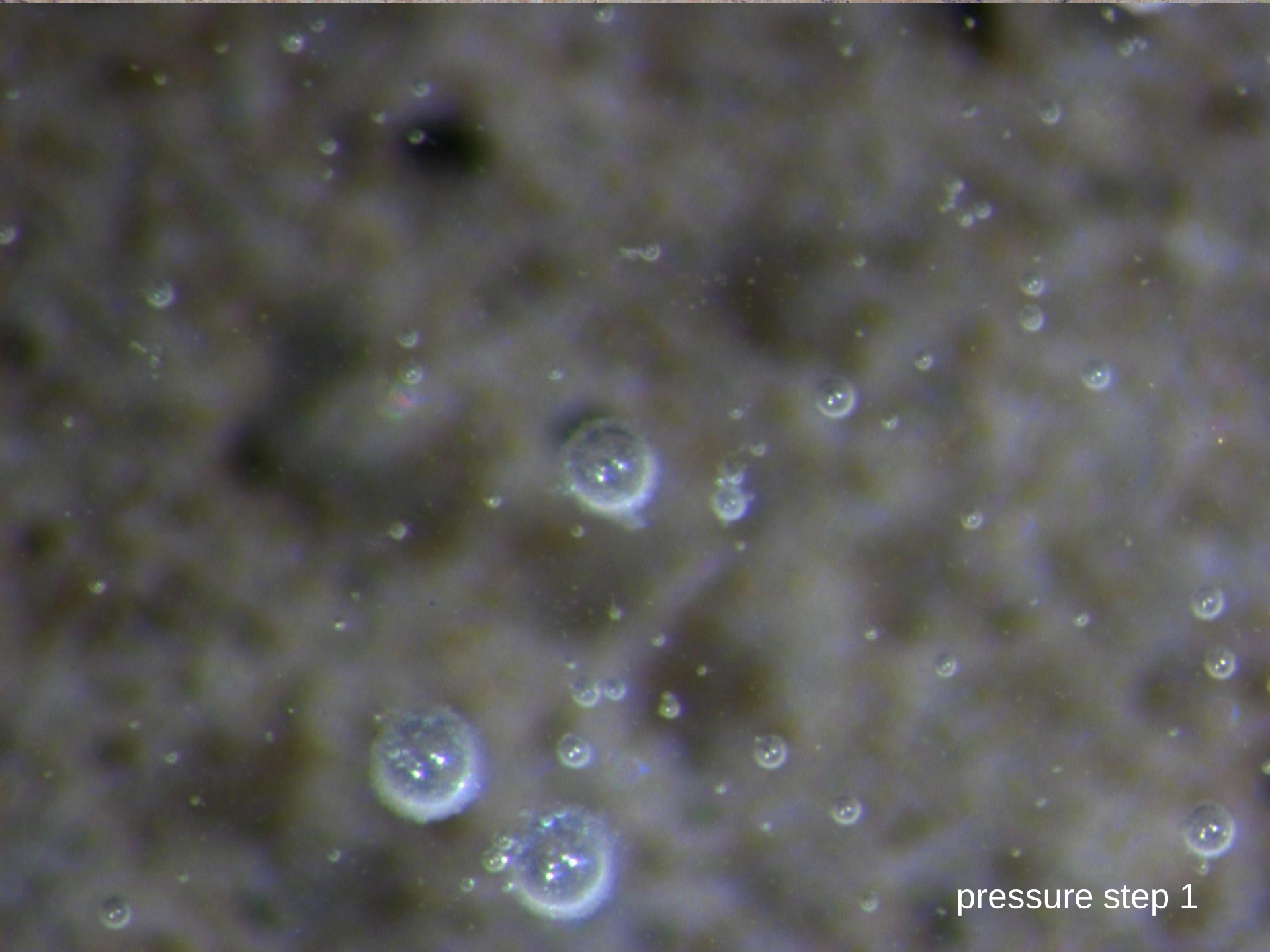
What is happening???

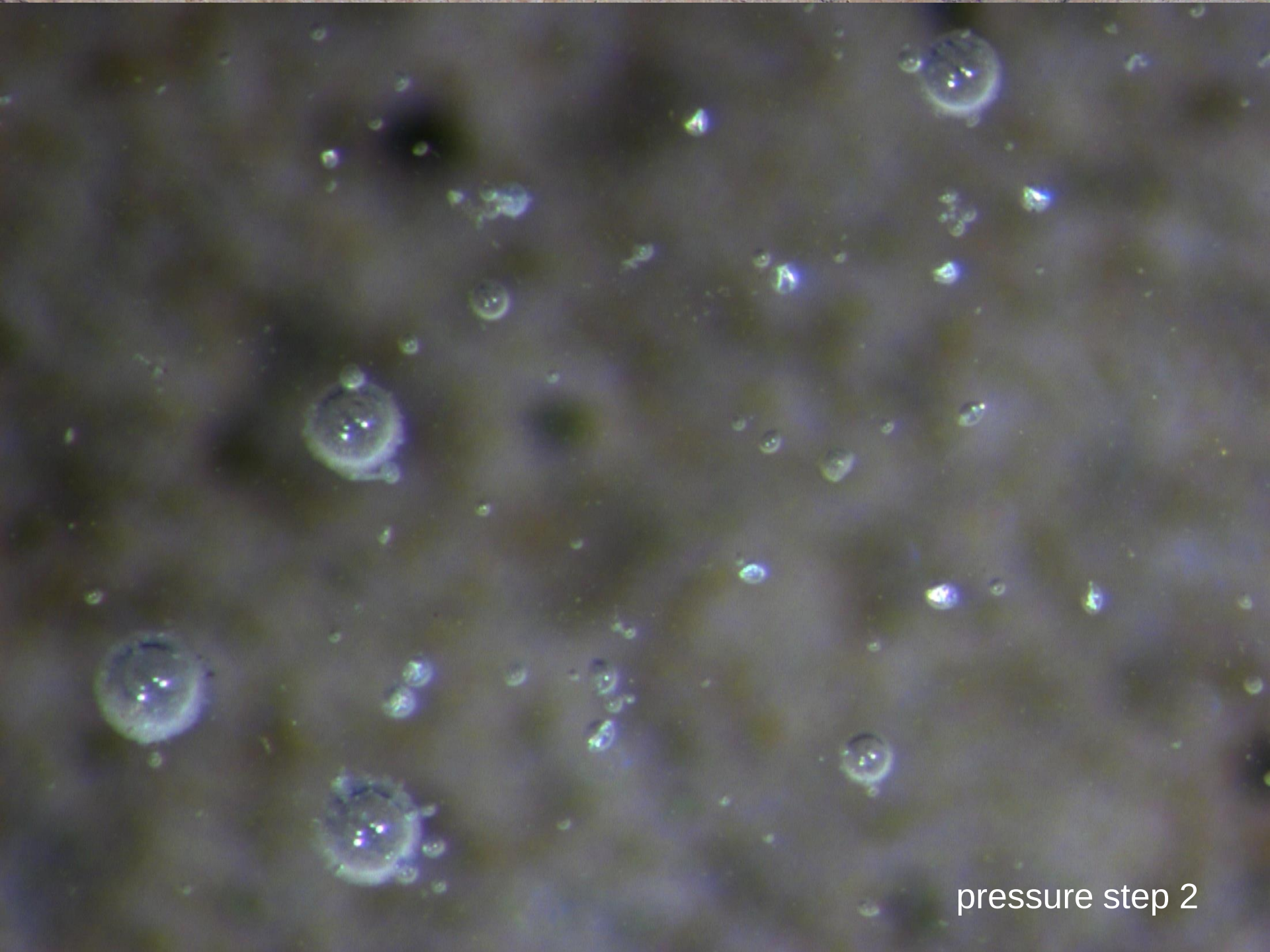

0.75”
2”
0.75”
2”

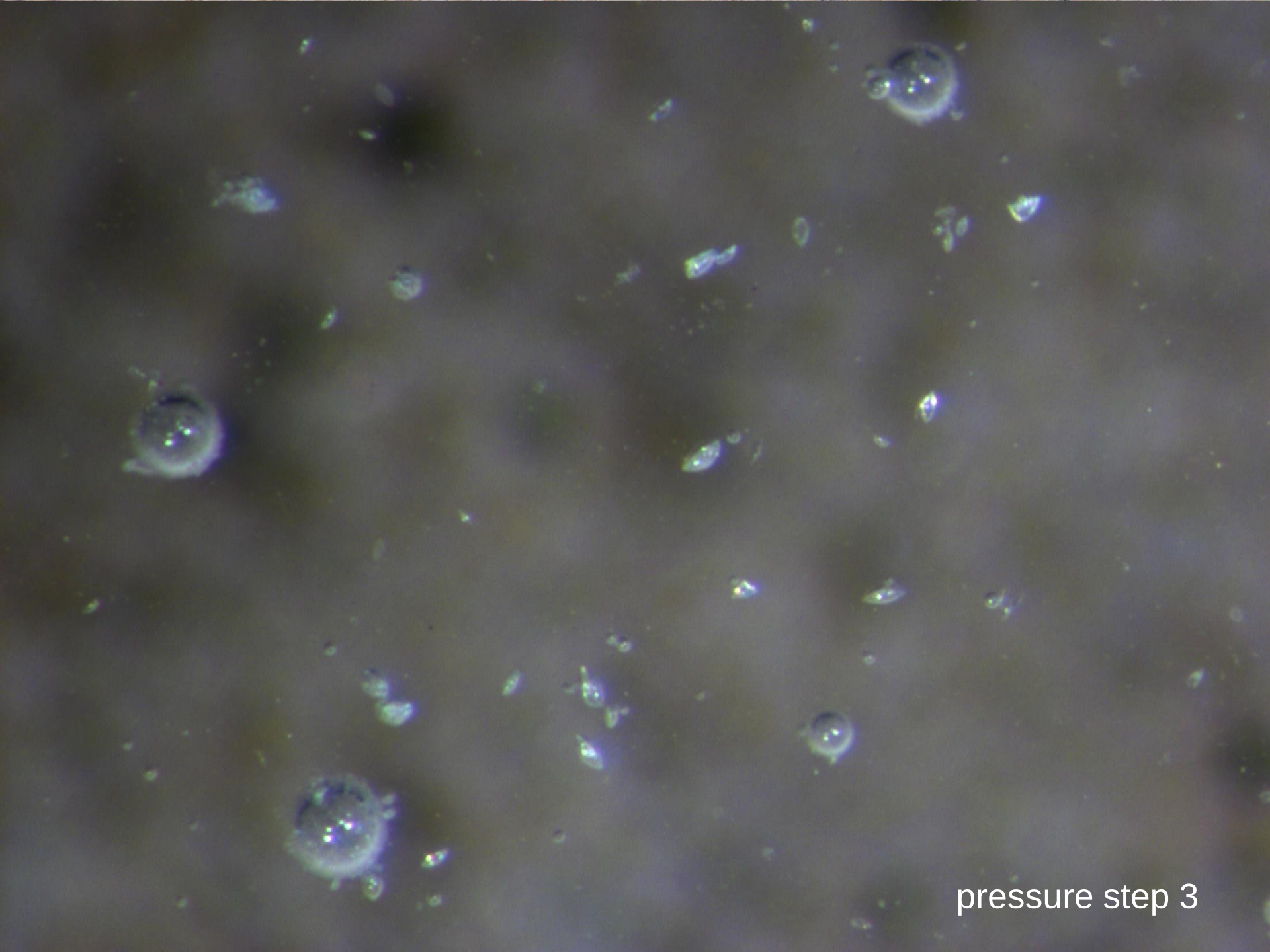

CORNING

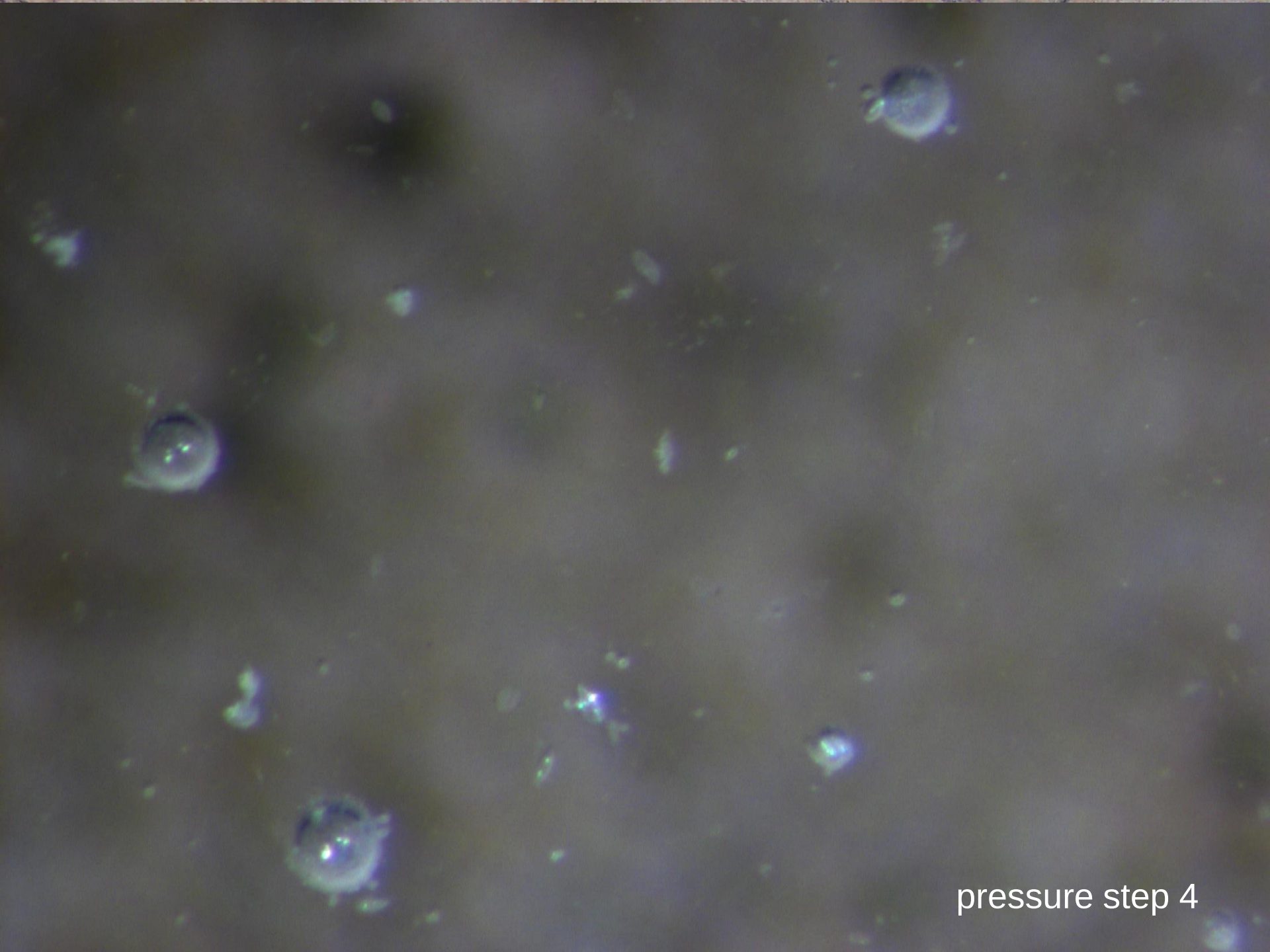
Air pump

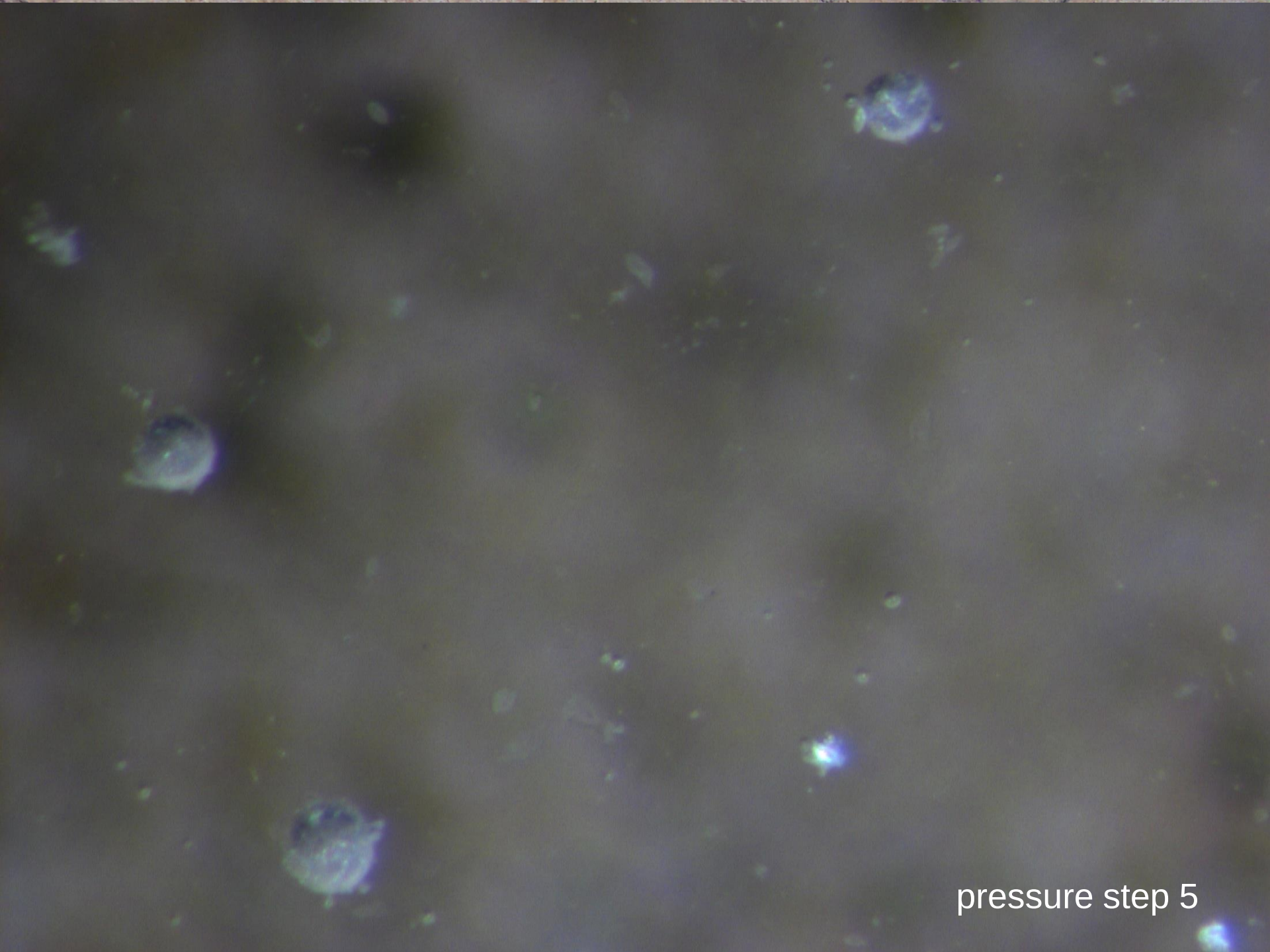

0.1 mm
0.14564 mm
0.01918 mm
0.04114 mm
synthetic AEA
pressure step 0
atmospheric pressure

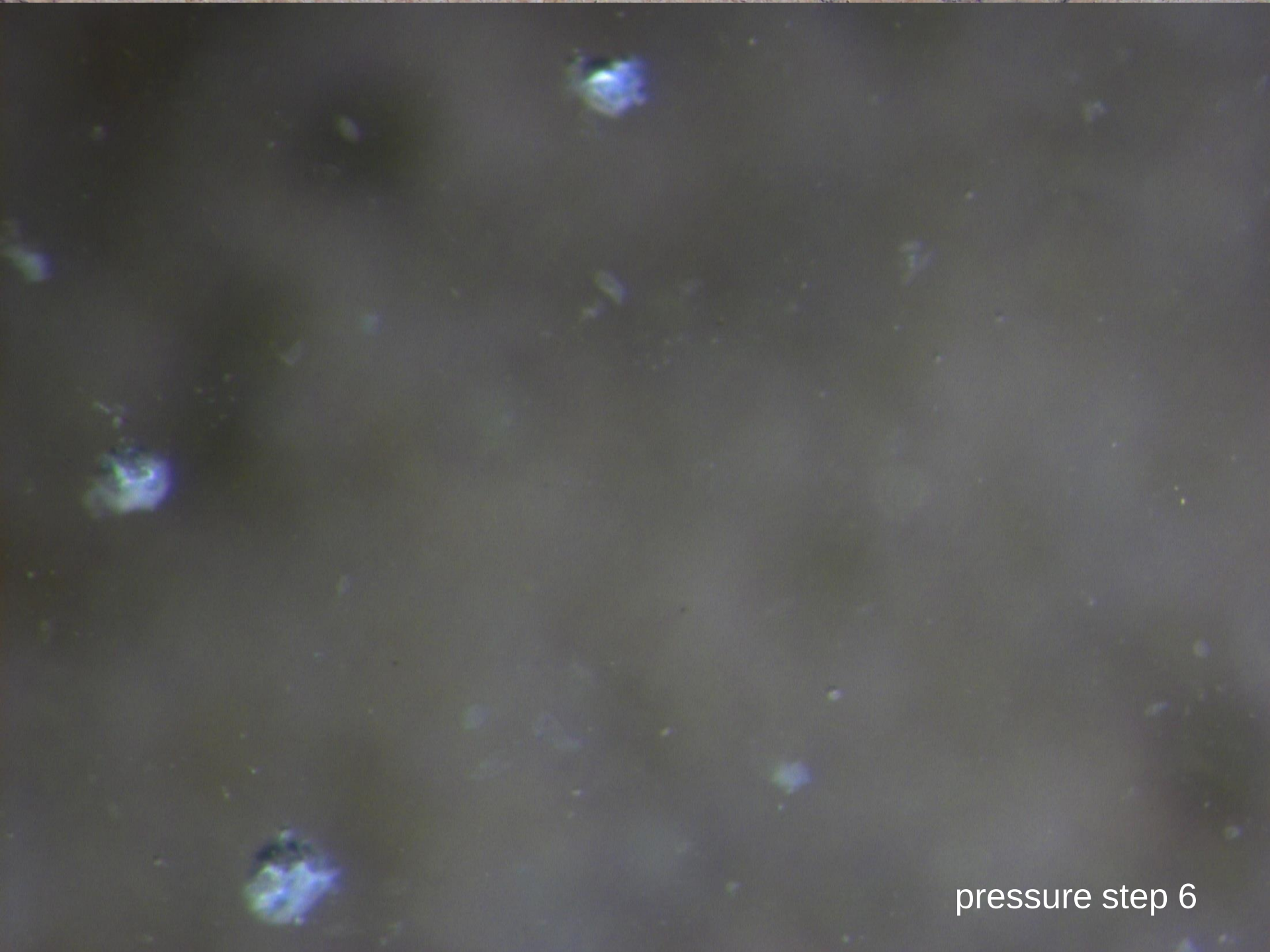

pressure step 1

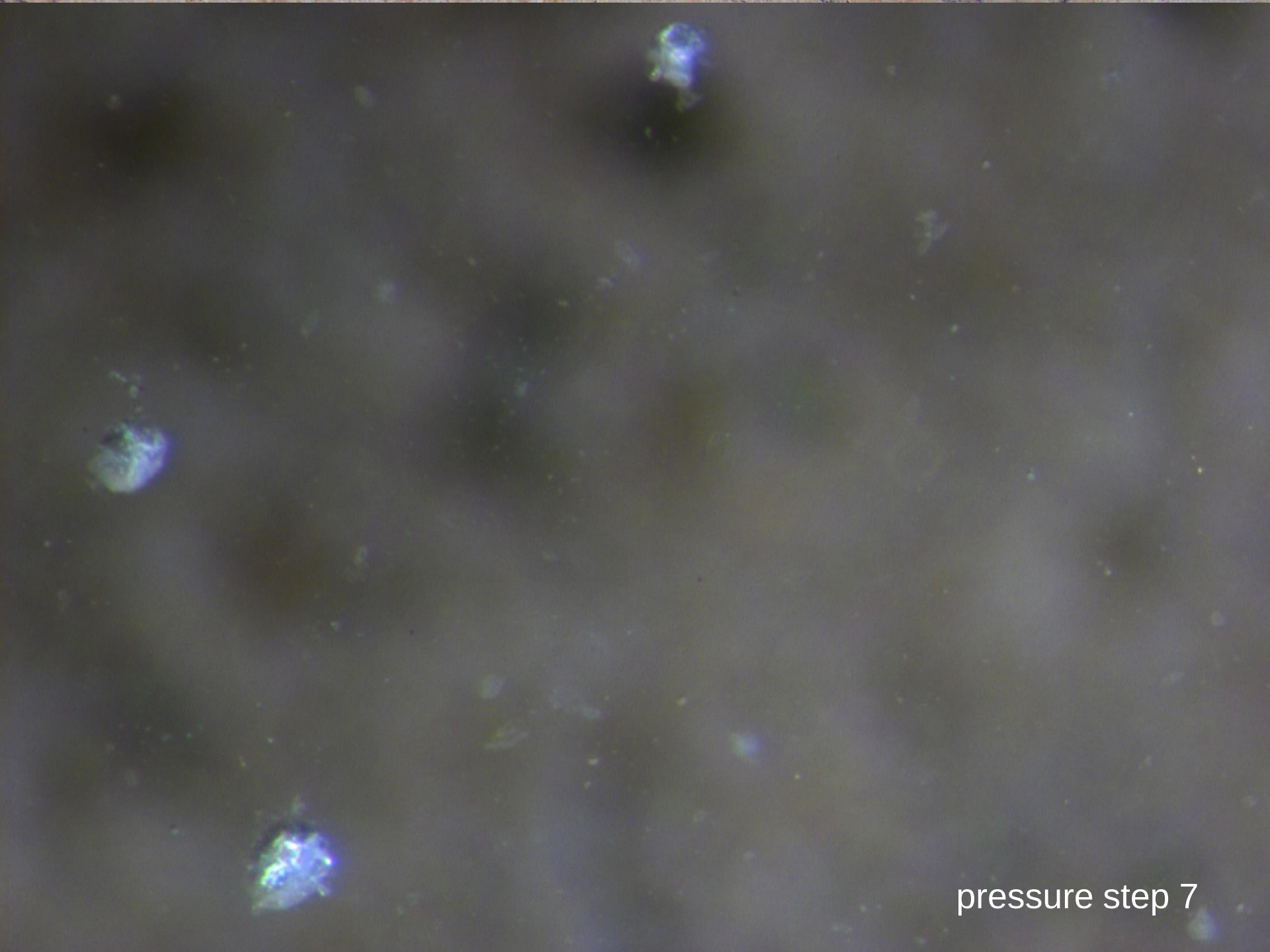

pressure step 2

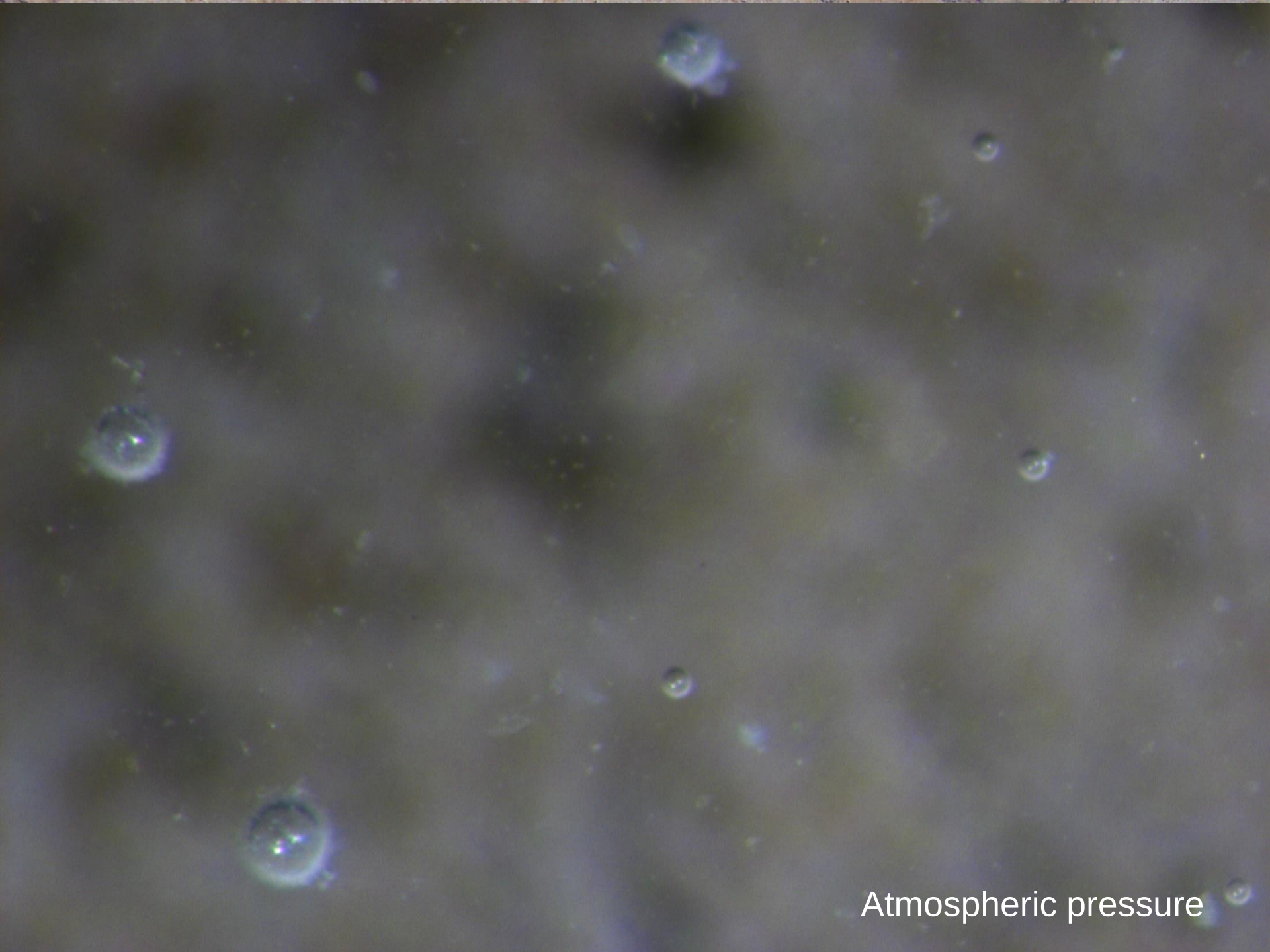

pressure step 3

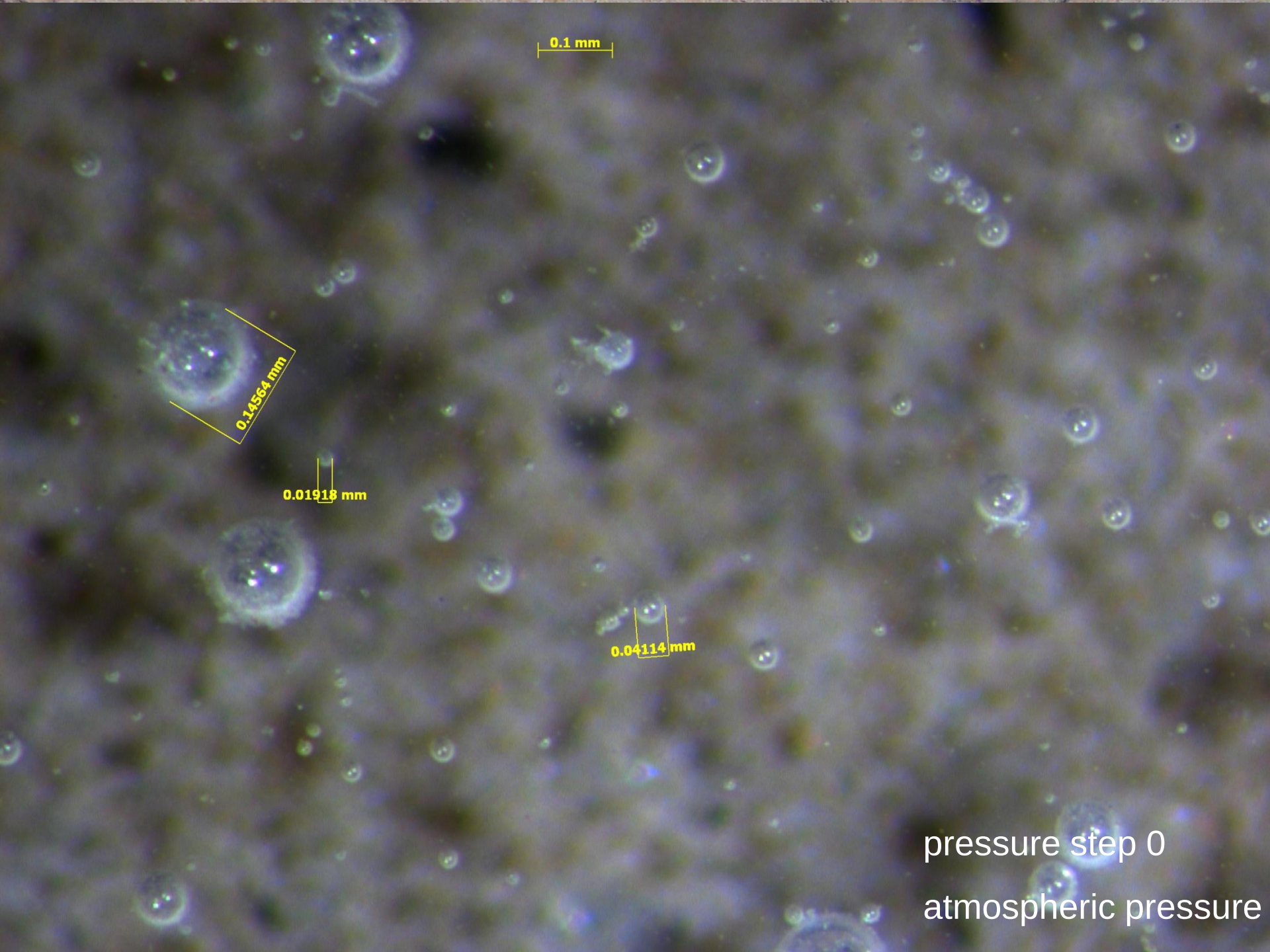

pressure step 4


pressure step 5


pressure step 6


pressure step 7


Atmospheric pressure


0.1 mm
0.14564 mm
0.01918 mm
0.04114 mm
pressure step 0
atmospheric pressure

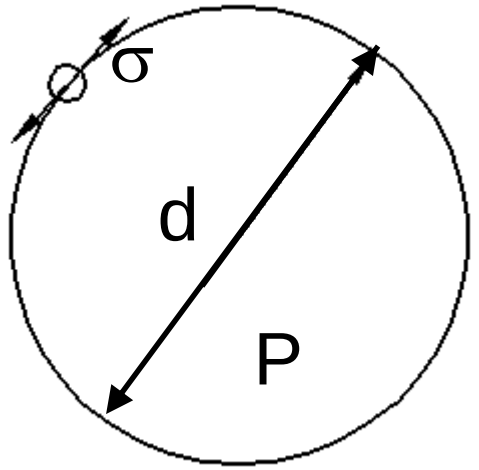
What is happening?

- As you increase the pressure you are dissolving the small bubbles into solution

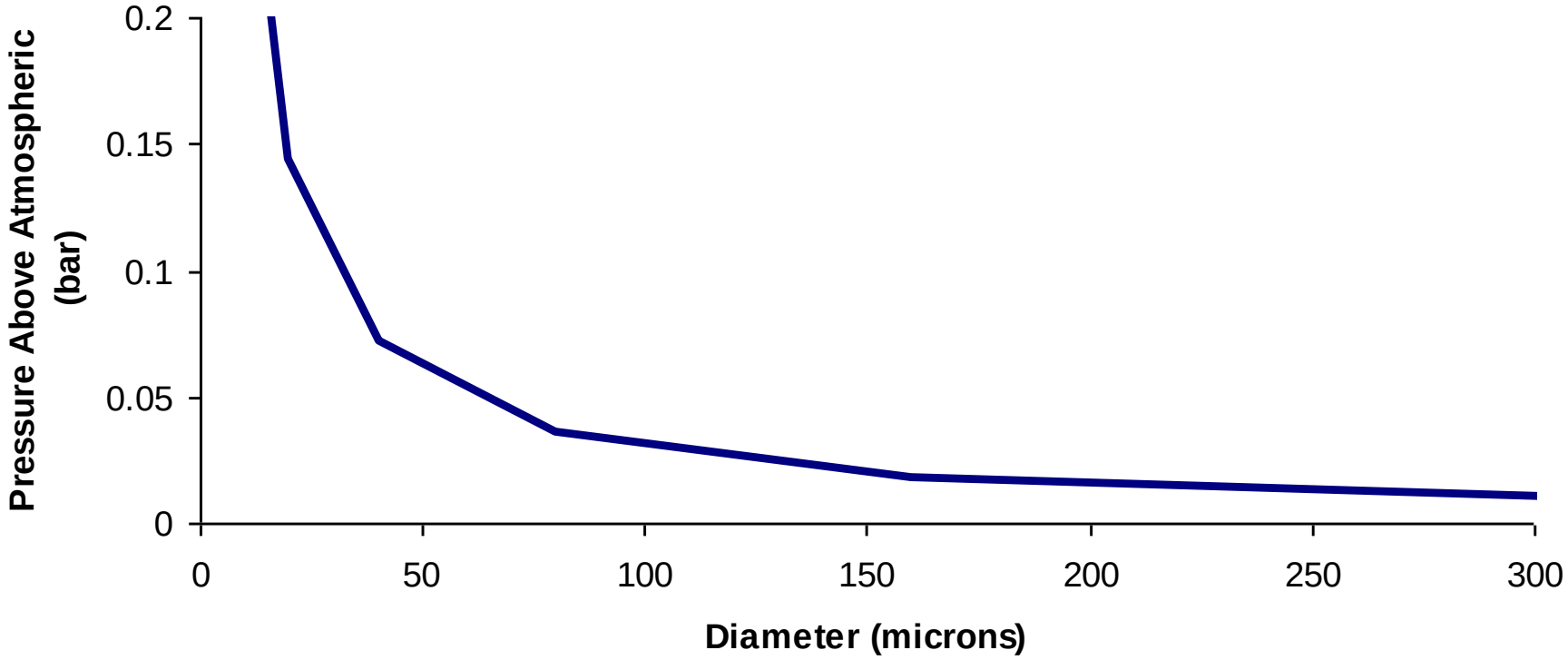
Why is this happening?

- According to the Laplace – Young equation smaller bubbles have higher pressures in them than larger bubbles

$$P = Po + 4\sigma/d$$



- This is caused by the differences in curvature of the bubble wall



Assumes σ = 72 dynes/cm

Atmospheric pressure

Why do the bubbles dissolve?

- Henry's Law states that at a certain pressure that a certain amount of the gas would rather dissolve in the liquid than remain a gas

$$p = k_H c$$

p = pressure

c = concentration

k_H = Henry's Law constant

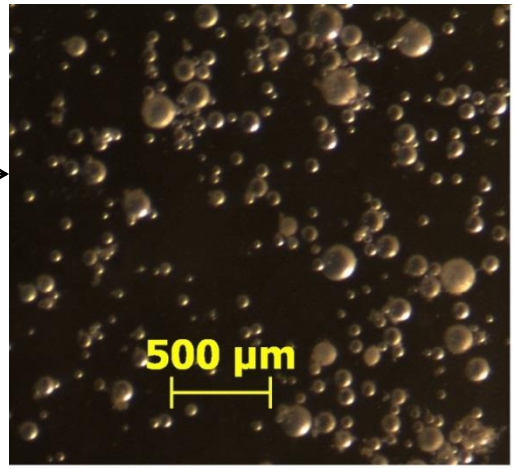
More pressure experiments

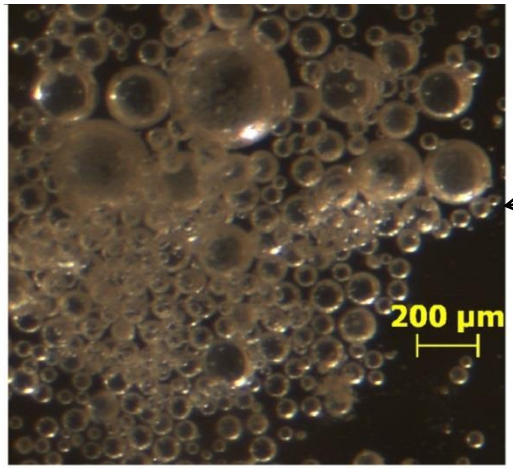
- We ran additional experiments where we tracked individual bubbles every 5 psi from atmospheric until 35 psi.

Spaced bubbles

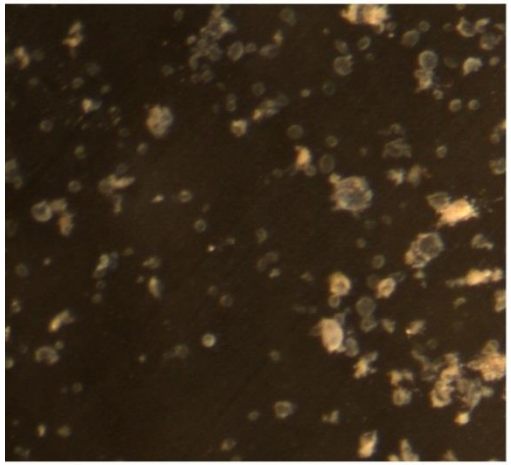
Close bubbles

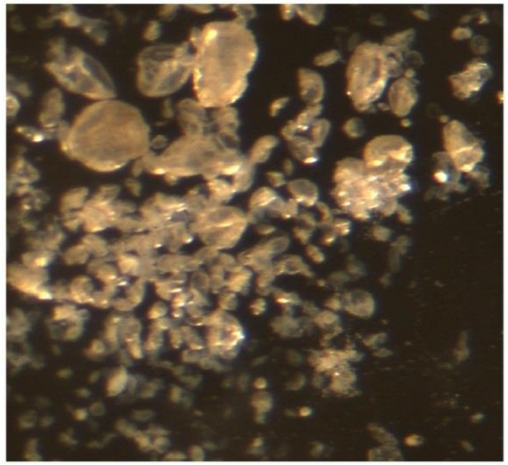
Atmospheric Pressure



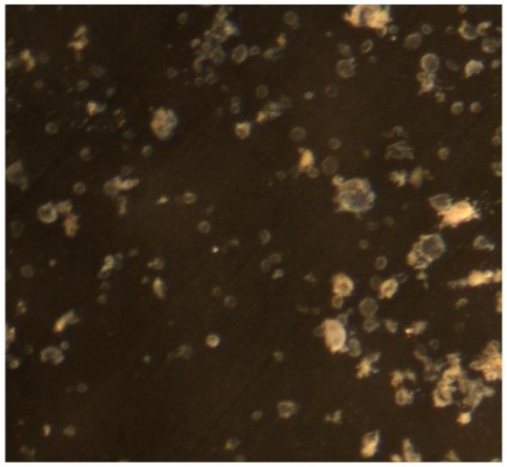


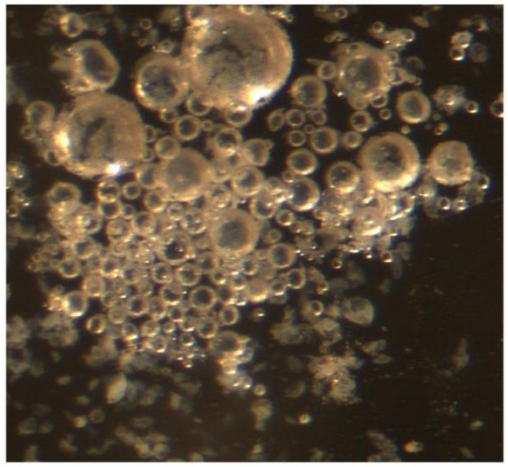
35 psi

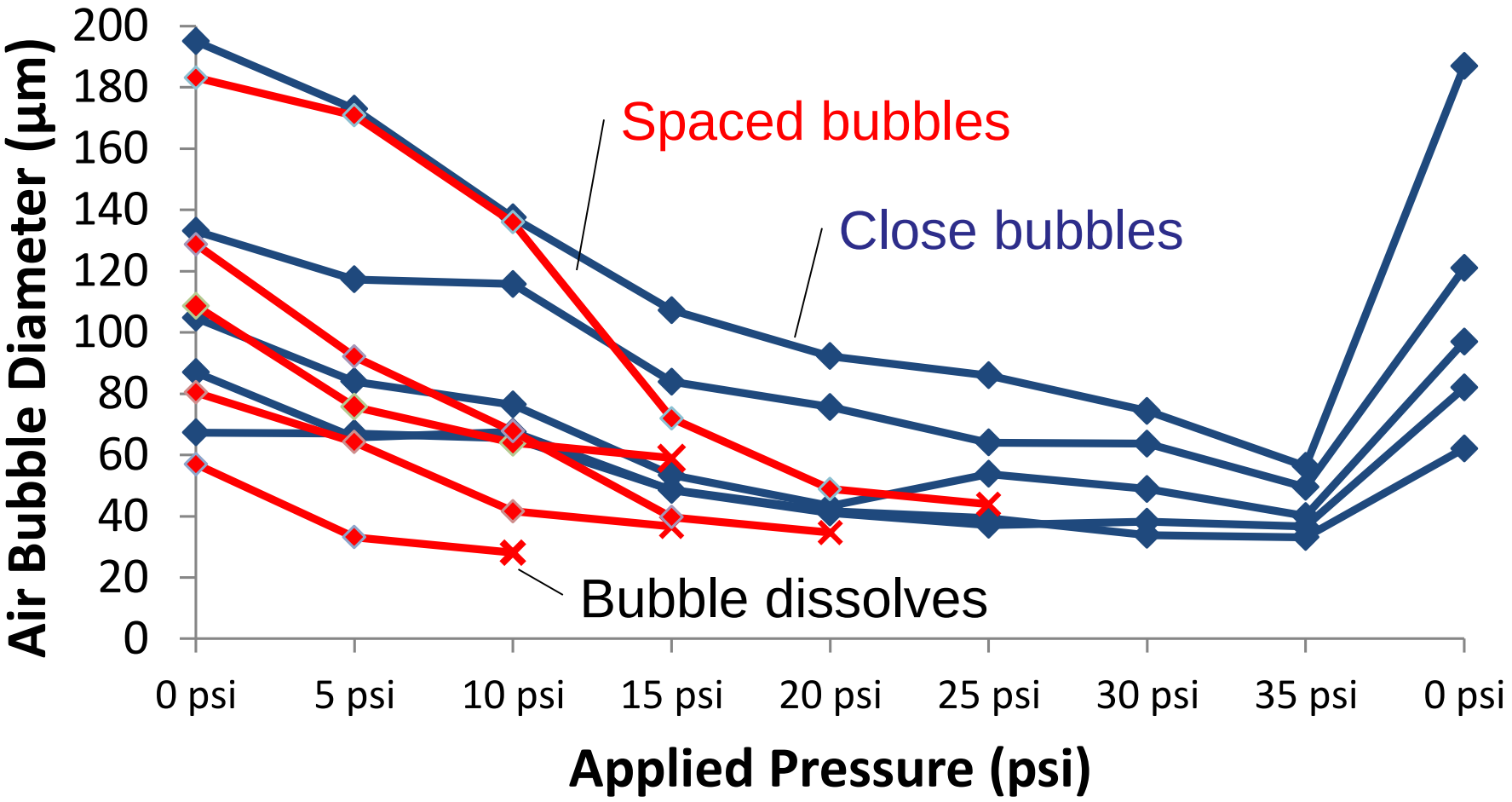




Returned to Atmospheric Pressure






Air Bubble Diameter (µm)
200
180
160
140
120
100
80
60
40
20
0
Spaced bubbles
Close bubbles
Bubble dissolves
0 psi
5 psi
10 psi
15 psi
20 psi
25 psi
30 psi
35 psi
0 psi
Applied Pressure (psi)

Results

- The close bubbles respond differently to the pressure then the spaced bubbles
- The close bubbles also do not dissolve at the same pressures as the spaced bubbles

Discussion

Two possible mechanisms are:

1. Bubbles respond differently to pressure when they are close
2. The fluid around the bubble may become saturated with air. This may make it harder for the close bubbles to dissolve in the solution.

Discussion

Two possible mechanisms are:

1. Bubbles respond differently to pressure when they are close
2. The fluid around the bubble may become saturated with air. This may make it harder for the close bubbles to dissolve in the solution.

More research is needed…

Why is the SAM useful?

- Air volume is no longer enough to evaluate some modern concrete mixtures
- The SAM number could be a tool to investigate the air void systems in the fresh concrete

Why is this useful?

- For example:
  - Admixture combinations
  - Cement types
  - SCMs
  - Sand gradations
  - Hauling
  - Consolidation from vibration
  - Pumping
  - Different types of mixers
  - etc…

What else have we done?

- An AASHTO Provisional Test Method has been approved and is in press
- The SAM is being used in 22 states.

How can this group help?

- Tell someone else about the SAM!
- Try the SAM for yourself
- **Share your data and send a cylinder**

Conclusion

- Air volume is sometimes not enough to determine the air void system quality in modern concretes and that air void size distribution is more useful
- A novel testing device was presented that can measure the air void volume and size distribution in fresh concrete

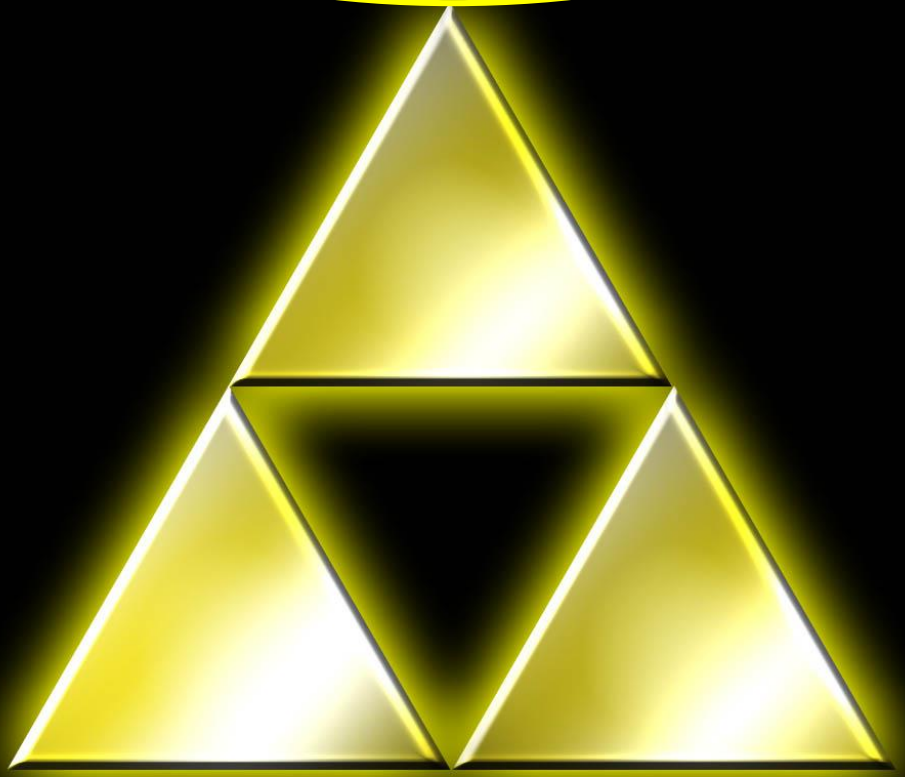
Conclusion

For the materials investigated:

- A SAM number of 0.20 seems to correspond to a spacing factor of 0.008”
- Over 90% of the lab and field data is correctly separated with this limit
- The SAM number seems to correlate well with limited ASTM C 666 testing

The Freeze Thaw Triforce!!!

Air void System Quality



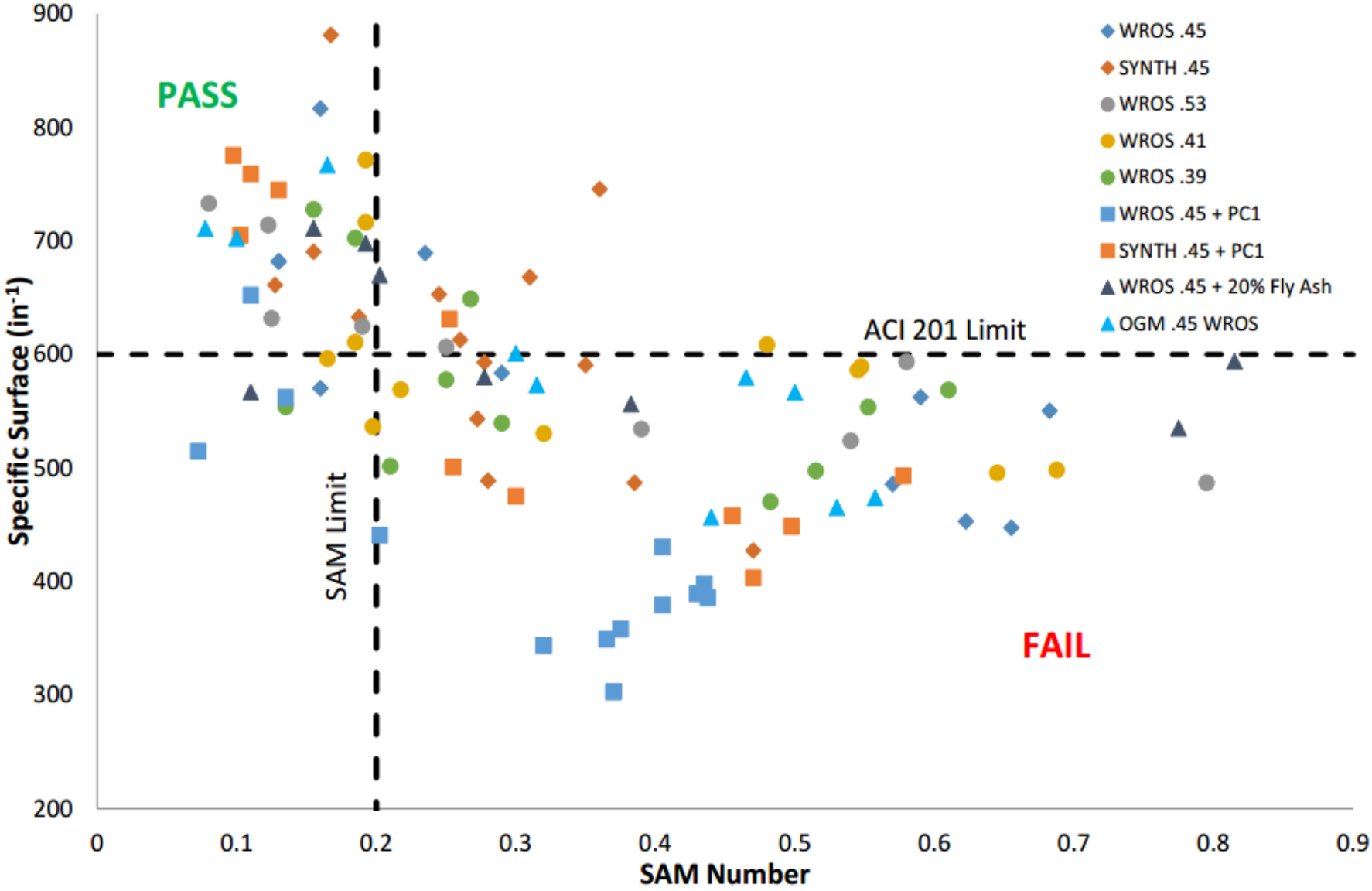
Durable Aggregate

Paste Quality

www.superairmeter.com

Questions???

Tyler.ley@okstate.edu
www.tylerley.com


PASS
FAIL
SAM Limit
ACI 201 Limit
WROS .45
SYNTH .45
WROS .53
WROS .41
WROS .39
WROS .45 + PC1
SYNTH .45 + PC1
WROS .45 + 20% Fly Ash
OGM .45 WROS
Specific Surface (in-1)
SAM Number
900
800
700
600
500
400
300
200
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

w/c ratio	Cement lb/yd ^{3}	Paste Content (%)	Coarse lb/yd^3	Fine lb/yd^3	Water lb/yd^3
0.41	611	29	1900	1217	250
0.45	611	30	1850	1203	275
0.53	611	33	1775	1150	324

Observations

- Recall that the spacing factor calculation is dependent on the specific surface calculation which is dependent on the voids per inch.

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(1 + \frac{p}{A}\right)^{1/3} - 1\right]$$

$$\alpha = \frac{4N}{T_a}$$

N — number of chords

T_a — traverse length