Stability and instability of foamed concrete

Jones, Martyn; Ozlutas, Kezban; Zheng, Li

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Stability and Instability of Foamed Concrete

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Corresponding Author:	M Roderick Jones University of Dundee Dundee, UNITED KINGDOM
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Dundee
Corresponding Author's Secondary Institution:	
First Author:	M Roderick Jones
First Author Secondary Information:	
Order of Authors:	M Roderick Jones
	Kezban Ozlutas
	Li Zheng
Order of Authors Secondary Information:	
Abstract:	Foamed concrete has proven to be an effective alternative to granular fills and is now widely used internationally. There is also increasing demand for lightweight materials for buildings to improve sustainability and foamed concrete has also developed as an ideal material for this purpose and many countries utilise construction with precast foamed concrete blocks. However, at densities lower than current technology allows, typically < 500 kg/m³ foamed concretes are more prone to instability of the fresh mix. Furthermore, at very low densities, ≤ 300 kg/m³, instability is almost inevitable, greatly limiting the potential of foamed concrete for applications where mass is critical, e.g. weak soils, backfilling damaged structure etc. This paper aims to illustrate the mechanisms of stability and instability in foamed concretes and demonstrates how ultra-low density (down to plastic density of 150 kg/m³) mixes can be successfully produced.
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Dear Editorial Team

Please find the above paper revised in accordance with the comments from the Reviewers/Editors for the MCR journal. Response to Reviewers/Editors is attached below. Please let me know if there are any problems.

I look forward to hearing from you soon.

Kind Regards

Roderick Jones

M R Jones

UNIVERSITY OF DUNDEE – Dundee DD1 4HN *t* +44 (0)1382 388326 *f* +44(0)1382 384389
e m.r.jones@dundee.ac.uk

Response to Reviewers/Editors:

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Stability and Instability of Foamed Concrete

M R Jones[a]*, K Ozlutas[a] and L Zheng[a]

March 2015

[a] **Concrete Technology Unit, Division of Civil Engineering, University of Dundee, Dundee, DD1 4HN, Scotland, UK**
* **Corresponding author. Tel.: +44 1382 388326; Fax.: +44 1382 384389.
Email: m.r.jones@dundee.ac.uk**

Stability and Instability of Foamed Concrete

Contents

Abstract

Foamed concrete has proven to be an effective alternative to granular fills and is now widely used internationally. There is also increasing demand for lightweight materials for buildings to improve sustainability and foamed concrete has also developed as an ideal material for this purpose and many countries utilise construction with precast foamed concrete blocks.

However, at densities lower than current technology allows, typically < 500 kg/m^3 foamed concretes are more prone to instability of the fresh mix. Furthermore, at very low densities, ≤ 300 kg/m^3, instability is almost inevitable, greatly limiting the potential of foamed concrete for applications where mass is critical, eg weak soils, backfilling damaged structure etc. This paper aims to illustrate the mechanisms of stability and instability in foamed concretes and demonstrates how ultra-low density (down to plastic density of 150 kg/m^3) mixes can be successfully produced.

Keywords: Foamed Concrete, Stability, Bubble Structure, CSA cement

Notations

F_b	bubble buoyancy force
F_c	bubble confinement force
F_d	drainage force
F_{st}	surface tension of bubbles
P_i	internal bubble pressure
r	bubble radius
$Ø$	bubble diameter
γ	interfacial surface tension
w/c	water to cement ratio

1. Introduction and Background

Foamed concrete is now widely used internationally, however, growing pressure for more sustainable construction technologies, such as lightening of structures, energy conservation, minimised use of primary resources, resource efficiency as well as reducing the impact of environmental noise underpin the need for developing ultra-low density foamed concrete, which current technology is unable to achieve.

'Conventional' foamed concrete can be regarded as having plastic densities from 500 to 1600 kg/m³ and, in this case, ultra-low density foamed concrete has been defined as having a plastic density ≤ 500 kg/m³. However, it has previously been reported that mixes at these latter densities have greatly increased susceptibility to instability (Aldridge, 2005; Jones and McCarthy, 2005; Jones and McCarthy, 2006). Indeed, at ≤ 300 kg/m³ consistently achieving stable foamed concrete mixes is extremely difficult. Instability of foamed concrete is the segregation of the fresh mix due to the separation of solids and air phases of the mix. Generally, this segregation is catastrophic leading to a complete loss of the air phase leaving only the base mix. There is no clear understanding of underlying mechanism of bubble stability in foamed concrete mixes or why ultra-low density mixes are more prone to becoming unstable.

Working with industry, the authors are aware that this has led to an inability to deploy ultra-low density foamed concrete, even though there is a demand from many construction sectors. Based on laboratory-based studies carried out over a decade, the authors have attempted to develop an empirical understanding of the factors that have been identified as being critical to bubble stability, which are reported here and, thereby, develop a method for consistently producing ultra-low density mixes.

2. Fundamental Issues and Observations of Foamed Concrete Stability

2.1 Effect of plastic density on bubble size

Figure 1 illustrates the typical appearance of instability in foamed concrete mixes, both in laboratory (Fig. 1a) and on site (Fig. 1b and c). Figure 1b illustrates a transition point where a mix is becoming unstable and bubbles have risen to the surface. This can happen from almost immediately to more typically after 10's of minutes but has been noted up to 24 hours after placement. Observationally, the lower the plastic density of the mix the shorter the time to the onset of instability.

It has been previously noted that foamed concrete average bubble size increases with decreasing plastic density (Visagie and Kearsley, 1999; Nambiar and Ramamurthy, 2007; Jones and Zheng, 2013; She et al, 2014). This is initially a surprising observation, as the nature of the input foam is the same for all mixes and, thus, bubbles must change size once combined with the base mix. It is not possible to say whether this is an immediate or more gradual process but it does underline that bubble formation is a dynamic process, rather than a simple incorporation of more or less foam into a base mix. It is also not clear whether foamed concrete bubbles are either larger or smaller than the bubble size of the parent foam, as it is difficult to obtain bubble size metrics in wet foam. However, once this dynamic stage is complete, the bubbles form a size essentially proportional to the plastic density of the fresh mix.

Figure 2 gives a typical example of protein-based foamed concretes with plastic densities of (a) 1000 and (b) 500 kg/m^3. This shows that the larger the bubble size also results in a thinner 'wall' separating adjacent bubbles. In addition, these thinner walls tend to contain many more 'small' bubbles. It is speculated that these bubbles are due to entrapped air in the base mix, which when constricted in the thin walls become more visible. The potential effect of these is discussed below.

2.2 Forces acting on bubbles in fresh foamed concrete mixes

Figure 3 is an attempt to provide a 2D schematic of the 'forces' acting on a single bubble when incorporated into fresh foamed concrete. Based on this a stable, equilibrium state of the bubble is obtained when the bubble confinement force, $\boldsymbol{F}_{\mathbf{c}}$, drainage force, $\boldsymbol{F}_{\mathbf{d}}$, internal bubble pressure, $\boldsymbol{P}_{\mathbf{i}}$, surface tension of bubbles, $\boldsymbol{F}_{\mathbf{st}}$ and bubble buoyancy force, $\boldsymbol{F}_{\mathbf{b}}$ are balanced.

$\boldsymbol{F}_{\mathbf{c}}$ is mainly due to the plastic density of the fresh mix but the type of constituent materials such as use of different fillers (e.g. sand or fly ash) and cement type also affect this force and can be related to the prevailing mix rheological characteristics of yield stress and plastic viscosity. At densities ≤ 500 kg/m^3, where fillers are generally not used, there likely to be a significant decrease in $\boldsymbol{F}_{\mathbf{c}}$ due to a decrease in yield stress, which results in larger and more closely spaced bubbles. To reach ultra-low densities both the cement and water contents of the mix have to be reduced and hence $\boldsymbol{F}_{\mathbf{c}}$. On the other hand, there is evidence to support the use of finer cementitious materials (such as fly ash) providing enhanced particle packing around the bubbles and a greater confining force (Nambiar and Ramamurthy, 2007) and hence smaller bubbles given the same overall plastic density.

The initial internal pressure, $\boldsymbol{P}_{\mathbf{i}}$, of the bubbles is assumed to be the same in the foam prior to incorporation into the base mix, given a particular surfactant type and foam generator pressure. Once the foam is mixed with the cementitious matrix, bubbles change size, and, the internal pressure varies, in order to maintain the equilibrium with the surrounding matrix. It is assumed that this process is elastic (Prins, 2006) and hence small bubbles have a higher internal pressure than larger bubbles.

This gives a coherent explanation for the observed bubble size characteristics at different densities and water/cement ratios, cement and filler types. Figure 4 provides a schematic illustration of end result of these force equilibration processes. However, this explanation does not predict instability and thus, additional time dependent changes to these forces must occur in fresh mixes.

2.3 Causes of Stability and Instability in Mixes of Conventional and Ultra-low Densities

What is clear from the observation of unstable mixes is that at some point in time the bubble size becomes sufficiently large to cause them to be buoyant and, separate from the mix. The following discussion attempts to describe the time dependent mechanics of buoyant, unstable bubbles and the comparative rate at which this happens with 'conventional' and ultra-low density foamed concrete mixes.

A major time-dependent force is due to the effect of the surfactant, ie its control of the surface tension of the aqueous bubble, $\boldsymbol{F_{st}}$ (Myers, 1992, Weaire and Hutzler, 1999). For liquid foams, the time-dependent effect of surface tension reducing and leading to liquid drainage due to the effects of gravity ($\boldsymbol{F_d}$) is well understood. As a result, the aqueous/surfactant liquid fraction of the foam changes, so does the surface tension, $\boldsymbol{F_{st}}$ of the bubbles. In turn, to maintain equilibrium the bubble size increases (Myers, 1992; Weaire and Hutzler, 1999; Stevenson, 2011).

However, unlike liquid foams, bubbles in a cementitious matrix are separated by the paste or mortar phase surrounding them. In this case, drainage that occurs through thin films separating the bubbles and Plateau borders (ie channels formed where three neighbouring films meet; Stevenson, 2011) in liquid foams may change. As a result, it is not possible to directly compare the situation to liquid foams. Stevenson (2011) has reported a slower drainage rate in foams with smaller bubbles, suggesting that drainage occurs at a faster rate in lower density foamed concretes than high densities. Furthermore, surface charges on bubbles and cement particles were reported to affect the mix stability (Jones and McCarthy, 2006). Cement particles are attracted to bubbles making it more difficult for the liquid to drain.

As noted above, as the mix plastic density is decreased down to ultra-low levels, firstly the total solids content is decreased through the reduction and eventual elimination of the sand/filler (below 600 kg/m^3), and secondly, the cement and water contents have to be reduced. Figure 4 is an idealised system in which bubbles have been considered to be of uniform size. However, in reality there are inevitably a range of actual bubble sizes in a mix, each of which has a slightly different internal pressure.

Varying bubble sizes vary within the mix gives rise to an internal pressure gradient. In turn, this can result in gas diffusion, which is referred to as Ostwald ripening in liquid foams. For aqueous foams, this is defined by the Laplace pressure (Weaire and Hutzler, 1999; Stevenson, 2011), which is $2\gamma/r$ for spheres, where γ is the interfacial surface tension and r the bubble radius. In this case, γ is the surface tension. Thus, due to this differential pressure gas contained in smaller bubbles diffuses into larger bubbles, which further increase in size and further increase pressure differentials. The process continues until the bubbles are sufficiently buoyant to float to the surface and burst releasing the gas contained to the environment. Ultimately, all foamed concretes are destroyed by this process. In mixes where the bubbles are closer together and inter-bubble walls are thinner, i.e. lower densities, this process is easier and the process happens more quickly as shown in Figure 5. As noted in Figure 2, SEM micrographs of low density foamed concrete mixes show the increased presence of 'small' bubbles within the inter-bubble separating walls. It is speculated that these could further aid inter-bubble gas transfer and hence reduce the time at which bubble would become buoyant.

As a result of the increase in bubble diameter, $\boldsymbol{Ø}$, the bubble buoyancy force, $\boldsymbol{F_b}$, increases. Once $\boldsymbol{F_b}$ is high enough to overcome the surrounding $\boldsymbol{F_c}$, the bubbles rise towards the surface of the mix, displacing the surrounding solids and eventually reaching the surface (Fig. 1b) and causes instability (Fig. 1c). This dynamic environment exists until the equilibrium is reached or the mix hardens. When the mix hardens, no more changes to the bubbles can occur. However, once the non-equilibrium state; ($\boldsymbol{F_b > F_c}$) is reached, the process of phase separation is irreversible.

3. Production of Stable Ultra-low Density Foamed Concrete

The discussion above, if correct, shows that the only way to prevent instability is for the mix to 'solidify' prior to bubbles becoming large enough to be buoyant. For denser foamed concretes this is easily achieved within the typical initial set times of Portland cement. However, for ultra-low density foamed concrete this is not fast enough. The authors have experimented in the laboratory with a range of high early strength PCs, increased mix temperatures and accelerating admixtures but none were found to be consistently successful. Thus, further series of laboratory trials were undertaken using a blend of PC with a compatible calcium sulfoaluminate (CSA) cement, the results of which are described below.

3.1 Constituent materials, mix proportions and production of foamed concrete

The following constituent materials were used to produce foamed concrete mixes for testing.

- CEM I 52,5N (Portland cement) conforming to BS EN 197-1.

- Commercially available calcium sulfoaluminate (CSA) cement compatible with Portland cement as an additive to provide rapid setting.
- Fine aggregate, natural siliceous sand conforming to BS EN 12620 Category G_F85.
- Surfactant (commercially available protein-based foaming agent), used in a 6% aqueous solution and foamed to a density of 50±5 kg/m³.
- Methods used for designing, producing and curing foamed concrete were as described by Jones and McCarthy (2005), except that a tolerance of ± 25 kg/m³ of the target plastic density was used rather than the more typical ± 50 kg/m³, as the latter could represent 25 to 50% of the target plastic density.

3.2 Test methodologies

Setting time

The initial setting time of the paste fraction was measured with an automatic Vicat apparatus in accordance with BS EN 196-3:2005+A1:2008 using a *w/c* ratio of 0.5.

Stability

Stability was measured by pouring fresh foamed concrete mixes into 500 mm deep and 75 mm diameter polycarbonate cylinders (see Fig. 1-a) lined with polythene film. The mix was further observed over 24 hours for any reduction in height, to measure any longer-term instability.

Bubble size analysis

Bubble size analysis was carried out using optical microscopy and automated image analysis software. Test samples were obtained from 500 mm high cylindrical specimens after 28 days of sealed curing. The cylinders were split longitudinally, and then sections from the top, middle and bottom (in the direction of cast) of the cylinder were taken and the average of these used to give mean bubble diameters. Broken surfaces were cleared from dust and sprayed with fluorescent paint to improve image contrast under UV illumination. A microscope-mounted digital camera was used to capture a 100 mm^2 image (with resolution of ≈ 2000 x 2000 pixels) and 2D image analysis was carried out by using Image J software, using a similar approach described in (Visagie and Kearsley, 1999; Nambiar and Ramamurthy, 2007).

4. Results and Discussions

4.1 Stability

For mixes with plastic densities from 1000 down to 400 kg/m³, 100% PC consistently produced stable foamed concretes. Then, on a trial and error basis, lower density mixes were made stable by incorporating CSA cement to partially replace PC. Firstly, 5% of PC (by mass of cement) was replaced with CSA, producing stable 300 and 200 kg/m³ foamed concrete mixes. The CSA content was increased to 10% (by mass of PC) to produce stable 150 kg/m³ density mixes consistently, as summarised in Table 1. Table 2 shows the relationship between collapse and base mix setting times.

It was not possible to produce mixes with plastic densities below 150 kg/m³, as the CSA content had to be increased above 10%. This caused the base mix to set within 2 minutes and there was insufficient time to incorporate foam and place the foamed concrete. However, with the use of CSA set controllers producing stable foamed concrete below 150 kg/m³ could be possible.

4.2 Bubble size analysis

Figure 6 summarises the bubble size analysis carried out by 2D image analysis in relation to stability. As expected, bubbles increased in diameter at ultra-low density foamed concretes. The average bubble diameter increased 2.6 times from the highest to lowest density. The 150 kg/m³ density samples did not split cleanly and fractured into multiple pieces, thus, it was not possible to carry out an analysis on these samples.

Figure 6 also gives the calculated bubble to solid area ratio obtained from the 2D image analysis. As the plastic density decreases the ratio increases due to the increased air content and at 300 kg/m³ density, where stability issues commence with utilisation of 100% PC, the bubble to solid area is around 1. As discussed above, the buoyancy forces of the bubble, $\boldsymbol{F}_{\mathbf{b}}$ will tend to be similar to the 'confinement' force, $\boldsymbol{F}_{\mathbf{c}}$ and shows that such mixes will be on the borderline between being stable or going unstable with typical PC set times.

5. Conclusions

By considering the internal forces likely to be affecting the bubbles and surrounding paste/mortar fractions of foamed concrete, it is possible to present a coherent reasoning and mechanism to explain instability in fresh foamed concrete mixes. The underlying cause of instability is the buoyancy force of bubbles, allowing them to float out of a fresh mix, and ultimately causing complete separation of the gas and solid phases. The buoyancy force is directly related to bubble size and this gets significantly larger at lower densities and are consequently much more buoyant and hence the mixes more prone to instability.

This is explained by the observations and as the air content fraction is increased in lower density mixes, the 'confinement' force due to the solids is reduced. In addition, larger bubbles and a smaller solids fraction results in bubbles being closer and the separating walls to be thinner. Established theory predicts that this makes it easier for gas to diffuse from smaller (high internal pressure) to larger (low internal pressure) bubbles. Hence with time bubbles become more buoyant. At a critical time, related to the bubble buoyancy, separation of solid and gas phases occur, ie instability, and fresh mix collapses. Following extensive laboratory trials, the only method of overcoming this was found to be the blending of rapid setting CSA cement with the PC.

The practical issues of placing ultra-low density foamed concretes that have base mixes produced with a cement with an initial setting time of 20-25 minutes are problematic and further research is needed to develop methods to retard the initial setting times for transportation and mixing then activate it immediately when rapid hardening is needed after placement.

Acknowledgements

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References

Aldridge, D. (2005) 'Introduction to foamed concrete: What, why, how?' in *Use of foamed concrete in construction* (Dhir, R.K., Newlands, M.D. and McCarthy, A. (eds)). Proceedings of the National Conference at University of Dundee. Thomas Telford, Dundee, UK, 2005, pp. 1-14.

Basiurski J (2000) 'Foamed concrete for void filling, insulation and construction' in *One day awareness seminar foamed concrete: properties, applications and potential*. University of Dundee, Scotland, pp. 42-52.

BS EN 12620:2013. Aggregates for concrete. BSI, London, UK.

BS EN 196-3:2005+A1:2008. Methods of testing cement. Determination of setting times and soundness. BSI, London, UK.

BS EN 197-1:2011. Cement. Part 1: Composition, specifications and conformity criteria for common cements. BSI, London, UK.

Jones, M.R. and McCarthy, A. (2005) 'Utilising unprocessed low-lime coal fly ash in foamed concrete". *Journal of Fuel*. No. 84, pp. 1398-1409.

Jones, M R and McCarthy, A. (2006) 'Heat of hydration in foamed concrete: effect of mix constituents and plastic density'. *Cement and Concrete Research*, Vol. 36(July), pp. 1032-1041.

Jones, M. R. and Zheng, L. (2013) 'Energy absorption of foamed concrete from low–velocity impacts'. *Magazine of Concrete Research*, Vol. 65(4), pp. 209-219.

Myers, D. (1992). 'Surfactant Science and Technology'. 2nd Edition, VCH Publishers, Inc, USA.

Nambiar, E.K.K. and Ramamurthy K. (2007) 'Air-void characterisation of foam concrete'. *Cement and Concrete Composites*, Vol. 37, pp. 221-230.

Prins, A. (2006). 'Surface forces' role in the foaming behaviour of liquids' in *Encyclopedia of colloid and surface science* (Somasundaran, P. (ed)), Vol. 8, 2nd edition'. Taylor&Francis Group, Oxford, UK, pp. 5926-5937.

She, W., Yunsheng, Z. and Jones, M.R. (2014) 'Using the ultrasonic wave transmission method to study the setting behaviour of foamed concrete'. *Construction and Building Materials*, Vol.51, pp. 62-74.

Stevenson, P. (2011) 'Foam engineering: fundamentals and applications'. 2nd edition, Chapter 5. Wiley, USA, 2011, pp. 75-89.

Visagie M. and Kearsley, E.P. (1999) 'Micro-properties of foamed concrete' in *Specialist techniques and materials for concrete construction* (Dhir, R.K. and Henderson, N.A (eds)). Proceedings of the International Conference 'Creating with concrete', University of Dundee, Scotland, 8 - 10 September 1999. Thomas Telford, Dundee, UK, pp. 173-184.

Weaire, D. and Hutzler, S. (1999) 'The physics of foams'. Clarendon Press, Oxford, UK.

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Figure 1a

Click here to download Figure: Figure 1(a).tif

Figure 1b

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Figure 1c
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Figure 2a
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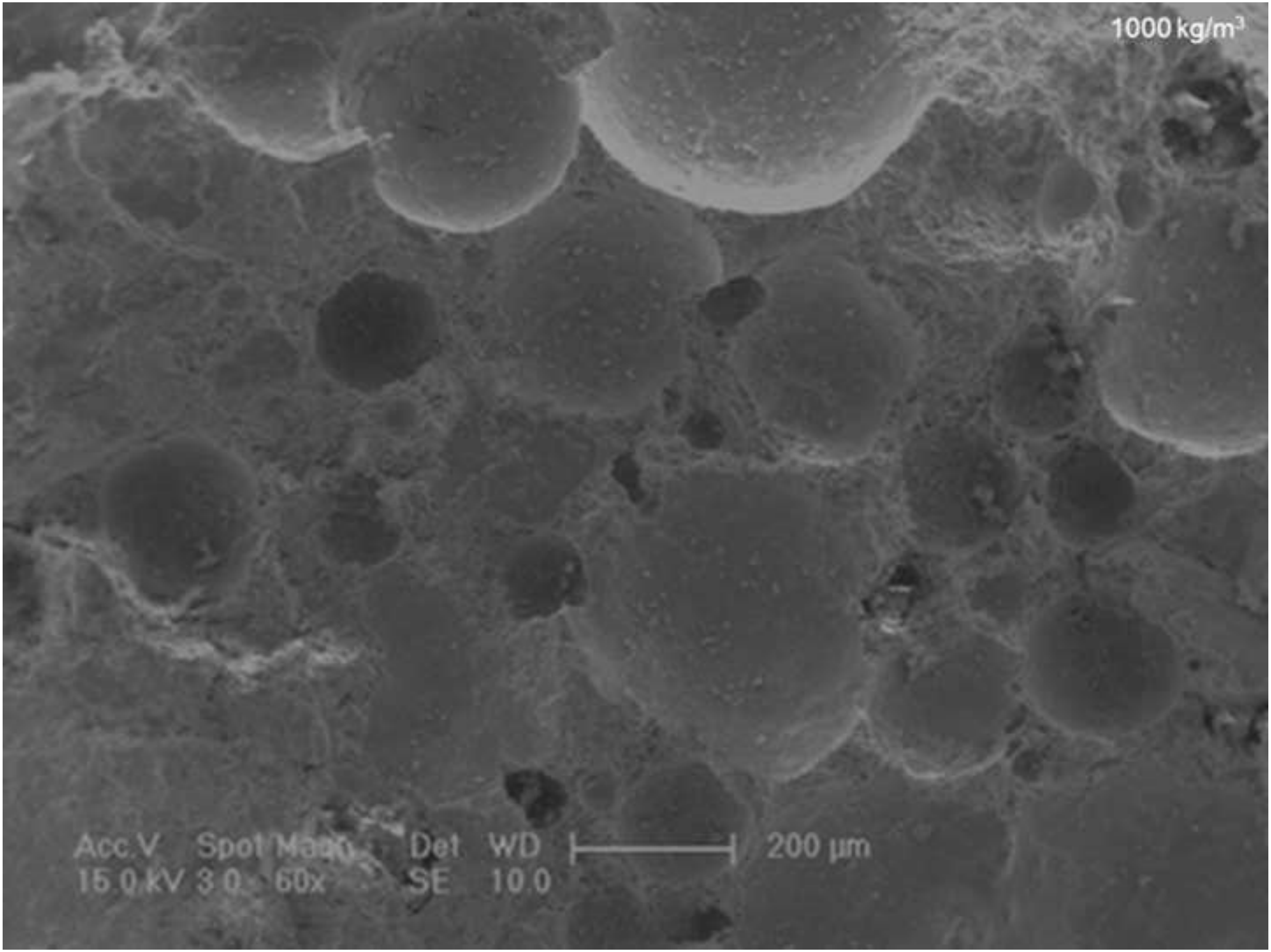

Figure 2b

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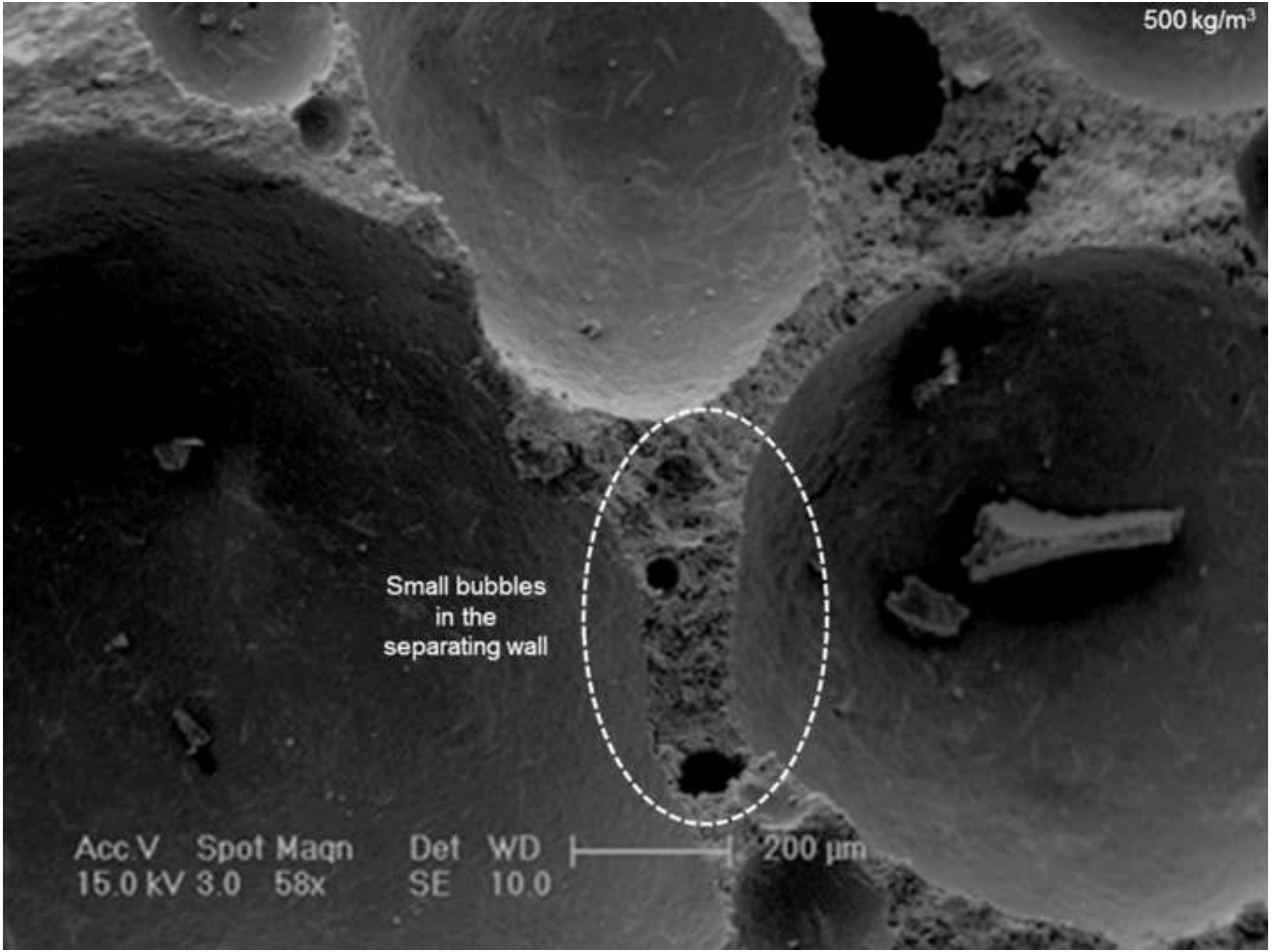
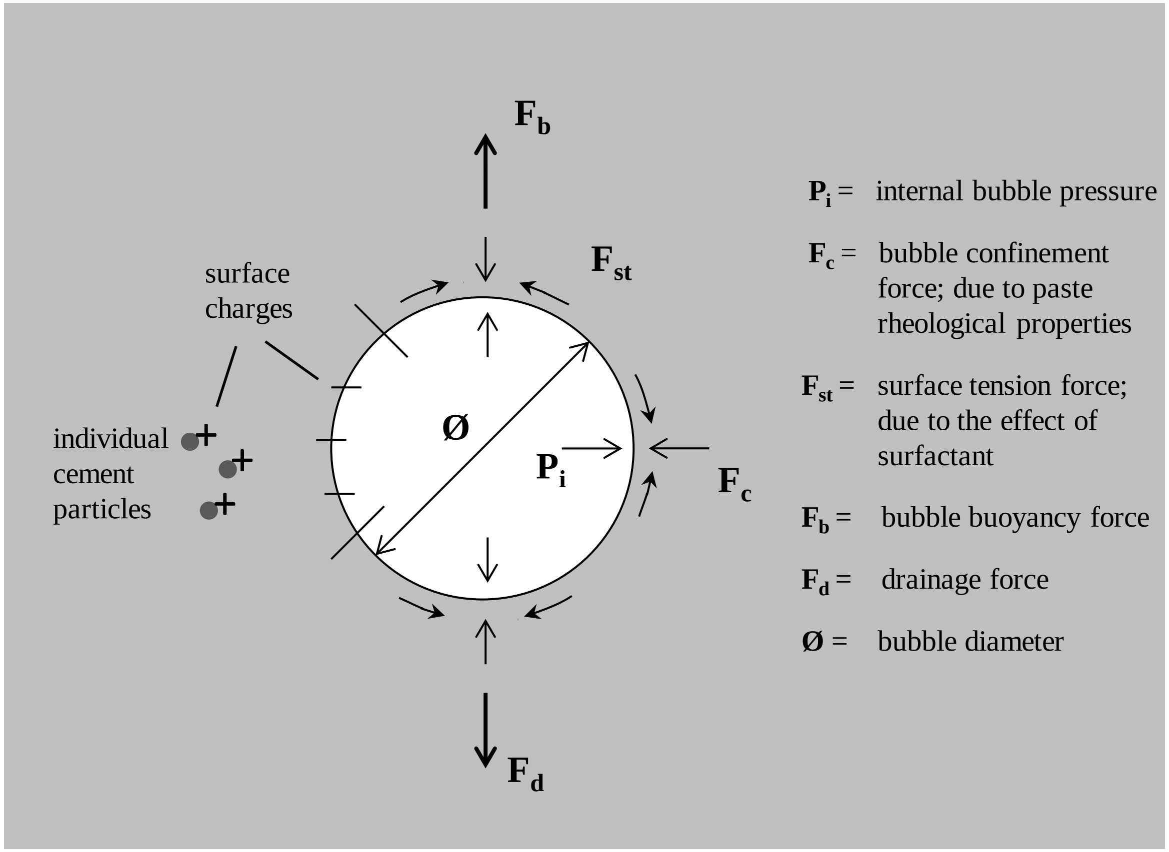
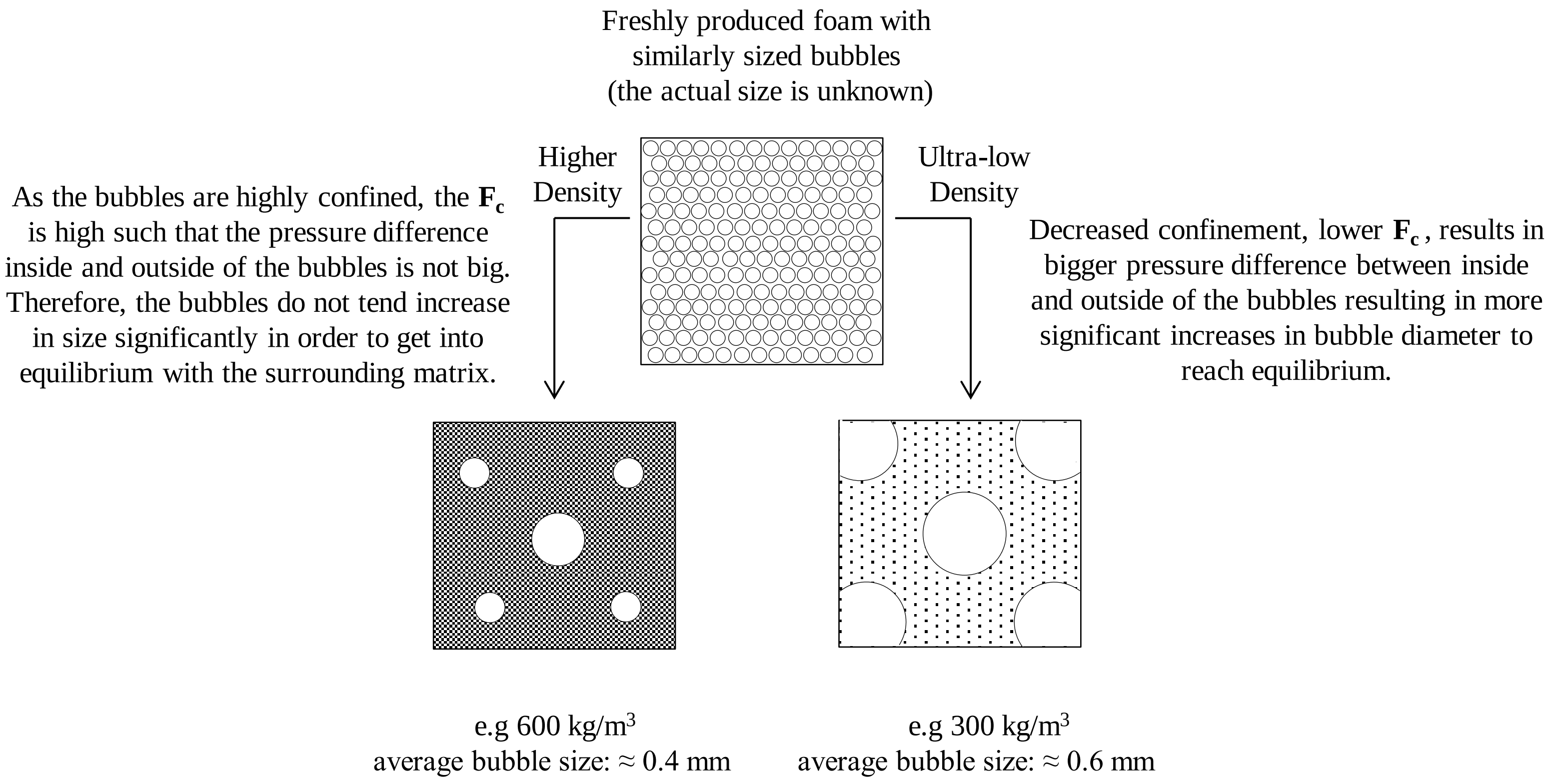


Figure 3



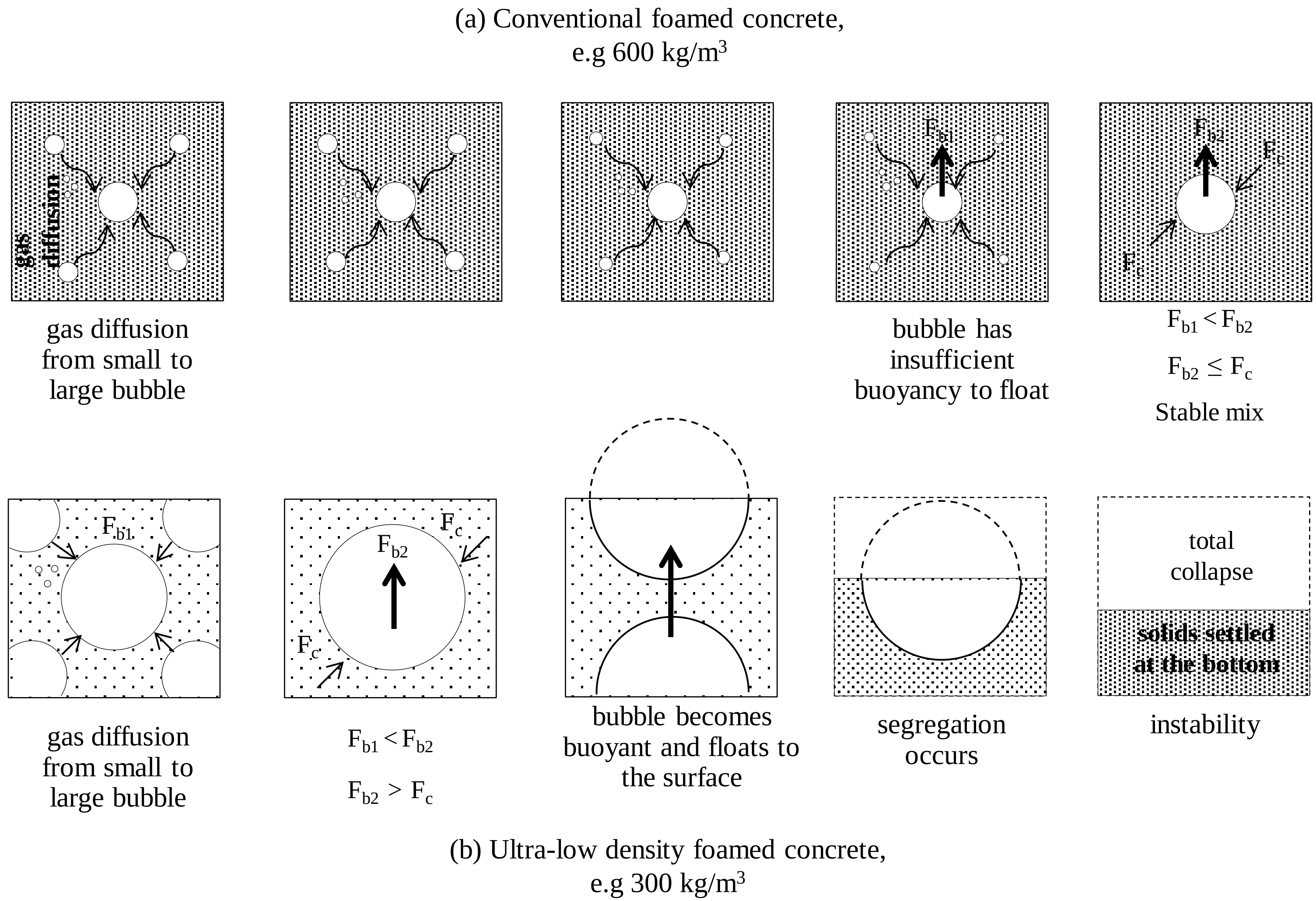
F_b
F_{st}
surface
charges
individual
cement
particles
Ø
P_i
F_c
F_d
P_i = internal bubble pressure
F_c = bubble confinement force; due to paste rheological properties
F_{st} = surface tension force; due to the effect of surfactant
F_b = bubble buoyancy force
F_d = drainage force
Ø = bubble diameter

Figure 4



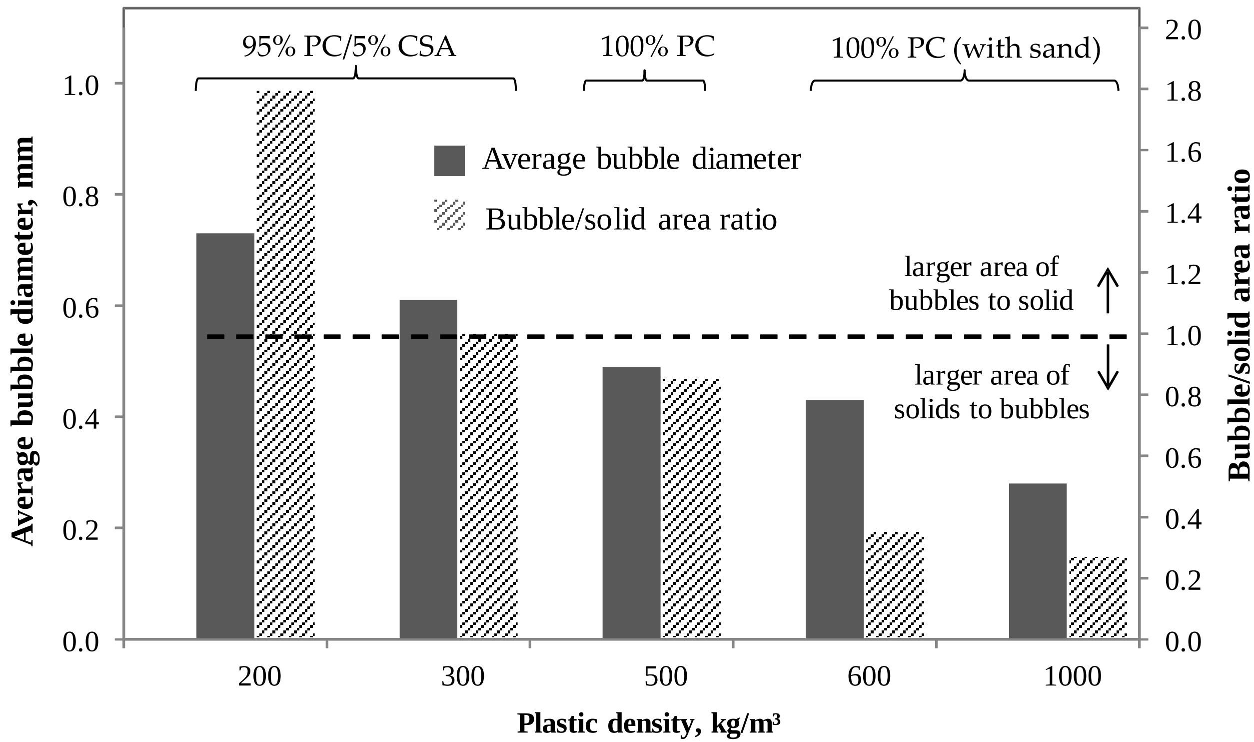
Freshly produced foam with
similarly sized bubbles
(the actual size is unknown)
Higher
Density
Ultra-low
Density
As the bubbles are highly confined, the **F_c** is high such that the pressure difference inside and outside of the bubbles is not big. Therefore, the bubbles do not tend increase in size significantly in order to get into equilibrium with the surrounding matrix.
Decreased confinement, lower **F_c**, results in bigger pressure difference between inside and outside of the bubbles resulting in more significant increases in bubble diameter to reach equilibrium.
e.g 600 kg/m^3
average bubble size: ≈ 0.4 mm
e.g 300 kg/m^3
average bubble size: ≈ 0.6 mm

Figure 5



(a) Conventional foamed concrete,
e.g 600 kg/m³
gas diffusion
gas diffusion from small to large bubble
F b1
bubble has insufficient buoyancy to float
F b2
F c
F c
F b1 < F b2
F b2 ≤ F c
Stable mix
F b1
gas diffusion from small to large bubble
F b2
F c
F c
F b1 < F b2
F b2 > F c
bubble becomes buoyant and floats to the surface
segregation occurs
total collapse
solids settled at the bottom
instability
(b) Ultra-low density foamed concrete,
e.g 300 kg/m³

Figure 6



95% PC/5% CSA
100% PC
100% PC (with sand)
Average bubble diameter
Bubble/solid area ratio
larger area of bubbles to solid
larger area of solids to bubbles
Average bubble diameter, mm
Bubble/solid area ratio
1.0
0.8
0.6
0.4
0.2
0.0
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
200
300
500
600
1000
Plastic density, kg/m³

Table 1. Test mix constituent proportions

Plastic density, kg/m³	Cement content, kg/m³		% of CSA (by mass of cement)	Water[†] content, kg/m³	Sand content, kg/m³	Air volume, %
	PC	CSA				
1000	300	-	-	150	550	55
600	300	-	-	150	150	70
500	335[*]	-	-	165	-	73
400	267	-	-	133	-	78
300	190	10	5	100	-	84
200	126	7	5	66	-	89
150	90	10	10	50	-	92

† w/c ratio of 0.5 was used for all mixes

- Material was not used in the specific mix

* Cement content increased to increase ‘fines’ content as sand was not used below 600 kg/m³

Table 2

Table 2. Collapse and initial setting times

Cement type (% by mass)		**Base mix initial setting time* (hh:mm)**	**Foamed concrete collapse time in the absence of CSA (hh:mm)**			**Stable (✓) / Unstable (x)**			
CEM I	CSA		†D150	D200	D300	D150	D200	D300	>D300
100	-	03:25	01:10	01:40	01:55	x	x	x	✓/x
95	5	01:30	n.m	n.a	n.a	x	✓/x	✓	✓
90	10	00:20	n.a	n.a	n.a	✓	✓	✓	✓

n.a: not applicable; n.m: not measured; * w/c ratio = 0.5; † D: plastic density (kg/m^3)