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Behaviour of PC/CSA/FA Blends in Foamed Concrete

M. Roderick Jones[1], Kezban Ozlutas[1], Anthoula Ouzounidou[1], and Robert F. Rathbone[2]

[1]University of Dundee, Concrete Technology Unit, Division of Civil Engineering; [2] Boral Materials, St Antonio, Tx

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1. INTRODUCTION AND BACKGROUND

Foamed concrete is now a well-established material and its use is widespread internationally for a variety of applications (eg [5] to [16]). Ease of use has been a major driving force for the uptake of the material but more recently the need for more sustainable construction has become a key driver.

In the EU, the Construction Products Regulations, which come into force in July 2013, will require all construction materials to meet seven basic requirements for construction works. These cover:

i. Mechanical resistance and stability
ii. Safety in case of fire
iii. Hygiene, health and environment
iv. Safety and accessibility in use
v. Protection against noise
vi. Energy economy and heat retention
vii. Sustainable use of natural resources.

Of particular relevance is Basic Works Requirements 7: Sustainable use of natural resources, which sets 3 key demands for designers and specifiers, viz:

i. Recyclability of the construction works, their materials and parts after demolition"
ii. Durability of the construction works
iii. Use of environmentally compatible raw and secondary materials in the construction works

Conventionally this means that buildings have to be packed with expanded polystyrene (EPS) foam and/or mineral wools to achieve these requirements. However, EPS is derived from hydrocarbons and there obvious questions over whether this is a sustainable use of a natural resource. In the case of mineral wools, the 'dusty silica' nature of the materials means particular care has to be made to avoid inhalation to the lungs. In addition, in both cases recycling is not easy.

Given this background a research project was undertaken to determine whether a low carbon foamed concrete could be developed that could work with or replace the conventional materials. It has already been shown that foamed concretes did perform well in terms of low thermal transmittance.[4-7] This paper describes the approach taken to measure sound absorbance in ultra-low density foamed concrete and the measures necessary to overcome issues with mix instability.

2. FUNDAMENTAL ISSUES AND THEORIES FOR FOAMED CONCRETE STABILITY

Previous research conducted in the University of Dundee and industrial experiences (Figure 2.1) has shown empirically that decreasing the density of foamed concrete down to ultra-low levels, eg density <300 kg/m³ greatly increases the tendency for mixes to become unstable.

Fig 2.1 Example of instability in the laboratory (left) and in practice (right; courtesy of Propump Engineering Ltd., 2009)

At this time there is not a clear picture as to why instability occurs.[1, 11] Clearly there is a significantly increased amount of foam and decreased solids in ultra-low density foam and intuitively it might be thought that this would be a more, rather than less stable mix, as it would be easy to 'support' the lighter material. However, it has been consistently shown that the opposite is true and industry will not generally supply foamed concrete with a plastic density below 300kg/m^3 and there is a significant risk below 400kg/m^3.

As it is extremely difficult to carry out fundamental scientific analyses with foamed concrete, so the authors have constructed a series of hypotheses that could potentially explain causes and solutions of instability in foamed concrete. These are based on observations of mixes over many years with a wide range of constituent materials, some of which have improved stability and some of which have exacerbated it, as well as discussions with industry. These are discussed as follows.

2.1 Theory 1: Bubble Size Variability With Plastic Density

One of the key observations of the concrete microstructure is that as the density of foamed concrete decreases, bubbles get bigger (eg Fig 2.2). The bubbles are, therefore, being 'stretched' (assuming that the surface tension force due to the surfactant is constant). At a critical size the bubbles will begin to burst and/or combine with an adjacent bubble, causing it to burst and so on, leading to a total loss of air and collapse of the mix. Although density is the main governing factor of bubble size, the nature of the solid phases also has an important influence on surface tension and hence bubble size.

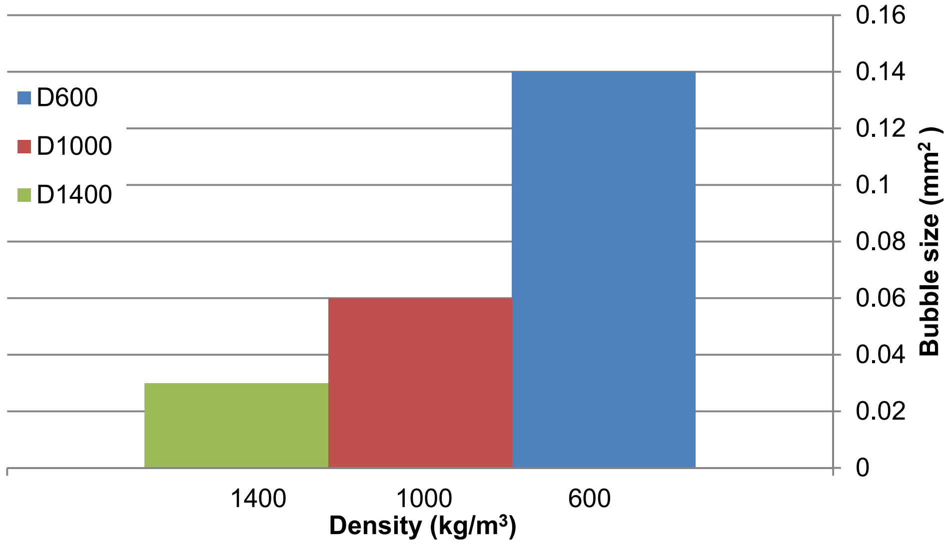


Fig 2.2 Increase in the bubble size as density of foamed concrete decreases.

Fig 2.3 represents how the bubble size changes with utilization of fly ash given its higher fineness. The effect of increased fineness on decreasing bubble size will be explained in ‘Rheological confinement and cement fineness for bubble wall stabilization’ hypothesis.

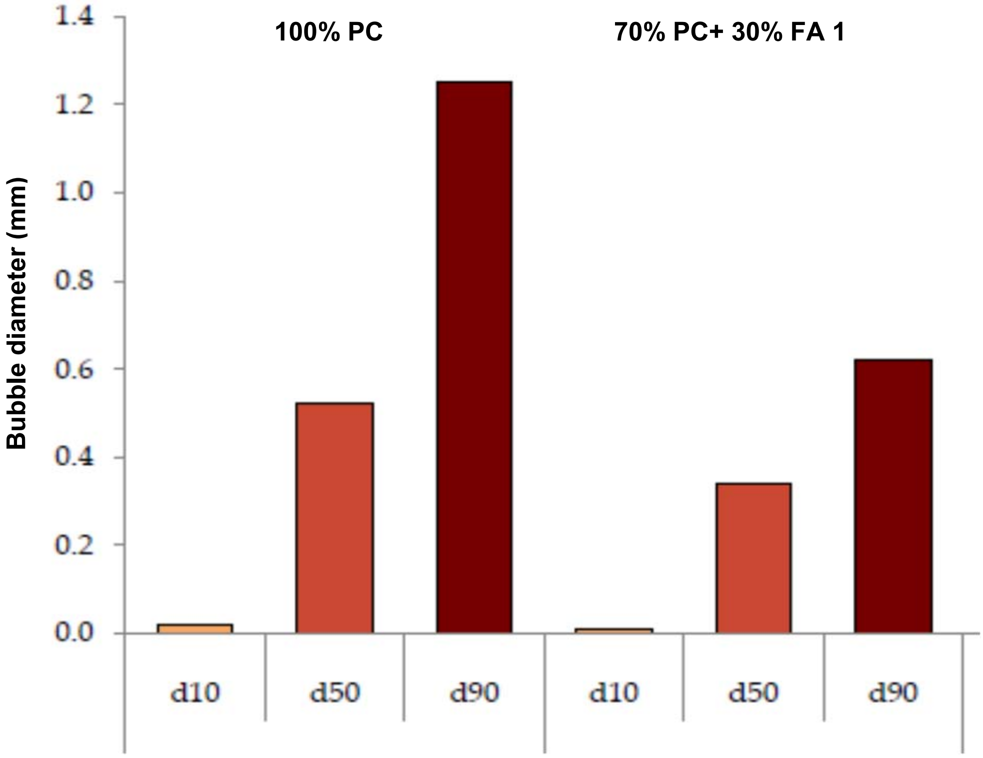


Fig 2.3 Decrease in the average bubble diameter with increased cement fineness by blending with fly ash (example from 600 kg/m³ density foamed concrete).

2.2 Rheological Confinement and Cement Fineness For Bubble Wall Stabilisation

To explain why bubbles change size this hypothesis assumes that for equilibrium there is a balance of forces between the surface tension of the bubble wall, the resulting internal pressure of the bubble and the self-weight of the mix. Thus as the self-weight decreases with lower densities the bubbles expand due to internal pressure until the forces equilibrate, ie there is a specific bubble size for any combination of solid materials and plastic density.

A further extension to this hypothesis concerns the size of the solid particles, ie mainly the cement-size materials. Fig 2.4 demonstrates two cements, one coarser (the PC) and one finer (in this case a CSA but any finer cement would produce the same result). The 'close packing' of the latter results in a more stable wall and potentially a more uniform balance of surface charges and hence stability. Therefore, a need for sufficient amount of cement particles/fillers in the base mix providing enough yield stress against the tendency of the bubbles to expand arises. Cement particles/fillers confine the spaces around the bubbles to form shell-like structures preventing them from growing bigger, hence leading to formation of smaller and stable bubbles.

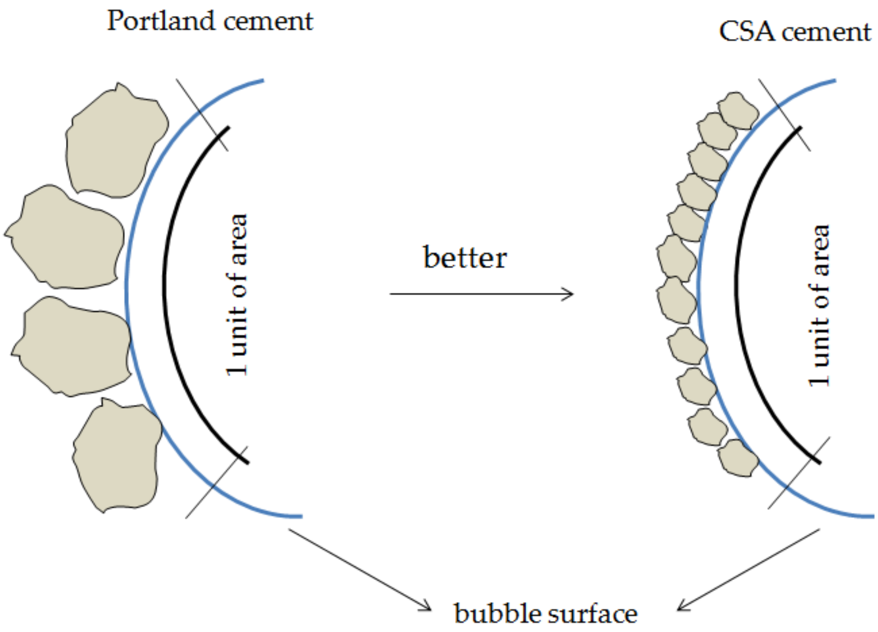


Fig 2.4 Schematics reflecting 'rheological confinement and cement fineness for bubble wall stabilisation' hypothesis. (Not to scale)

Furthermore, finer cement particles present in the mix form more stable, fuller walls around the bubbles reduce the tendency for them to coalesce. This can be a particular issue with the high amount of bubble walls in high foam content, low density mixes since the amount of solid materials pre unit volume is considerably reduced and there are not enough cement/filler particles to fully 'complete' the bubble walls. With finer cements/fillers that have more particles per unit area help to form the bubble walls.

2.3 Surface Charge In Foam Bubbles

When the cement particles are not oppositely charged with the bubbles, then the cement particles cannot be adsorbed to bubble surfaces to form stable shell-like structures around the bubbles. Therefore, cement particles drain downwards leaving the bubbles at the top, hence causing instability. However, it must be noted, it is difficult to know whether the collapse is caused by the repelling surface charges, unless the charges of the constituents are known.

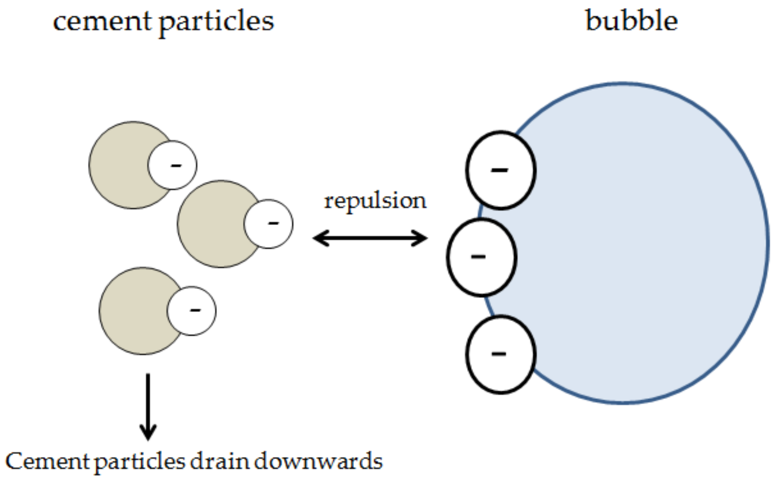


Fig 2.5 Schematics reflecting ‘surface charges’ hypothesis. (Not to scale)

2.4 ‘Liquid’ to Solid Transition Rate

This overarching hypothesis assumes that all foamed concrete are inherently unstable or at least the lowest energy position is where the bubbles have reverted to a aqueous solution, ie given long enough all foamed concrete are able to collapse.

Initially then, the self-weight of foamed concrete is ‘carried by the surface tension in the bubbles and as long as this remains the mix will be stable. However, foams can only retain their surface tension for a specific period after which it reduces, the bubbles consequently get bigger and either burst or combine with adjacent bubbles and burst. This defines the period of stability and the onset of instability in foamed concrete. In lower density mixes this happens more quickly, firstly due to the bigger bubbles and the thinner walls, as discussed above.

However, at some point the initial set of the cement will occur and the liquid foamed concrete becomes a solid. At this point the self-weight is carried by the cement hydrates and not the bubbles. If internal pressure is, therefore, lost the mix does not collapse. Thus, there is a critical point for any mix at which time initial set must occur or the mix will inevitably become unstable.

Fig 2.6 is an attempt to schematically show these phenomena and relationships but more importantly the figure shows that the cement setting time is the only controllable factor to achieve a stable mix.

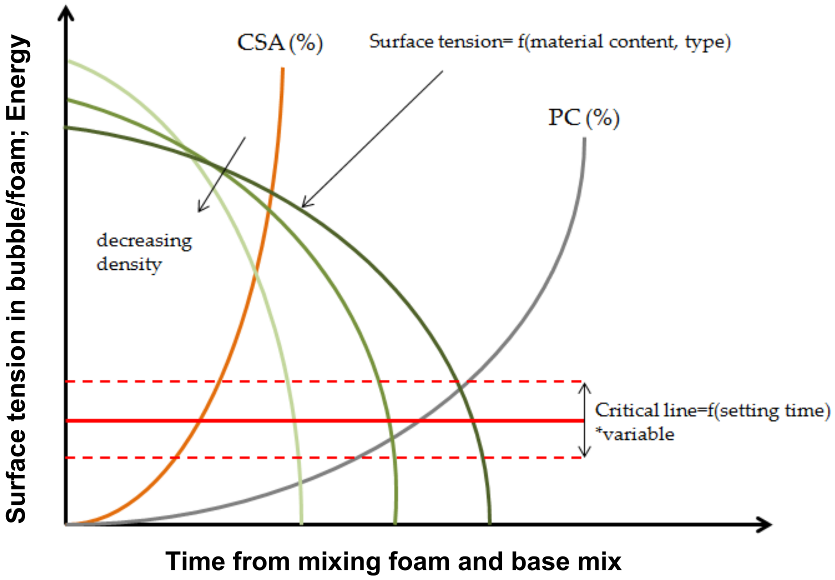


Fig 2.6 Hypothetical graph showing the relationship among instability, surface tension and energy of the bubbles and setting time. (Not to scale)

Fig. 2.6 that, there is a critical line regarding instability that is believed to be variable and function of mainly the setting time, whereas lines labelled as CSA and PC represents initial setting times of cements. As time passes, surface tension of the bubbles decreases because of decreasing energy of the bubbles and breaking bubbles. It is believed that at the point where the surface tension and energy levels meet the critical line before the initial setting time, foamed concrete mixes collapse. If correct the schematic shows that as the density decreases faster set times are necessary and although the x-axis is not show with actual time, empirically the authors have found that ultra-low densities need set times in 10's of minutes and not hours. As a result Portland cement set times are too slow for such mixes, as these are generally 4 to 6 hours.

Thus, a much faster setting cement is required and, hence, the authors' have adopted the use of CSA. The corollary is, however, that CSA's alone would set too quickly if used alone and may to be too complex to batch and handle in practice. Thus the authors have aimed to continue to use PC as the main cement but control setting times using CSA. This has the added advantage of being an established practice and if successful would be an easier technology to transfer to industry than, say using pure CSA and a retarder. The general behaviour and setting times of mixes with composite cements of PC, CSA and fly ash are discussed below.

3. BEHAVIOUR OF CSA/FLY ASH/PC COMPOSITE CEMENT

3.1 Characteristic Analyses of Cements

CSA is not produced in bulk in Western Europe and is normally used as an addition to PC to enhance particular properties, eg early strength, dimensional stability and low temperature placement. For this reason the research data show in this paper used the same methodology was adopted. Three different commercially-sourced CSA's (1 US sourced and 2 & 3 UK sourced) were initial selected and characterised.

It was found that CSA3 was pre-blended with PC and for that reason was dropped from the main test series (data here is given for completeness).

Physical properties

Fig 3.1 and Table 3.1 represent the physical properties of cements used, particle size distribution and specific surface area respectively. Regarding the stability, in order to gain a better understanding on why certain cements yield stable mixes while certain do not, it is vital to compare the fineness of the cements/fillers used.

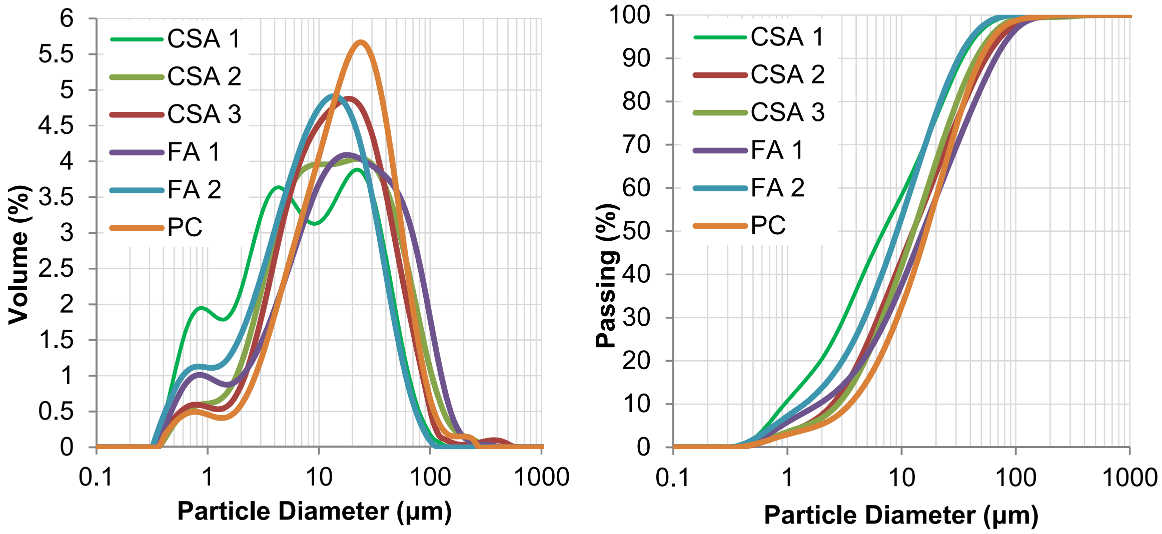


Fig 3.1 Particle size distribution of cements

Table 3.1 Specific surface area

Specific surface area (m^2/kg)	CSA 1	CSA 2	CSA 3	PC	FA 1	FA 2
BET	1790	1226	1160	1130	2260	2590
Laser	450	353	344	286	563	688

Chemical properties

Table 3.2 and 3.3 outline the chemical properties of the cements under consideration.

3.2 Calorimetry of blends

As noted the key to achieving mix stability with ultra-low density foamed concrete is converting the material from a plastic/liquid to a solid before the foam-supported bubbles collapse. The selection of fast-setting cement such as CSA has achieved this requirement and it was, therefore, important to review the underlying reaction processes driving the setting behaviour.

In addition, as noted in the introduction the European Construction Products Regulations also require designs that protect natural resources and, in this research, the aim was to use as much fly ash as possible to displace PC. This is particularly advantageous as fly ash has only 4 kg/tonne of embodied CO_2 compared to 930 kg/tonne in PC. There is no agreed level of embodied CO_2 in CSA cement, as production methods and calcining temperatures vary. However, the general consensus is that CSA cements embodied less energy than PC and values of around 850 kg/tonne are often quoted.

Table 3.2 X-ray fluorescence analysis of cements

Oxide composition (% by mass)	CSA 1	CSA 2	CSA 3	PC	FA 1	FA 2
CaO	45.63	36.89	59.33	62.43	3.37	4.4
Al_2O_3	23.26	47.21	11.35	4.48	20.19	34.3
SO_3	13.98	5.41	6.97	2.51	2.03	-
SiO_2	8.39	4.64	17.26	18.63	43.15	53.5
Fe_2O_3	2.98	1.47	2.56	2.89	9.79	3.6
MgO	0.92	1.10	1.08	0.97	1.24	-
TiO_2	1.04	2.22	0.67	0.42	1.06	-
K_2O	0.46	0.45	0.55	0.63	2.84	-
Na_2O	0.12	0.07	0.27	0.29	1.99	-
P_2O_5	0.12	0.09	0.21	0.21	0.41	-
Cl	0.00	0.00	0.04	0.07	0.00	-
MnO	0.09	0.02	0.04	0.04	0.08	-
Total	96.99	99.56	100.32	93.58	86.15	95.8

Table 3.3 X-ray diffraction analysis of cements

Phase composition (% by mass)	CSA 1	CSA 2	CSA 3	PC
C_4A_3S	34.61	52.87	8.83	-
C_2S	14.61	19.33	17.41	16.6
$CaSO_4$	24.02	-	7.52	-
C_4AF	-	-	3.94	9.1
CA	-	7.64	-	-
C_3A	4.53	6.71	6.46	10.8
$Ca(OH)_2$	-	1 .06	-	-
$CaCO_3$	-	-	-	-
C_2AS	-	17.52	-	-
C_3S	-	-	27.32	54.1
Total	77.77	105.13	71.48	90.6

Figures 3.2 to 3.5 compare the early age reactions in terms of heat produced for the pure PC (Fig 3.2 note: expanded scale y-1 axis) and pure CSA1 and blends of CSA1 and PC up to 30% (Fig 3.3); anhydrite 'activated' CSA1 (Fig 3.4); and blends of CSA1 and fly ash up to 30% (Fig 3.5).

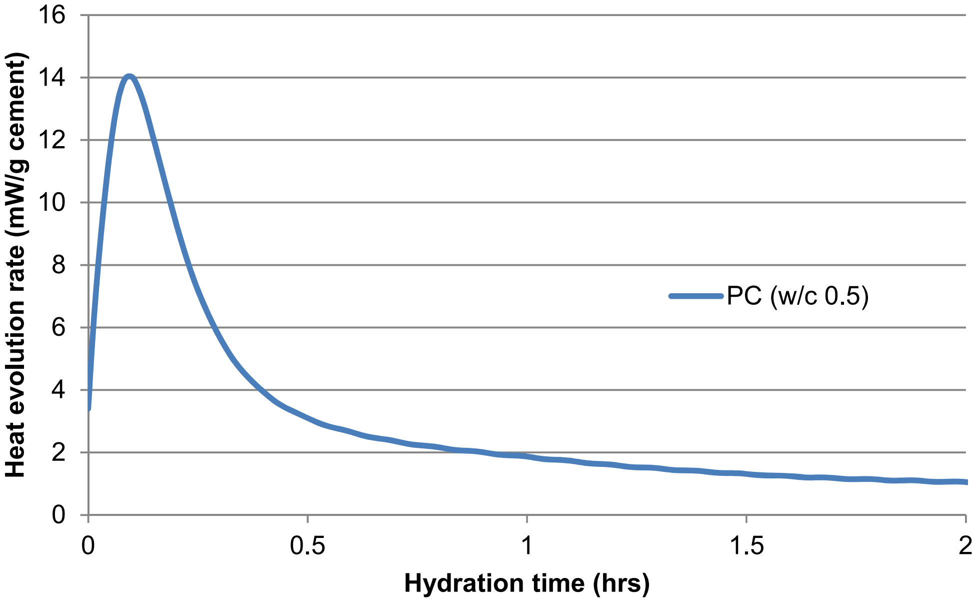


Fig 3.2 Rate of heat evolution of PC.

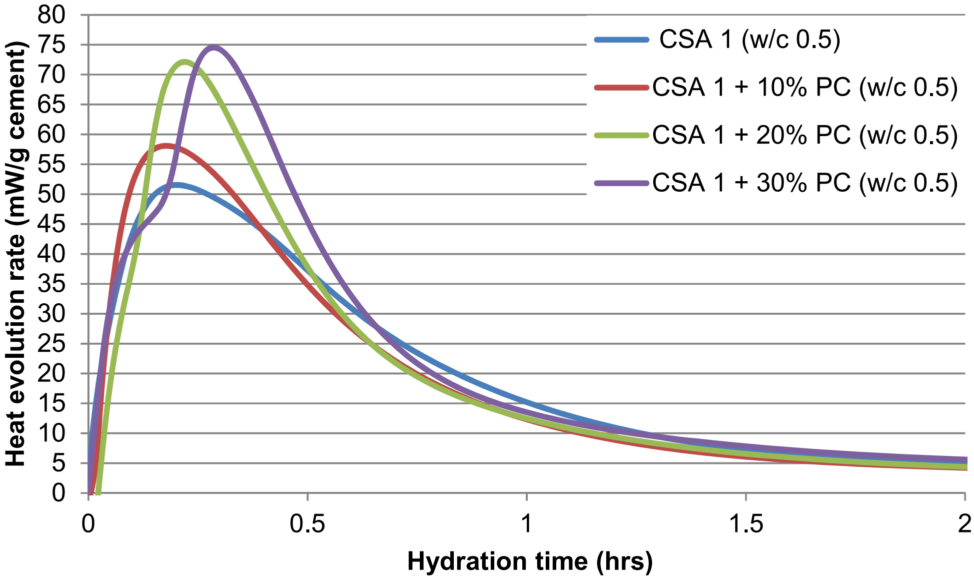


Fig 3.3 Rate of heat evolution of CSA 1 blended with PC.

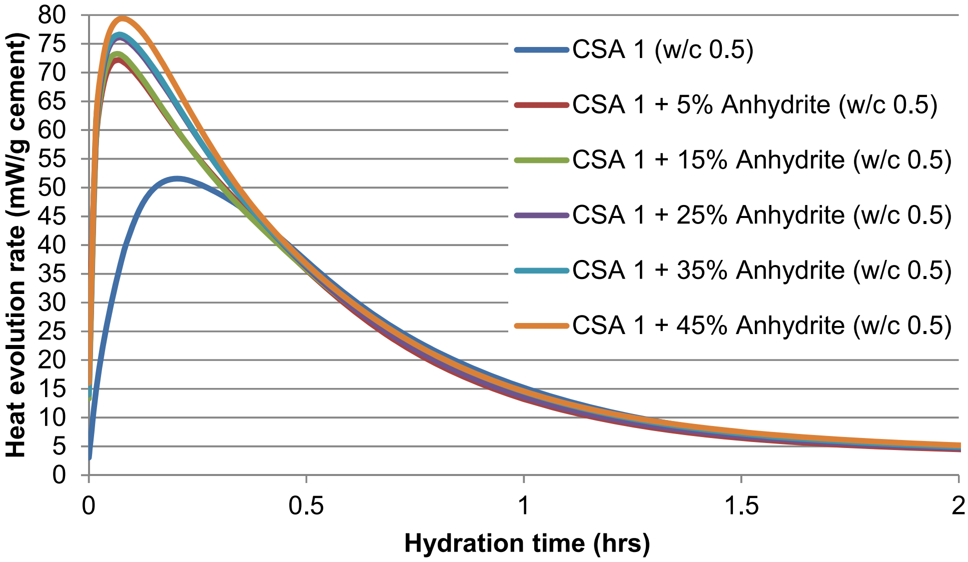


Fig 3.4 Rate of heat evolution of CSA 1 with an anhydrite addition.

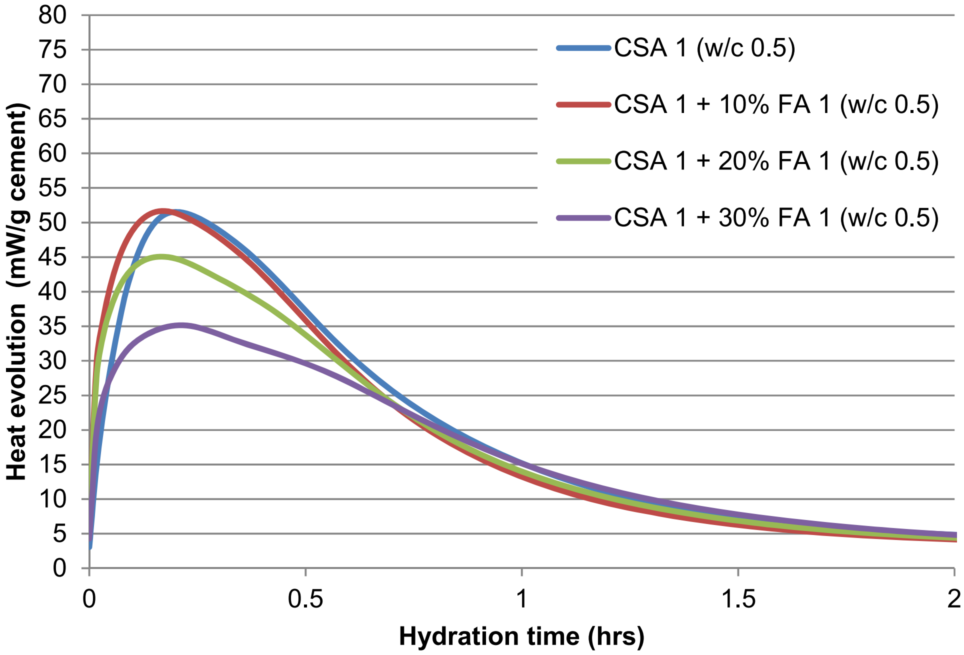


Fig 3.5 Rate of heat evolution of CSA 1/FA 1 combinations.

As described above the need for a rapid early set was intrinsic to producing stable low density foamed concrete and role that CSA can be seen from the calorimetry data. Indeed, since PC’s are generally designed to have as long as initial set as possible, to enable transport and handling on site, it is not possible to achieve low density (ie <300kg/m^3) without a faster setting cement. In addition to blending with PC, tests were carried out ‘activating the CSA with anhydrite, which produced an even faster set. However, this caused a problem of ‘flash set’ in the base mix and was, therefore, not tested further. As a result, fly ash was blended with the CSA, which had the desired balance of preventing flash set, reducing the heat evolution rate as well as the usual benefits of adding fly ash to mixes.

3.3 Setting Times

As mentioned earlier, setting time is believed to be one of the most important parameter governing stability of foamed concrete. Table 3.4 reflects the initial setting times of the cement blends used that yielded stable mixes.

As it can be seen from the table, the lowest applicable plastic density is 150 kg/m³ that can only be achieved when the initial setting time of the paste is 20 minutes. When it comes to utilize fly ash in150 kg/m³ mixes, it appeared that at same fly ash levels with same setting times, the mix with FA1 collapsed while it was stable with FA2. At this point, cement/filler fineness is believed to take the action for achieving stability.

Table 3.4 also shows that above 50% fly ash, setting times starts to increase while below 50% setting times are in the range of 20-25 minutes. This increase is possibly caused by the lack of PC in the mix that there is no enough alkaline environment formed for fly ash to react. Furthermore, although it is believed that setting time is mainly governed by CSA, effect of PC on setting time cannot be disregarded. Therefore, around and below 50% can be taken as an optimum fly ash level, although further analysis regarding the effect on the properties of foamed concrete should be carried out.

Table 3.4 Setting times of CSA 2/FA/PC blends

Blend	Cement type (% mass)				Initial setting time (hh:mm)	Plastic density (kg/m³)†
	FA 1	FA 2	PC	CSA 2		
B1	-	-	100	-	05:00	400
B2	-	-	95	5	01:30	200
B3	30	-	65	5	00:50	300
B4	-	-	90	10	00:20	150
B5	30	-	60	10	00:25	200
B6	-	30	60	10	00:25	200
B7	-	40	50	10	00:20	150
B8	40	-	50	10	00:20	200
B9	-	50	40	10	00:25	200
B10	-	60	30	10	00:40	200
B11	-	70	20	10	00:45	200
B12	-	90	-	10	00:35	200

† Minimum applicable plastic density of foamed concrete for a given blend.

Note. Only the initial setting times of pastes were measured without adding any foam.

4. CHARACTERISTICS OF CSA/FA/PC FOAMED CONCRETE

4.1 Mix Design

Mix proportions used to produce foamed concrete are given in Table 4.1. As noted, in the table, 300 kg/m³ and densities below need to be produced utilizing CSA cement in order to yield stable mixes.

Table 4.1 Mix proportions (w/c 0.5)

Plastic density (kg/m³)	Cement	Cement (kg)	Water (kg)	Foam (kg)	Aggregates (kg)
1000	PC	300	151.5*	23	550
600	PC	300	151.5*	30	150
500	PC	333	166.5	31	n.a.
300	PC-CSA	200	100	35	n.a.
250	PC-CSA	167	83.5	36	n.a.
200	PC-CSA	133	66.5	37	n.a.
150	PC-CSA	100	50	37	n.a.

*Water content is increased by 1% by weight of sand considering the water absorption of sand.
n.a. not applicable.

4.2 Stability

Importance of setting time and cement/filler fineness on stability of foamed concrete was noted earlier as a conclusion of proposed hypotheses. Regarding the effect of setting time on stability, it can be derived from Table 3.4 that, optimum of 20-25 minutes initial setting time yields stable mixes in most cases.

For certain blends, it appeared that, regardless of the 20-25 minutes setting time range, instability occurred at low densities. At this point, looking at the constituent materials and their proportions, it can be seen, even if the same proportions were used, replacing one type of cement/filler with a coarser one failed the mix to be stable.

According to the data given in Table 3.1 and Fig 3.1, FA 2 is finer compared to FA 1. Although they have same setting times when used at same percentages, in some cases FA 2 yielded stable mixes at lower densities proving cement fineness and bubble wall stabilization hypotheses. Therefore, it can be concluded that stability is mainly governed by a combined effect of setting time and fineness.

4.3 Flow Behaviour

Foamed concrete is known to have high flowability. Its flow behaviour is checked against its flow time[2]. Regarding the density range of 200 to 1000 kg/m³, flowability decreases as density decreases. This behaviour is mainly due to the self-weight effect. More air is introduced in the mix as density decreases, hence mass of the mix decreases. As a result, when it comes to a certain point, self-weight effect considerably overcomes gravity leaving a mix that would hardly flow.

As it is shown in Fig 4.1 and 4.2, there is a considerable decrease in flowability of foamed concrete while shifting from 300 to 200 kg/m³ compared to other densities. Considering the self-weight effect, it is shown that the difference between m_{foam}/m_{mix} ratio (mass of foam to mass of mix ratio) is the biggest between 300 to 200 kg/m³ density causing a big drop in flowability (see Fig 4.3).

Fig 4.1 Comparison of flowability in foamed concrete regarding the self-weight effect (left hand image is 200 kg/m^3, right hand image 300 kg/m^3; both at 0.5 w/c ratio).

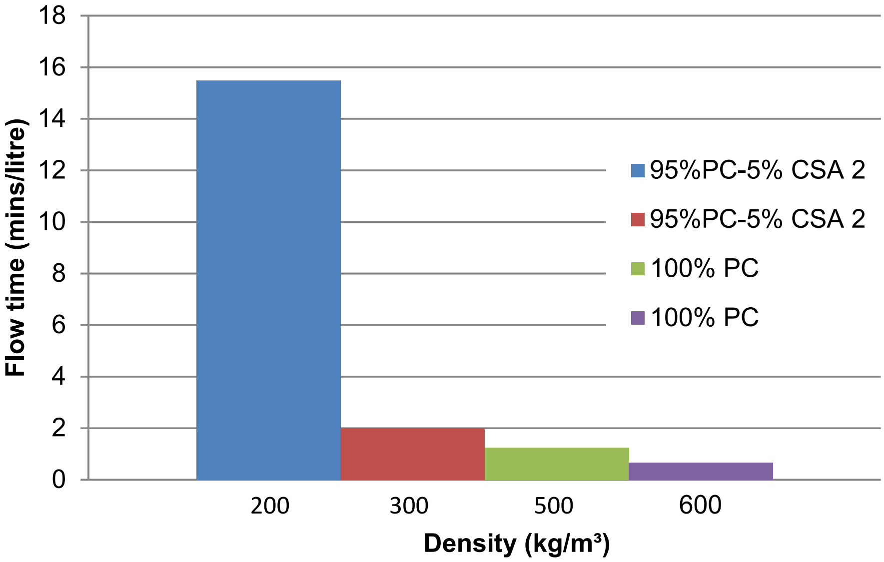


Fig 4.2 Change in the flow behaviour of foamed concrete as density increases.

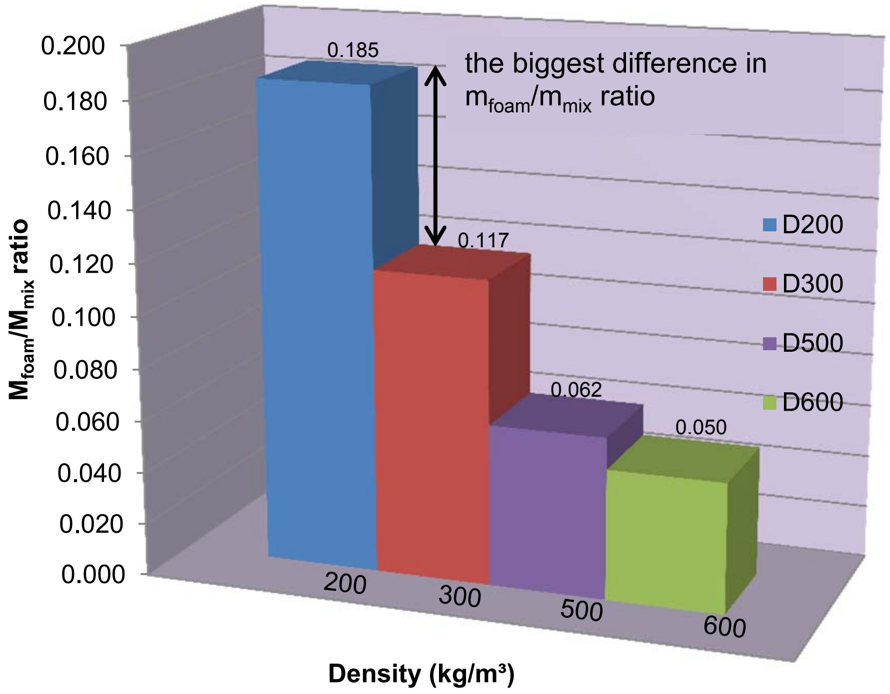


Fig 4.3 Change in the m_{foam}/m_{mix} ratio of foamed concrete as density increases.

In case of utilizing fly ash in foamed concrete, fly ash cenospheres may improve the flowability because of their smooth, rounded structure, particles rolling over each other and making the flow easier. On the other hand, when fly ash content reaches to a certain point fly ash starts to have an adverse effect on flowability. This is because fly ash has large surface area that would lead to higher water absorption leaving a stickier, less flowable mix.

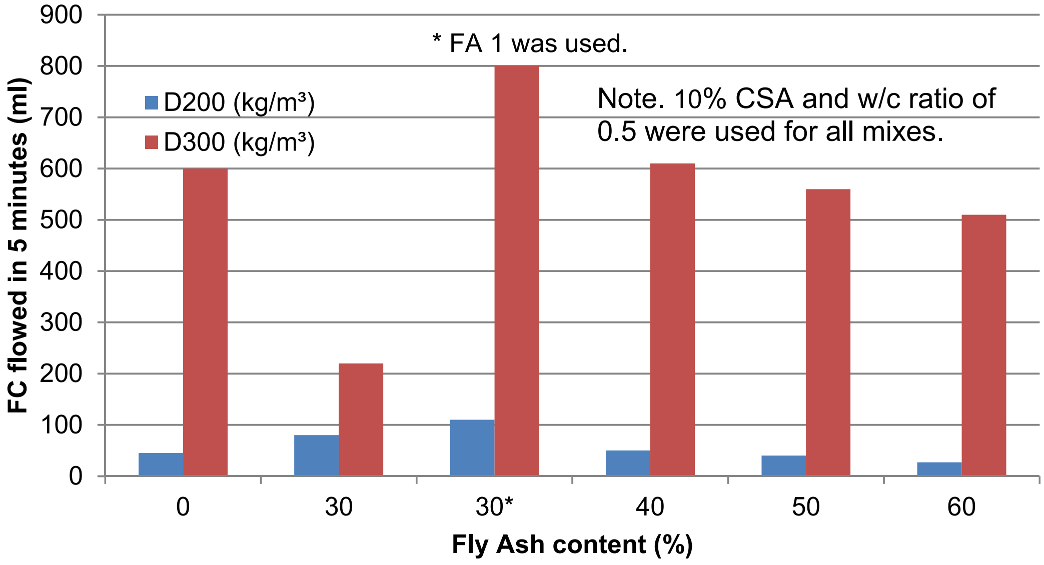


Fig 4.4 Flow behaviour of ultra-low density CSA 2/FA 2/PC foamed concrete.

Considering 200 kg/m^3 density, utilizing 30% FA 2 increased flowability of foamed concrete, while further increase in flowability was observed when 30% FA 1 was used instead. This can be explained by smaller surface area of FA 1 compared to FA 2. As it can be seen from Fig 4.4, increasing the fly ash content from 30% to 40, 50 and 60% respectively decreased flowability due to the increased fineness.

Same trend was also observed with 300 kg/m^3 density foamed concrete except from a decrease in flowability when 30% FA 2 was utilized. Although the test was repeated, same results were obtained. Therefore, further investigations are needed to clarify this exceptional behaviour by widening the density range of foamed concrete under consideration.

4.4 Thermal Insulation Properties

Given its cellular structure, foamed concrete has good thermal insulation properties with proven applications as a thermally insulating material. Indicative thermal conductivity of foamed concrete was measured by using the modified hot box method.[6, 7]

Results showed that utilizing fly ash improves thermal insulation properties of foamed concrete up to a certain point. Compared to the 200 kg/m^3 control mix, blend B2, foamed concrete produced with blend B6, showed an improved thermal insulation. Comparing 300 kg/m^3 density foamed concrete produced with blend B3 and B6 that have 30% of fly ash of type 1 and 2 respectively, to the blend B2 with no fly ash, mixes with fly ash exhibited lower thermal conductivity (see Table 4.2).

Table 4.2 Indicative thermal conductivity

Material density (kg/m^3)	Indicative thermal conductivity, λ_{ind} (W/mK)
Styrofoam-40	0.063
FC-200 (95% PC/5% CSA2)	0.078
FC-200 (60% PC/10% CSA2/30% FA2)	0.073
FC-300 (95% PC/5% CSA2)	0.100
FC-300 (65% PC/5% CSA2/30% FA1)	0.096
FC-300 (60% PC/10% CSA2/30% FA2)	0.093
FC-300 (20% PC/10% CSA2/70% FA2)	0.111
FC-500	0.130
FC-600	0.177
FC-1000 (McCarthy, 2004)	0.230
FC-1200 (McCarthy, 2004)	0.420

Note 1. w/c ratio = 0.5 for all mixes.

Note 2. 100% PC for all foamed concrete mixes, unless otherwise noted.

These improvements are considered to be caused by the increased fineness of the cements through the utilization of fly ash and higher percentages of CSA cement. This can be confirmed by comparing the mixes with FA 1 and FA 2, where FA 2 mix showed lower conductivity given its higher fineness.

Fly ash, as a fine material, is known to improve the microstructure of foamed concrete resulting in denser structure. On the other hand, it is know that thermal conductivity increases with increased density of a material. Although fly ash produces foamed concrete with denser microstructure, there are reasons why fly ash improves thermal insulation performance.

The main reason is the low particle density of fly ash, in addition to its low thermal conductivity, given the air-filled nature of cenosphere cores. Moreover, it is believed that larger surface area of fly ash would increase the heat flow paths and increased interface area would act as a thermal barrier decreasing the amount of heat transfer.[20]

Unreacted fly ash cenospheres may change the path of heat flow making the path longer instead of letting the heat directly flow through the walls. Therefore, heat travels inside the material for a longer period of time, decreasing conductivity (see Fig 4.5).

On the other hand, it was shown that at 300 kg/m^3 when high fly ash content was used (70% fly ash, blend B11), thermal conductivity increased. This can be due to the very high porosity of the walls that would let the heat to flow through the material more easily. It can be seen in the microstructure images of 70% FA2 samples that, there is almost no hydration products visible which could be due the lack enough PC. Instead, walls of the bubbles seem to be made up of fly ash cenospheres with high porosity (see Fig 4.18).

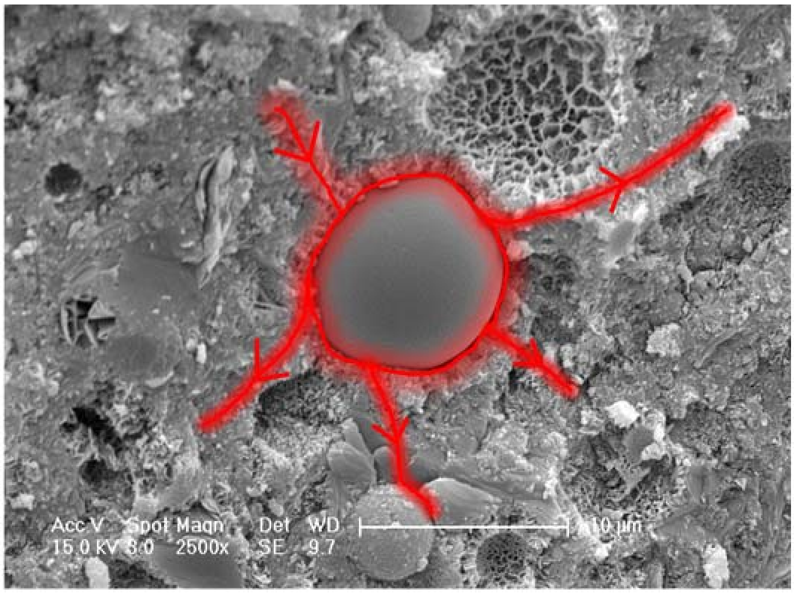


Fig 4.5 Unreacted fly ash cenospheres that possibly change the direction of heat flow paths.

As only 200 and 300 kg/m³ density samples with certain percentages of fly ash were tested, effect of fly ash at lower densities as well as the effect of wider range of fly ash contents are not known leaving a need for further research.

4.5 Sound Insulation Properties

Sound insulation capacity of foamed concrete was assessed in terms of sound absorption coefficient (α) in accordance with[4] using a standing wave apparatus. Low density foamed concrete was found to have higher sound absorption capacity compared to high densities (Fig 4.6).

This behaviour can be explained by the increased porosity of the material as density decreases, hence the increased surface area that would be exposed to interact with sound waves, converting sound into heat energy by friction. However, it should be noted, if the porosity is too high sound waves can pass through the material.[17]

Given the effect of increased surface area on sound absorption properties, utilization of fly ash was expected to improve the sound insulation. Fig 4.7 shows the improvement on the sound insulation of foamed concrete when fly ash is used. It can be explained by the effect of fly ash on improving the microstructure of low density foamed concrete decreasing very high porosity that would let sound waves to pass through easily. Additionally, increased surface area in the microstructure of foamed concrete caused by unreacted fly ash cenospheres may increase friction. See Fig 4.9 and 4.10 for increased surface area.

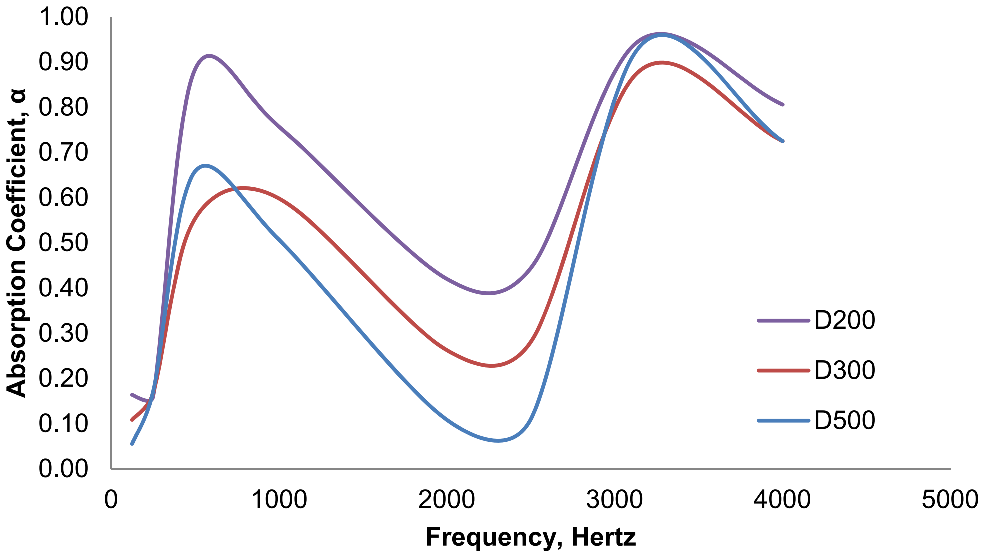


Fig 4.6 Sound absorption coefficient: Comparison of foamed concrete with densities 200(B2), 300(B2) and 500(B1) kg/m³ (70mm).

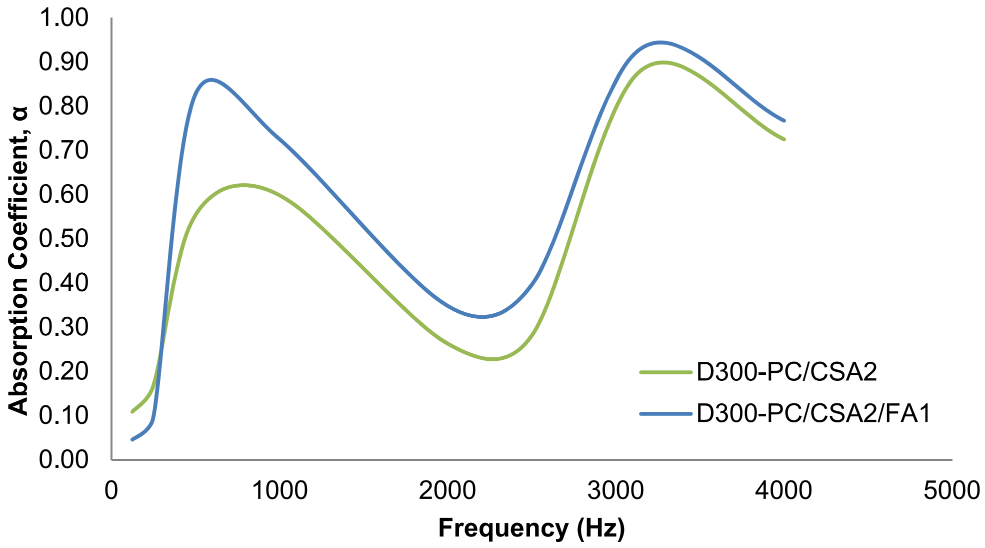


Fig 4.7 Sound absorption coefficient: Effect of fly ash on; comparison of 300 kg/m³ density blends B2 and B3 (70mm).

4.6 Embodied Carbon Dioxide (eCO_2)

Given its nature, foamed concrete is a sustainable building material. Its high air content and small amount of constituents, specifically at low densities, contribute to its sustainability. Additionally, production of foamed concrete utilizing by-products, waste materials and secondary aggregates as well as the chances to re-use foamed concrete make it a greener material.[15]

Fig 4.8 shows the calculated eCO_2 content (using the UK agreed data) of foamed concrete with varying density and constituents. ECO_2 arising from the transportation of materials was not included in the calculations and eCO_2 figures in [18, 19] were used for the calculations as well as the mix proportions in Table 4. As density of conventional foamed concrete of densities around 600-1000 kg/m³, decreases down to ultra-low densities, considerable decrease in eCO_2 contents occur naturally. For instance, decrease in the eCO_2 of conventional foamed concrete to 300 and 200 kg/m³ foamed concrete are 34 and 57% respectively.

Additional reductions in eCO2 content of foamed concrete can be managed through the replacement of PC with CSA cement and fly ash. For a given density of foamed concrete, use of fly ash reduces the eCO2 of a mix at a rate it is utilized. On the other hand, cutting out the PC totally, replacing it with 70% CSA and 30% fly ash shows a considerable reduction in eCO2 as well as producing high early strength foamed concrete.

However, it should be noted that, because of the unpractical fast setting times of high CSA foamed concrete, combination of some chemicals were used to retard the setting of the mix.

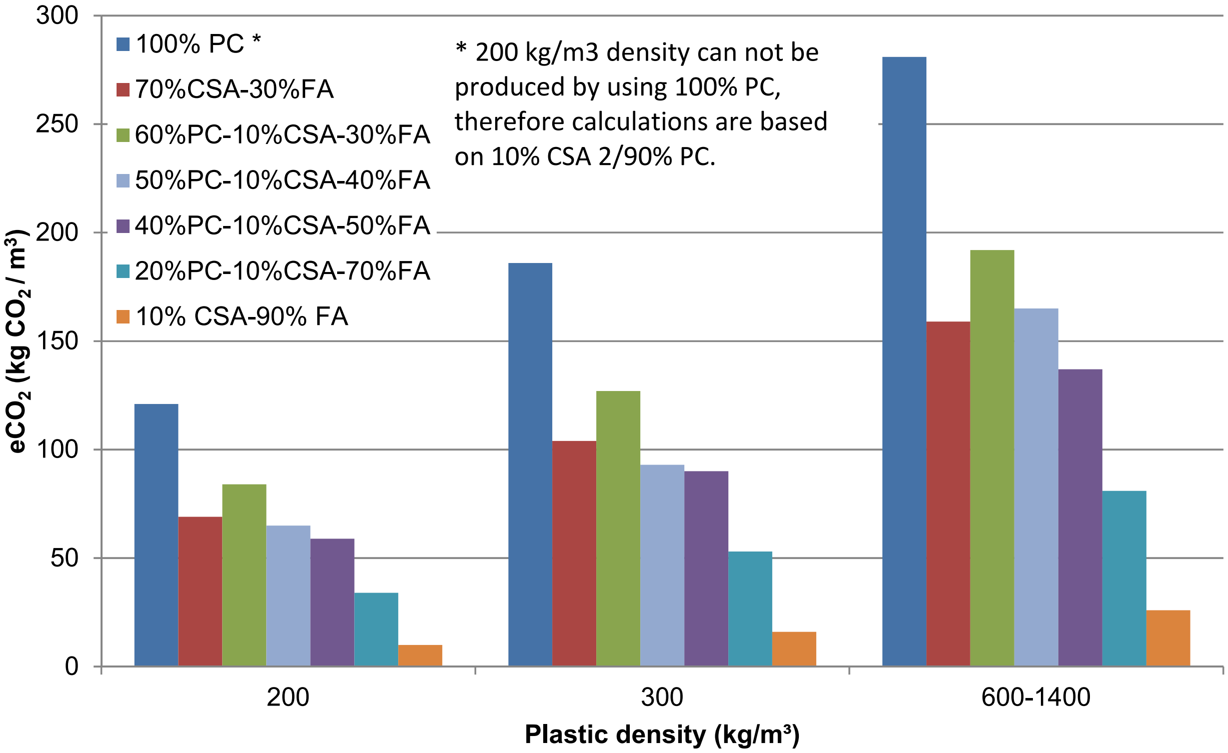


Fig 4.8 Change in eCO_2 of various blends as density of foamed concrete decreases.

4.7 Microstructure

Microstructural analysis is a vital factor to understand the performance of a material. In case of foamed concrete, microstructure has more importance, since foamed concrete has an extremely variable and complex microstructure directly affecting its performance, when different materials are used. Environmental Scanning Electron Microscopy (ESEM) was used to analyse the microstructure of foamed concrete. All the samples analysed under ESEM were 28 days old, unless noted otherwise.

From Fig 4.9 to Fig 4.14 and from Fig 4.15 to 4.18 changes observed in the microstructure of 300 kg/m³ and 200 kg/m³ foamed concrete are presented respectively. Fig 4.9 and 4.15 show the control mixes produced by using only PC and CSA with densities 300 and 200 kg/m³ respectively.

Comparing Fig 4.9 and 4.10, improved microstructure of 300 kg/m³ foamed concrete was observed with the utilization of foamed concrete. As can be seen in Fig 4.10 (a), fly ash seems to have a crack blunting effect which improves the microstructure.

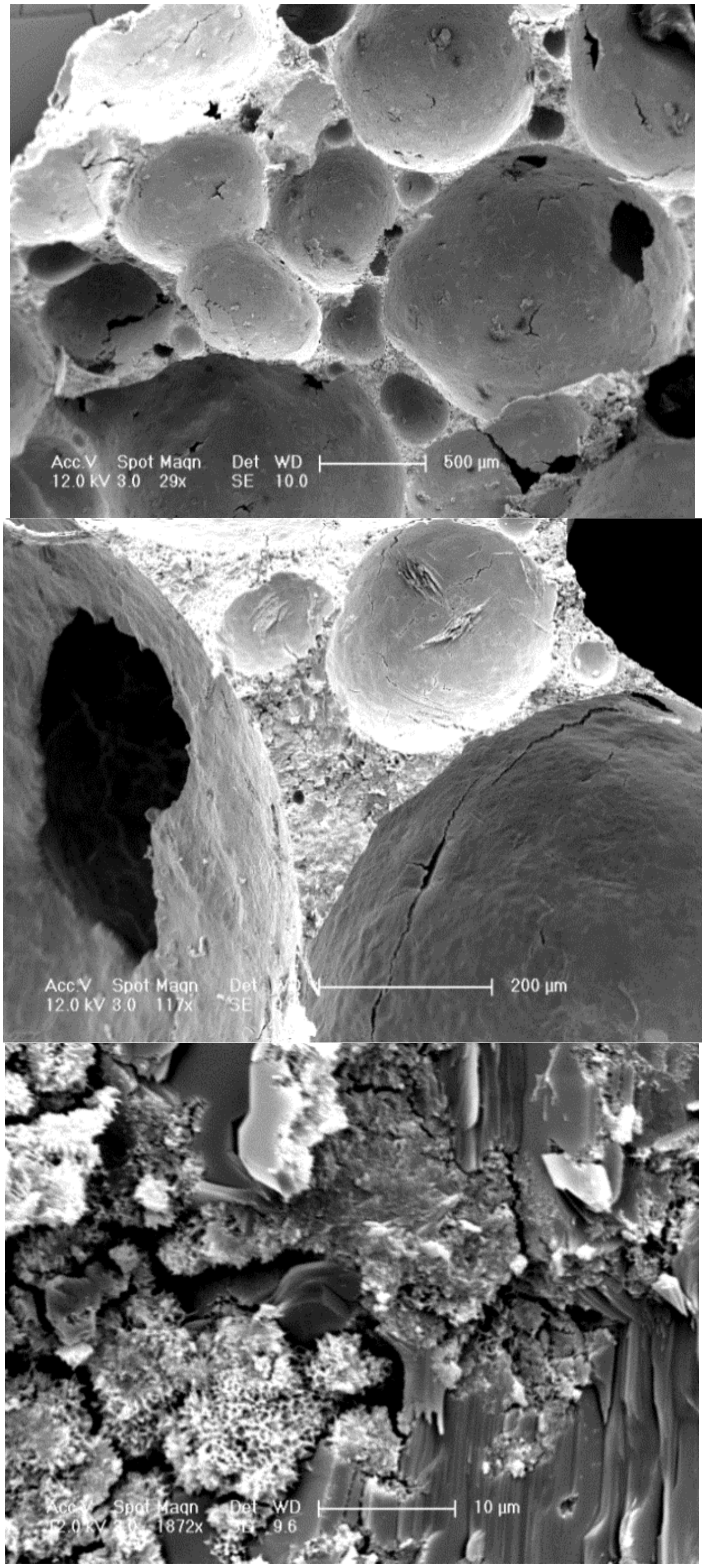
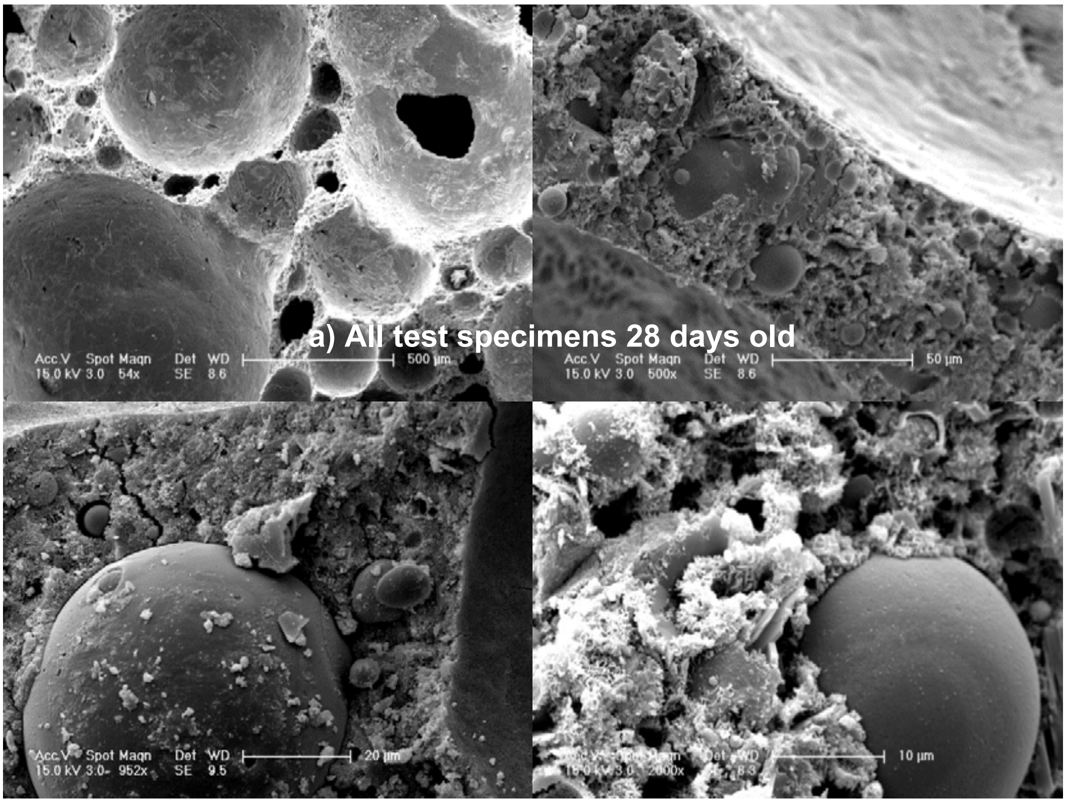
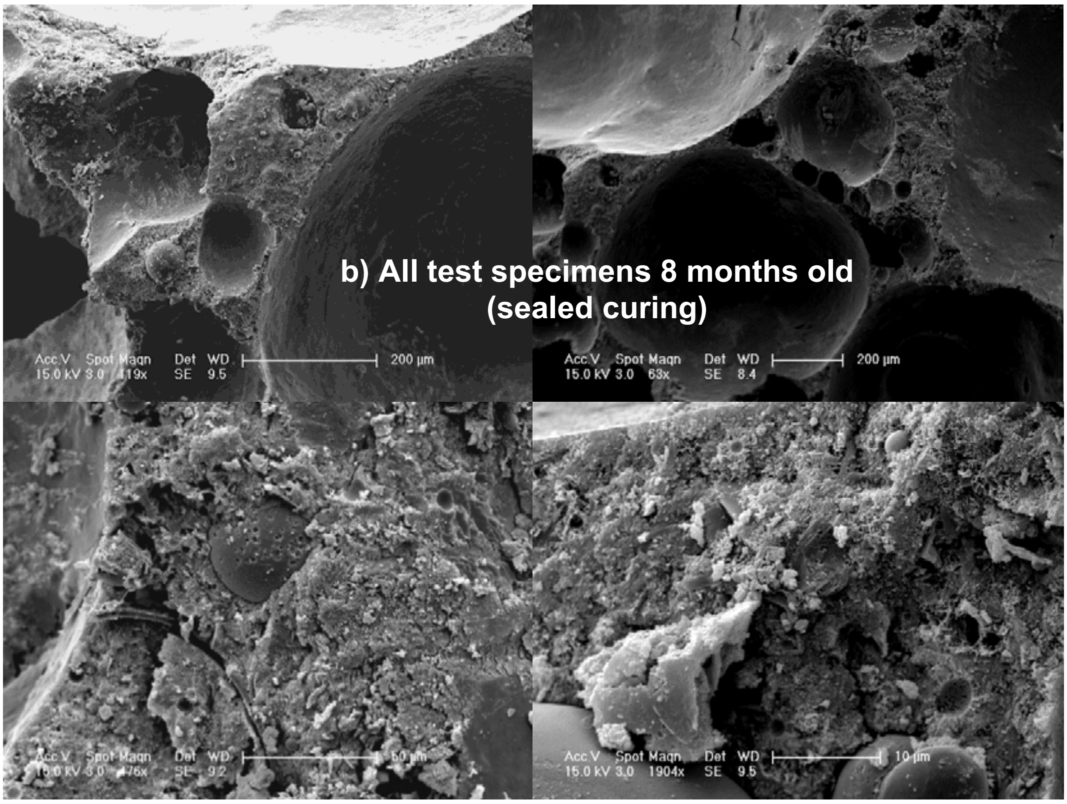


Fig. 4.9 D300-95% PC/5% CSA 2



a) All test specimens 28 days old



b) All test specimens 8 months old
(sealed curing)

Fig. 4.10 D300-60% PC/10% CSA 2/30% FA 1

As it is shown in Fig 4.10 (b), considerable densification in the walls of 8 months old samples was observed, as well as the improvements in the bubbles that have fewer holes. 8 months old samples were sealed cured, it was thought there would not be enough water for long-term hydration but the samples seem to have been undergone continued hydration. There seem to be less cracks in older samples, perhaps fly ash has a crack healing effect in long term.

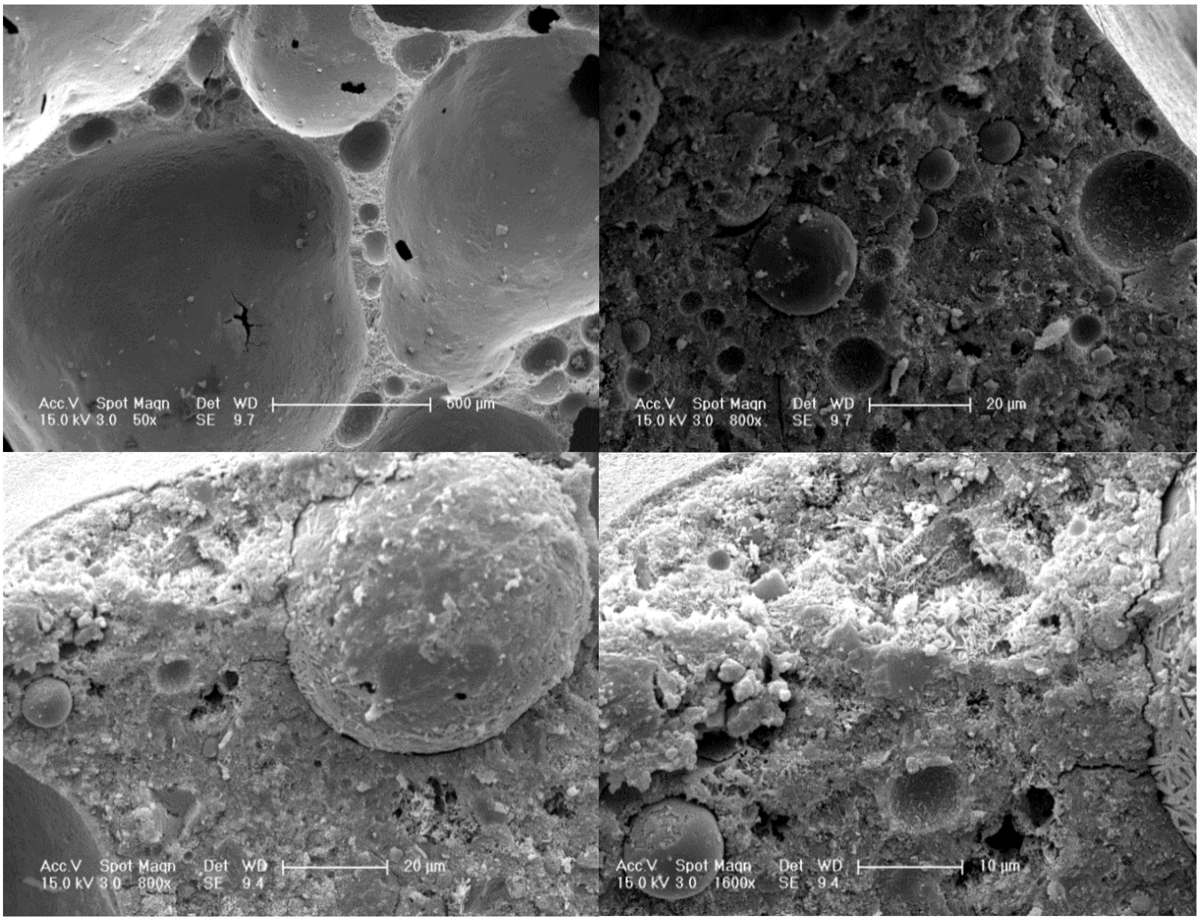


Fig. 4.11 D300-60% PC/10% CSA 2/40% FA 1 (8 months old)

‘Squeezed’ ellipse-shaped bubbles (Fig 4.11, top left), possibly suggest that fine fly ash particles stabilize walls of the bubbles preventing them from bursting and since the walls are stabilized they may change shape without bursting in order to stay stable.

There is no strong bonding between fly ash cenospheres and the paste as fly ash cenospeheres were pulled out (Fig 4.11, top right). Perhaps, it is the gap between fly ash cenosopheres and the paste causing fly ash to stay away from the alkaline environment without getting into reaction.

Comparing Fig 4.10 (a) and Fig 4.12, 30% FA 2 formed denser foamed concrete microstructure than FA 1. Moreover, given its higher fineness, FA 2 seems to form smoother bubble surfaces with much fewer micro cracks than FA 1. Increasing from 30 to 40% FA, micro holes in the bubbles appeared (Fig 4.12 and 4.13).

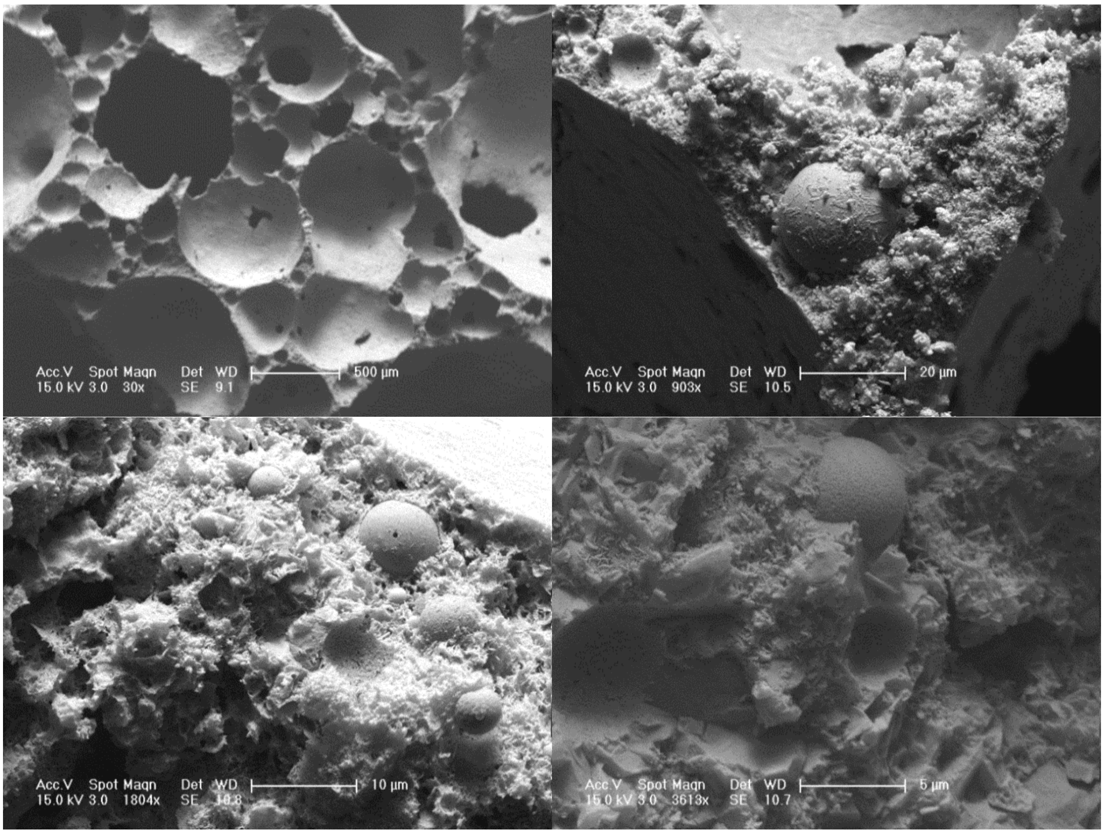


Fig. 4.12 D300-60% PC/10% CSA 2/30% FA 2

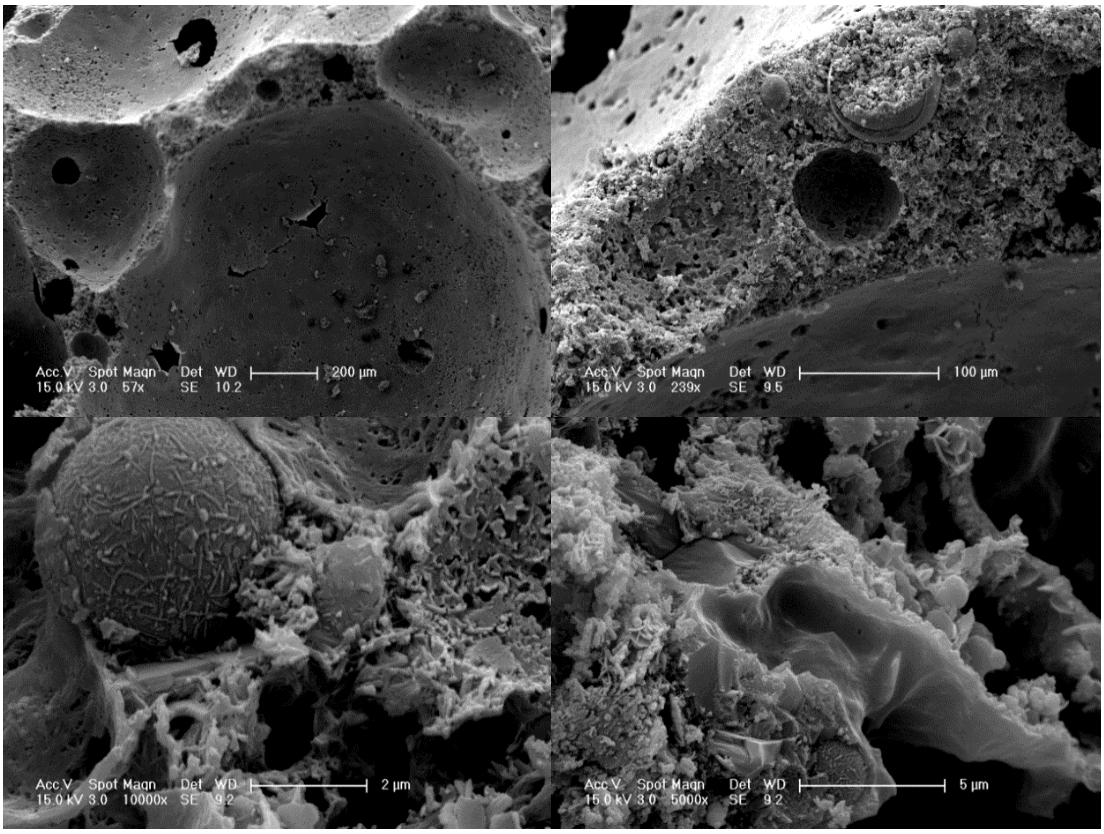


Fig. 4.13 D300-50% PC/10% CSA 2/40% FA 2

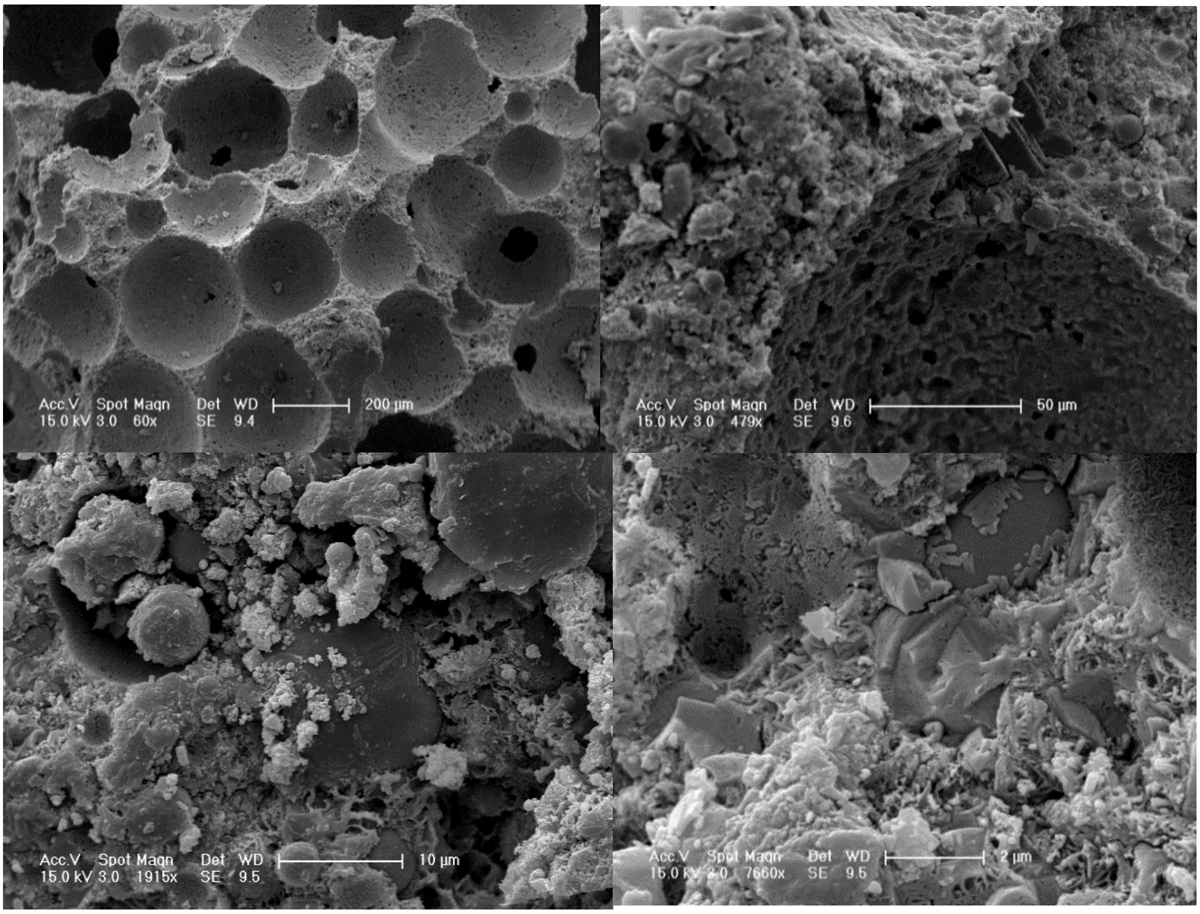


Fig. 4.14 D300-40% PC/10% CSA 2/50% FA 2

Utilization of 50% FA 2 in 300 and 200 kg/m³ density foamed concrete resulted in different texture inside the bubbles. 300 kg/m³ had less dense bubble surfaces with many micro holes while, smoother surfaces were formed in the bubbles in latter case. (See Fig 4.14 and.4.17). Compared to 40% FA 2 samples (Fig 4.13), increased number of micro holes formed in the bubbles of 50% FA 2 samples.

Compared to 50, 70 % fly ash contents (Fig. 4.14, 4.17 and 4.18), there seem to be higher number of bubbles in the walls with lower fly ash contents. Moreover, increase in the fly ash content seems to increase the wall thickness both in 300 and and 200 kg/m³ density foamed concrete.

At 30% fly ash, many bubbles are formed in the walls both in 200 and 300 kg/m³ foamed concrete while the number of bubbles in the walls decreases and the main bubbles grow bigger as the fly ash content increases.

As it can clearly be seen in Figs 4.15 to 4.17, utilization of fly ash in 200 kg/m³ density foamed concrete greatly improved both the bubbles and the walls

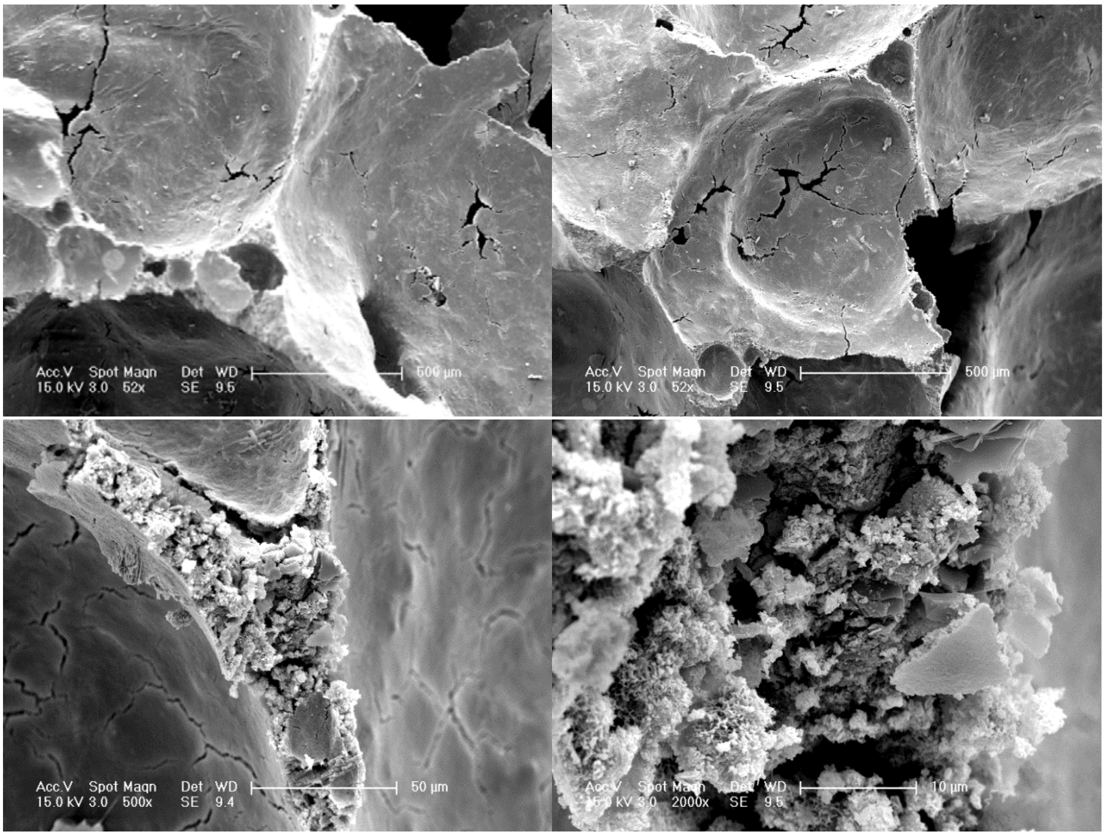


Fig 4.15 D200- 95% PC-5% CSA 2

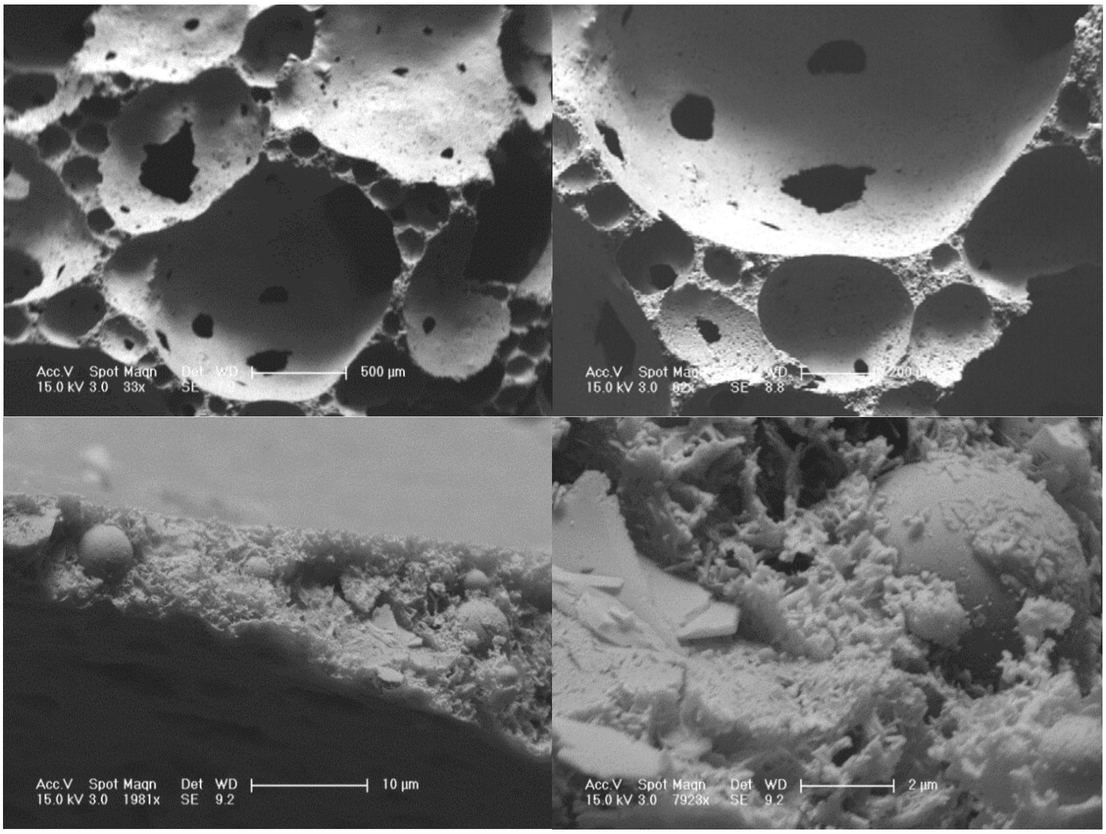


Fig 4.16 D200-60% PC/10%CSA/30%FA 2

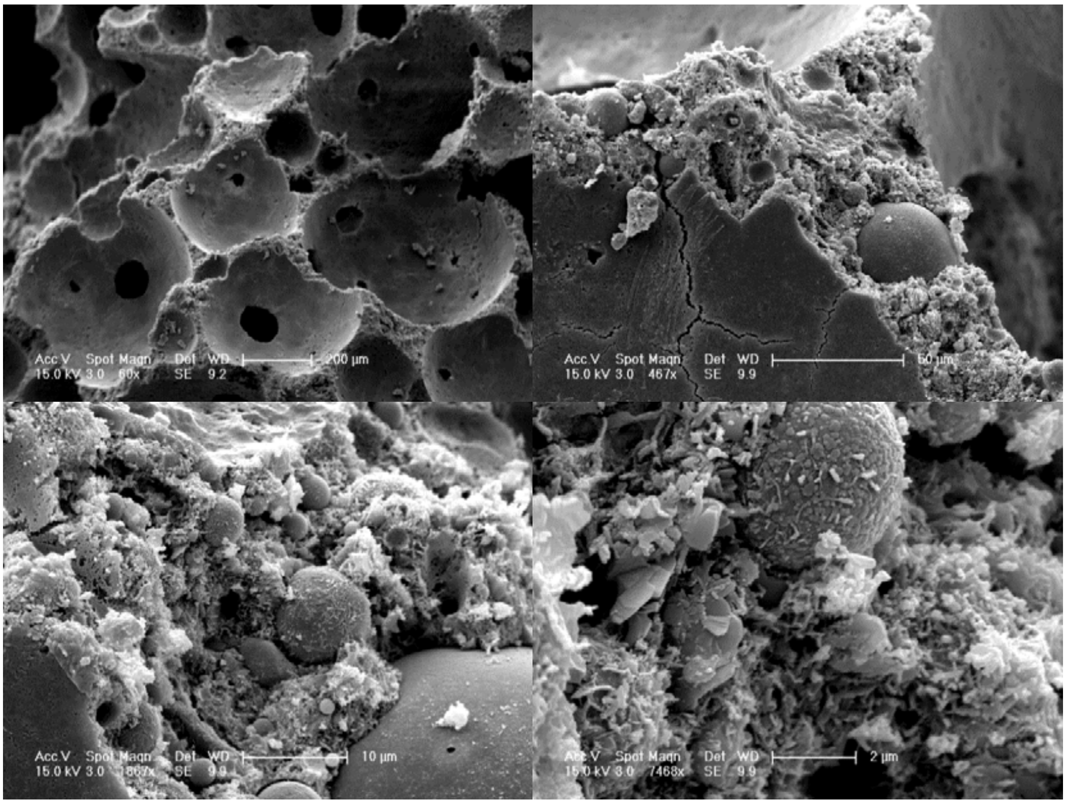


Fig 4.17 D200-40% PC/10%CSA/50%FA 2

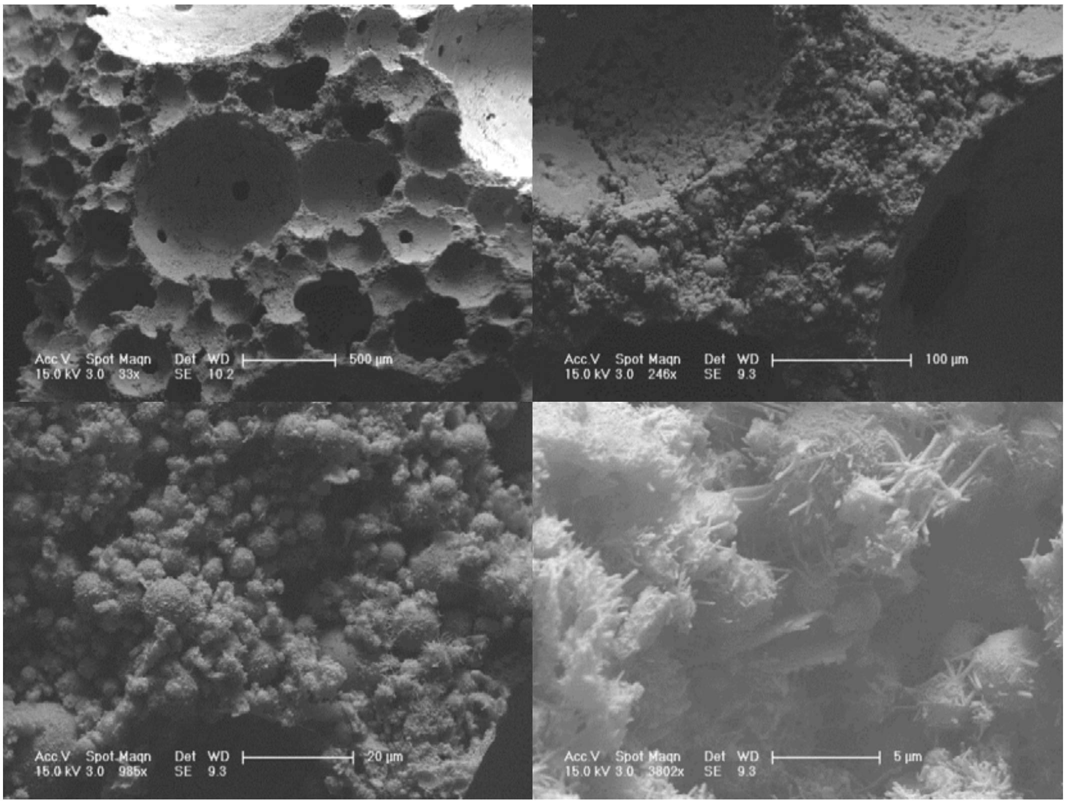


Fig 4.18 D200-20% PC/10%CSA/70%FA 2

At 70% fly ash content, many small bubbles of similar sizes surrounding bigger bubbles, whereas at lower percentages of fly ash bigger bubbles of similar size exist all around the sample. Moreover, 70% fly ash samples seem to be full with unreacted fly ash cenospheres with very few hydration products visible. This is due to the lack of enough PC to provide alkaline environment for fly ash to react (Fig 4.18).

In general, apart from the 70% fly ash sample, almost same amount of fly ash seems to be left unreacted even after 8 months curing regardless of percentage of fly ash used. More visible improvement in the walls of 200 kg/m³ samples as fly ash content increases up to 50 %.

5. CONCLUSIONS

A series of hypotheses are presented to attempt to explain why instability increases with reducing foamed concrete density. These predict that the using a fast setting and fine particle size cement would to produce stable foamed concrete at ultra-low densities and data is presented, which confirms this. It was found that an initial setting time of not more than 25 minutes always resulted in stable mixes with densities down to 150 kg/m³. However, if any faster than 20 minutes, mixes set too quickly for practical purposes.

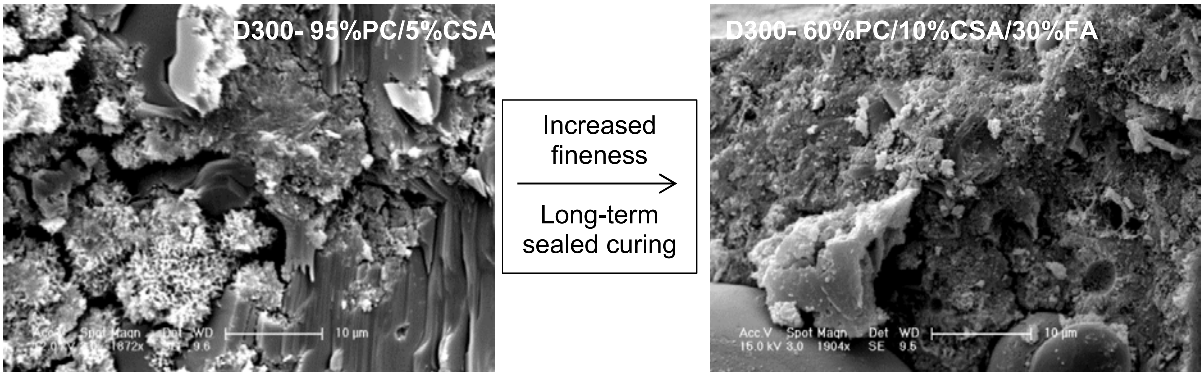
Cement fineness was also shown to be important and test showed that a fine fly ash (FA 2) gave a stable mix at ultra-low densities compared with FA 1, which was a coarser ash, even both mixes had the same setting times. Composite cements with fly ash also significantly reduced heat of hydration, which was very high given the insulating nature of foamed concrete.

Compared to non- fly ash foamed concrete, indicative thermal conductivity decreased by around 7% when 30% FA 2 is utilized both in 200 and 300 kg/m³ mixes, whereas using 30% FA 1 in 300 kg/m³ mix yielded 4% reduction. The difference arising between two types of fly ash is due to the higher fineness of FA 2 which has a better effect on improving the bubble structure, yielding more closed bubbles. Furthermore, using 70% FA 2 in 300 kg/m³ increased the thermal conductivity.

Fly ash was found to improve the sound insulation properties of foamed concrete over the tested frequencies. 300 kg/m³ foamed concrete produced with 30% FA 1 was found to absorb up to 25% more sound compared to non-fly ash foamed concrete.

Embodied CO_2 content of foamed concrete is reduced up to 57% when ultra-low densities are used instead of conventional foamed concrete. Using 40 % fly ash reduces the eCO_2 of 200 kg/m³ foamed concrete down to 65 kg CO_2/m³ compared to the non-fly ash mix with eCO_2 of 121 kg CO_2/m³.

Fly ash considerably improves the microstructure of foamed concrete, especially after long-term curing. Utilization of fly ash up to 50% seems to yield foamed concrete with denser microstructure and thicker walls. Therefore, performance and properties of fly ash foamed concrete must be assessed again after long-term curing.



Fly ash seems to have a crack blunting effect and a crack-healing effect in long-term.

Considering the stability issues, flow behaviour, eCO2 contents and microstructural properties, 40% fly ash (FA 2) seems to be the optimum. Insulation properties seem to improve compared to non- fly ash mixes when 30% fly ash was used, however, further investigations on foamed concrete with higher fly ash contents are required to decide the optimum fly ash content yielding the best performance.

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