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Preliminary views on the potential of foamed concrete as a structural material

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Low self-weight (800 to 1600 kg/m³), high workability (flowing and self-compacting) and excellent thermal insulating properties (< 0·50 W/mK) make foamed concrete attractive for many construction applications. Indeed, it is now a well-established material in void filling and highway reinstatement uses. However, its wider use in structural applications has been inhibited by its technical and engineering unfamiliarity and a perceived difficulty of achieving sufficiently high strength (say > 25 N/mm²). This paper describes a laboratory study of the development of foamed concrete, utilising two types of fly ash, with the potential for use in structural applications. 'Fine' fly ash (i.e. to BS EN 450) was used to partially replace Portland cement and a 'coarse' fly ash (i.e. to BS 3892-2) to replace sand fine aggregate. In addition, the potential of polypropylene fibres in foamed concrete to enhance plasticity and tensile strength was examined. The key early age, engineering and durability properties were measured and these data show that foamed concrete is indeed viable for structural uses. To further demonstrate the concept, the results of full-scale pilot tests on conventionally reinforced foamed and normal weight concrete beams are also reported and their performance compared with the BS 8110 and Eurocode 2 requirements for serviceability. However, the characteristics of foamed concrete, particularly high drying shrinkage strain and relatively low tensile strength and stiffness performance, mean that straight substitution for normal weight concrete is not possible and more innovative structural forms will need to be developed.

Introduction

Foresight groups around the world have identified the future need for construction materials that are light, durable, simple to use, economic and yet more environmentally sustainable. Although reinforced autoclaved aerated concrete panels (e.g. roof, floor) are available, these are controlled by the requirements of factory autoclaving and, as a consequence, in size, although modern developments have allowed much larger sections to be manufactured.[1] An alternative material, however, that has the potential to fulfil all these requirements is foamed concrete.[2,3] It can be designed to have any density within the range of 400–1600 kg/m³ and is flowing and self-compacting. Conventional foamed concrete is typically proportioned to achieve only low compressive strengths (e.g. between 1 and 10 N/mm²), suitable for its use in void fill and trench reinstatement, and thus, the material is largely disregarded for use in structural sections. Although there may be highly innovative solutions, unless strengths of at least 25 N/mm² can be achieved, both economically and in an environmentally sustainable manner, most engineers and designers are unlikely to give foamed concrete serious attention for structural application. This begs the question: what is the achievable performance envelope of foamed concrete with respect to its engineering properties?

Responding to this technological challenge, this paper reports a laboratory-based research programme, carried out at the Concrete Technology Unit at the University of Dundee, into the use of 'fine' fly ash (FA_{fine}) in foamed concrete to partially replace Portland cement and 'coarse' fly ash (FA_{coarse}) to replace sand fine aggregate. The overall aim of the work was to derive the strength/plastic density relationship for foamed concrete made with constituent materials that are widely available to the industry. More specifically, the objective was to determine the lowest foamed concrete density that could be produced to have a compressive strength of, at least, 25 N/mm² and which could be

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viable for full-scale in-situ applications, without raised temperature or autoclaved curing.

Materials, mix constituent proportions and foamed concrete production

Combinations of the following constituent materials were used to produce the test foamed concrete mixes.

(*a*) Portland cement (PC/CEM I) conforming to BSEN 197-1.[4]
(*b*) 'Fine' fly ash (FA_{fine}) with a 45 μm sieve retention of 7·5%, loss on ignition (LOI) of 5·0% and conforming to BS EN 450.[5] It was used to replace PC at 30 to 50% by mass fraction (note: the unit volume was maintained by adjusting the fine aggregate content).
(*c*) 'Coarse' fly ash (FA_{coarse}) with a 45 μm sieve retention of 26·0%, LOI of 7·5% and conforming to BS 3892-2.[6] This ash was used as a replacement for sand fine aggregate at 50 or 100% by mass fraction (note: although these were arbitrary figures, they are representative of industry practices). The total replacement of sand with FA_{coarse} was investigated as it does not result in any consumption of primary aggregate sources, even though it represents the most extreme case with respect to drying shrinkage, stiffness, and brittleness. However, all the FA_{coarse} content was treated as part of the cement phase for the purposes of the water/cement (w/c) ratio, to ensure that sufficient free water was used in the mix to 'wet' the large surface area of these fine particles. In this work, no attempt was made to optimise either the cement or sand replacement level.
(*d*) Fine aggregate, a natural siliceous sand conforming to BS EN 12620[7] Category G_F85 as supplied, but in this case additionally sieved to remove particles greater than 2·36 mm, to help improve the foamed concrete flow characteristics and stability.
(*e*) Surfactant (a commercial, synthetic type foaming agent), used in a 6% aqueous solution and foamed to a density of 50 kg/m^3 (again, this is typical of industry practice).
(*f*) Superplasticiser conforming to BS EN 934-2.[8]
(*g*) Polypropylene fibres (mono-filament type, 19·2 mm length, used at 0·25 and 0·50% by mix volume in selected mixes only).

Although there are no standard methods for proportioning foamed concrete,[9] the general rules regarding w/c ratio, free water content and maintaining a unit volume apply, but it is a specified target plastic density that becomes a prime design criterion.[10] It should be noted that it is difficult to design for a specific dry density, as foamed concrete will desorp between 50 and 200 kg/m^3 of the total mix water, depending on the concrete plastic density, early curing regime and subsequent exposure conditions. Assuming a given target plastic density (D, kg/m^3), water/cement ratio (w/c) and cement content (c, kg/m^3), the total mix water (W, kg/m^3) and fine aggregate content (f, kg/m^3) are calculated from equations (1) and (2) as follows.

Target plastic density, $D = c + W + f$,

$$\text{where } c = \text{PC} + \text{FA}_{\text{fine}},\ f = \text{FA}_{\text{coarse}} + \text{sand} \quad (1)$$

Free water content,

$$W = (w/c) \times (\text{PC} + \text{FA}_{\text{fine}} + \text{FA}_{\text{coarse}}) \quad (2)$$

Foamed concrete was produced in the laboratory using a standard inclined rotating drum mixer by the addition of pre-formed foam to a mortar (i.e. mix with sand fine aggregate) or paste (i.e. mix with no sand, just FA_{coarse} fine aggregate) 'base' mix and mixing until uniform consistency was achieved.[10] The plastic density was measured in accordance with BS EN 12350-6[11] by weighing a foamed concrete sample in a pre-weighed container of a known volume. A tolerance on plastic density was set at $\pm$ 50 kg/m^3 of the target value, which is typical of industry practice for foamed concrete production. The specimens were then cast in steel moulds lined with domestic plastic 'cling' film, as foamed concrete was found to adhere strongly to the mould surface, irrespective of the type and quantity of release agent used. After de-moulding at 24 h, the specimens were sealed-cured (i.e. wrapped in 'cling' film) and stored at 20°C until testing. It is recognised that sealed-curing may result in specimens having different degrees of pore saturation. This effect was considered to be minor for the range of constituent materials studied and certainly more representative of the actual properties of the material than would be the case if standard curing was applied. Again, sealed-curing reflects typical industry practice for foamed concrete.

The mix constituent proportions of all the foamed concretes tested are summarised in Table 1. In order to provide a comparison of the engineering properties of foamed concrete with those of normal weight (NWC) and lightweight aggregate (LWC) concretes, the split cylinder tensile strength and static modulus of elasticity (E) were calculated for NWC and LWC, assuming equivalent compressive strength. For the full-scale trials, however, a 25 N/mm^2 normal weight, reinforced concrete beam was prepared and tested alongside two reinforced foamed concrete beams of 1400 and 1600 kg/m^3 plastic densities.

Plastic density and cube strength repeatability of a single mix

The specialised production method and relatively low strength of this less familiar type of concrete may require that a greater margin on the minimum characteristic cube strength required is applied in the short term,

Table 1. Mix constituent proportions of foamed concrete mixes

Mix no.	Target plastic density: kg/m^3	Cement content[a]: kg/m^3		Fine aggregate content[a]: kg/m^3		w/c ratio[b]
		PC	FA_{fine}	Sand	FA_{coarse}	
1	1400	500	–		–	0·35
2		350	150	725	–	
3		300	200		–	
4		250	250		–	
5	1400	300	–	950	–	0·50
6			–	380	380	
7			–	–	633	
8	1400	210	90	950	–	0·50
9			90	380	380	
10			90	–	633	
11	1400	500	–	–	577	0·30
12	1600		–	–	731	
13	1800		–	–	885	
14	1400	500	–	750	–	0·30
15	1600		–	950	–	
16	1800		–	1150	–	
17	1400	500	–	–	500	0·40
18	1800		–	–	786	
19	1400	500	–	700	–	0·40
20	1800		–	1100	–	
21	1400	500	–	–	611	0·26
22	1600		–	–	770	
23	1400	500	–	–	545	0·34
24	1600		–	–	694	

[a] Per m^3 of foamed concrete.

[b] w/c ratio, in this case, includes PC, FA_{fine} and FA_{coarse} quantities to 'wet' the high surface area of these particles.

until more data become available. Some indicative repeatability measurements (ten repetitions), regarding foamed concrete production and sealed-cured 100 mm cube strength, were obtained under laboratory conditions by a single operator and are summarised in Table 2. As can be seen, for a given amount of foam addition and following the same mixing procedure, the plastic densities obtained ranged from 1563 to 1650 kg/m^3, all within ± 50 kg/m^3 of the target plastic density (in this case 1600 kg/m^3). The standard deviation and coefficient of variation of foamed concrete plastic density were 33 kg/m^3 and 2% respectively. Similarly, the 2, 7 and 28 day measurements of 100 mm cube compressive strengths of the ten mixes exhibited standard deviations and coefficients of variation between 2·0 and 4·0 N/mm^2 and between 7·3 and 23·9% respectively. As can be seen, the repeatability of plastic density and 28 day strength values, in particular, were satisfactory, with coefficient of

Table 2. Repeatability of 1600 kg/m^3 target plastic density foamed concrete (mix 12) production and cube compressive strengths

Mix no.	Actual plastic density: kg/m^3	100 mm cube sealed-cured compressive strength[a]: N/mm^2		
		2 day	7 day	28 day
12	1648	15·0	21·0	28·5
	1638	11·5	17·0	27·0
	1627	10·0	14·5	26·0
	1635	13·5	22·5	29·0
	1573	10·0	12·5	24·5
	1640	11·0	19·5	27·0
	1563	9·5	10·5	23·5
	1639	11·0	16·5	26·5
	1586	10·5	12·0	24·5
	1650	14·5	22·5	29·0
Mean	1620	11·5	17·0	26·5
Standard deviation	33	2·0	4·0	2·0
Coefficient of variation: %	2·0	16·9	23·9	7·3

[a] Mean of three results and reported to the nearest 0·5 N/mm^2.

variation values of less than 10%. This is generally considered an acceptable level of repeatability for laboratory-produced normal weight concrete. Although it was not possible, in the scope of this project, to repeat these tests at other plastic densities, there is no obvious reason why the repeatability should be significantly different.

Early age properties

Heat of hydration

The heat of hydration was determined using 165 mm cube specimens subjected to a near adiabatic cycle in a highly insulated 'hot-box', with the temperature rise measured using a Type K thermocouple placed in the centre of the test specimen. The test was carried out to determine the magnitude of self-induced temperature rises, given the highly insulating properties of foamed concrete and high PC contents (mixes 1–4). In addition, the potential of using a partial (30 to 50%) replacement of PC with FA_{fine} to reduce the magnitude of temperature rise was examined. As can be seen from Fig. 1 and Table 3, peak temperatures up to 60·5°C were encountered with the PC reference mix, which is a 40°C rise above ambient. This shows that there is a potential for significant surface/core temperature differential (i.e. $> 20°C$)[12] with foamed concrete. Although the thermal strain capacity and expansion were not measured (as they were outside the scope of the present study), it has been reported, albeit with gravel aggregate normal weight concrete, that a differential of this magnitude can lead to an increased risk of thermal cracking in large pour volumes[13] and/or thermal shock due to early formwork stripping. In a related study,[14] a foamed concrete strip foundation, forming a concentric square around a mass of soil (which provided significant restraint), was cast, using a similar foamed concrete mix. However, no cracking was detected up to 28 days, when the foundation was covered to be utilised for a small building.

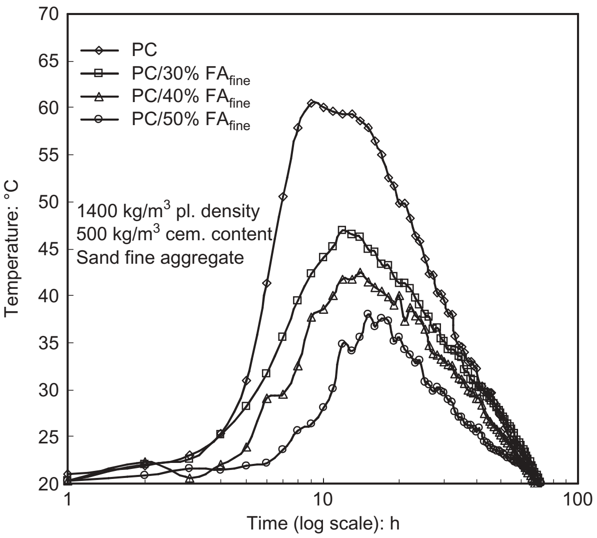

Fig. 1. Effect of PC replacement with FA_{fine} on heat evolution of foamed concrete (mixes 1–4) as measured in a 'hot-box'. Note: a large number of data points were generated by frequent automatic computer logging, which have been omitted from the Figure for clarity

The maturity curves indicate that the use of FA_{fine} significantly reduced the rate of temperature rise (by up to 83%) as well as the peak temperature reached. More specifically, with a 30, 40 and 50% by mass fraction of FA_{fine} in cement, the peak temperature, which was retarded by between 3 and 6 h, was between 13·5 and 22·5°C lower than that of the PC reference. This resulted in a reduction in maturity of up to 540 °C h (assuming –12°C datum temperature)[15] noted over the first 42 h. Overall, the reduced peak temperatures with FA_{fine} addition, sustained over a shorter period of time, should minimise the risk of thermal strain, cracking or even potential delayed ettringite formation.[16]

Drying shrinkage

The drying shrinkage was measured on 40 mm × 40 mm × 200 mm prisms for test mixes 5 to 10, which were stored at 20°C and 55% relative humidity after demoulding at 24 h. The relative ranking of foamed concrete mixes with the different fine aggregate types was consistent throughout (see Fig. 2), with 100% FA_{coarse}, 50% FA_{coarse}/50% sand and 100% sand in decreasing order of drying shrinkage strains. This trend was also reflected in the mass loss measurements, which were greater for the FA_{coarse} than the sand foamed concretes. Overall, for the 1400 kg/m^3 plastic

Table 3. Effect of FA_{fine} on maturity of 1400 kg/m^3 sand fine aggregate concretes[a]

Plastic density: kg/m^3	Cement combination: % by mass	Peak temperature: °C	Time to peak: h	Max. rate of rise: °C/h	28 day maturity: °C h	Equiv. 28 day maturity: days
1400	PC	60·5	9	9·0	24 033	24·7
	PC/30% FA_{fine}	47·0	12	3·6	23 774	25·0
	PC/40% FA_{fine}	42·5	14	2·5	23 609	25·3
	PC/50% FA_{fine}	38·0	15	1·5	23 387	25·5

[a] Total cement (PC and FA_{fine}) content = 500 kg/m^3.

density concretes examined, drying shrinkage strains between 940×10^{-6} and 1900×10^{-6} were observed after 12 months. These values are in line with other studies on foamed concrete.[17,18] The FA_{coarse} mixes exhibited the largest shrinkage due to higher actual mix water quantities (at equal *w/c* ratio) and consequently the largest volume of paste than the equivalent sand specimens. However, it is possible that the air bubbles also provide a degree of volume stability to the cementitious matrix.

Generally the use of fly ash as a cement replacement reduces drying shrinkage strains and thus, the effect of FA_{fine} as a PC replacement was examined. As can be seen in Fig. 2, when 30% FA_{fine} was used with PC, drying shrinkage strains were up to 2·6 times smaller on the 1400 kg/m^3 specimens at a given test age, generally assumed to be due to restraint provided by unreacted fly ash particles. Lower foamed concrete shrinkage strains have been observed, when lightweight aggregate is employed.[19] Although the drying shrinkage of higher density concretes was not considered in this study, this is expected to be smaller than that of 1400 kg/m^3 mixes, as reported in the literature.[9,18]

Engineering properties

Compressive strength

The compressive strength was measured in accordance with BS EN 12390-3[20] on 100 mm sealed-cured cube specimens stored at 20°C (mixes 11–16) and the effect of FA_{coarse} and sand fine aggregates is compared in Fig. 3. As expected,[9,18,21] strength reduced with decreasing density. The use of 100% FA_{coarse} fine aggregate greatly improved strength development at all test ages[9,18,22] and, by 56 days, strengths were up to 2·5 times higher than those of the corresponding sand fine aggregate foamed concrete. Furthermore, by 56 days, all the FA_{coarse} specimens had exceeded 25 N/mm^2 and it is, therefore, suggested that this is a more appropriate test age for foamed concrete.

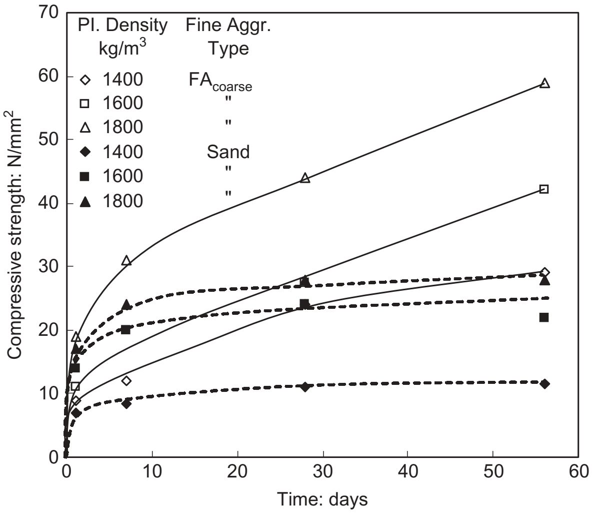

Fig. 3. Effect of FA_{coarse} fine aggregate on 100mm cube sealed-cured compressive strength development (mixes 11–16)

The comparatively lower strengths of the sand foamed concretes may also be attributed to the need for slightly higher quantities of air compared with FA_{coarse} mixes to achieve the target plastic density, due to differences in their particle densities (in this case 2630 kg/m^3 for sand and 2270 kg/m^3 for FA_{coarse}).

Overall, the results suggest that 1400 kg/m^3 is the minimum density at which foamed concrete with FA_{coarse} fine aggregate could be used in structural elements. Further optimisation of the mixes may be possible by using fine and coarse FA simultaneously but substantial gain could only be realistically achieved if

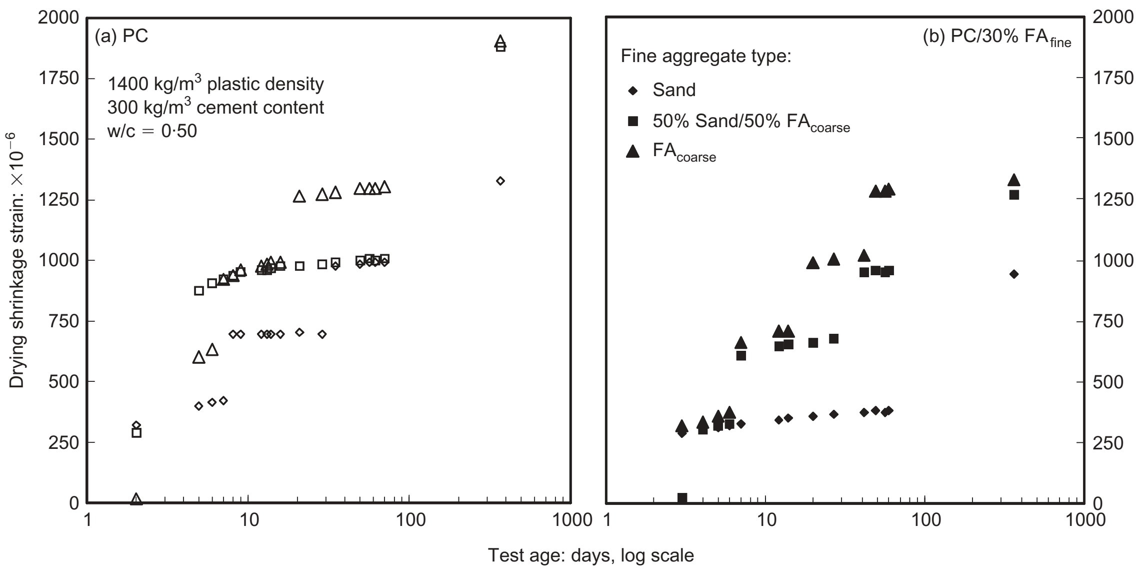

Fig. 2. Influence of FA_{coarse} and FA_{fine} on early age drying shrinkage strain of foamed concrete (mixes 5–10)

lower *w*/*c* ratios could be used. To enable this, new types of plasticising admixtures, compatible with the foam will be required.

Split cylinder tensile strength

Split cylinder tensile strength tests (mixes 11, 13, 14, 16, 17–20), were undertaken in accordance with BS EN 12390-6[23] and are compared with corresponding 28 day compressive strengths in Fig. 4 and Table 4. For a given 28 day compressive strength, the sand fine aggregate concretes produced higher tensile strengths than the FA_{coarse} specimens, most likely due to improved shear capacity between the sand particles and the paste phase. As expected, the tensile to compressive strength relationships of FA_{coarse} fine aggregate foamed concretes were lower than the calculated values for normal weight (NWC) and lightweight aggregate (LWC) specimens, assuming an equivalent compressive strength. In addition, the tensile/compressive strength ratios of both sand and FA_{coarse} concretes were slightly lower than those reported in other studies[19] on foamed concrete, probably due to the use of lightweight aggregate in these mixes.

Static modulus of elasticity

The static modulus of elasticity (*E*), was measured in accordance with BS 1881-121[26] and the relationship with corresponding 28 day sealed-cured 100 mm cube strengths is given in Fig. 5. The majority of foamed concrete *E*-values were significantly lower than those

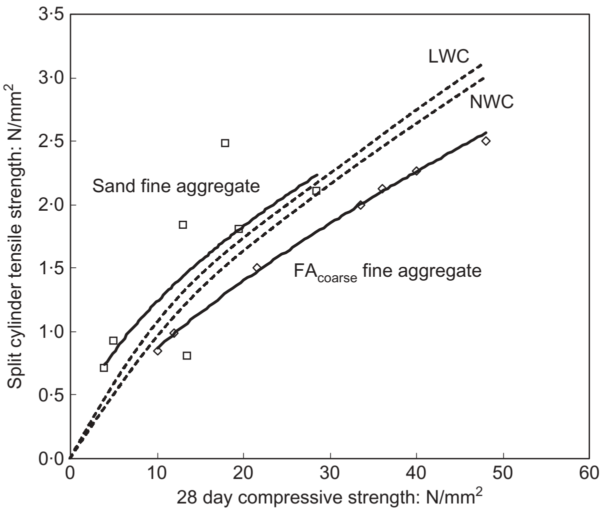

Fig. 4. Relationship between split cylinder tensile strength and 28 day sealed-cured 100 mm cube compressive strength of foamed, NW and LW concretes (mixes 11, 13, 14, 16, 17–20). (Note: the NWC and LWC data were derived from calculations using equations $f_t = 0{\cdot}2(f_c)^{0{\cdot}70}$ and $f_t = 0{\cdot}23(f_c)^{0{\cdot}67}$, respectively)[14, 15]

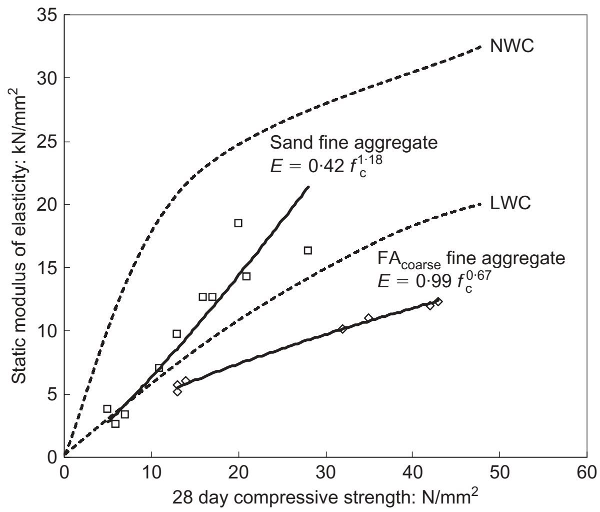

Fig. 5. Relationship between E-value and 28-day sealed-cured 100 mm cube compressive strength of foamed, NW and LW concretes. (Note: the NWC and LWC data were derived from calculations using equations $E_c = 9{\cdot}1(f_c)^{0{\cdot}33}$ and $E_c = 1{\cdot}7 \times 10^{-6}\rho^2(f_c)^{0{\cdot}33}$, respectively given in BS 8110[13]*)*

Table 4. Relationship between split cylinder tensile and compressive strength and E-value and compressive strength of foamed, normal weight and lightweight aggregate concrete (mixes 11, 13, 14, 16, 17–20)

Fine aggregate type	Target plastic density: kg/m^3	Actual plastic density: kg/m^3	f_t/f_c ratio			E/f_c ratio		
			Foamed concrete	NWC[a]	LWC[b]	Foamed concrete	NWC[c]	LWC[d]
Sand	1400	1415	0·06	0·09	0·10	519	1593	963
	1600	1625	0·09	0·08	0·09	579	1241	753
	1800	1795	0·07	0·07	0·08	505	965	584
FA_{coarse}	1400	1430	0·07	0·08	0·08	284	1163	705
	1600	1605	0·06	0·07	0·07	281	866	524
	1800	1810	0·05	0·06	0·07	258	679	412

[a] The values were calculated from the equation $f_t = 0{\cdot}20(f_c)^{0{\cdot}70}$ by Oluokun.[24]
[b] The values were calculated from the equation $f_t = 0{\cdot}23(f_c)^{0{\cdot}67}$ by FIP.[25]
[c] The values were calculated from the equation $E_c = 9{\cdot}10(f_c)^{0{\cdot}33}$ given in BS 8110.[13]
[d] The values were calculated from the equation $E_c = 1{\cdot}70 \times 10^{-6}\rho^2(f_c)^{0{\cdot}33}$ given in BS 8110.[13]

calculated for equivalent compressive strength NWC and LWC specimens, with values increasing almost linearly with density and hence, with strength, as can be seen in equations (3) and (4) obtained from the data given in Fig. 5.

$$\text{Sand fine aggregate: } E = 0{\cdot}42 f_c^{1{\cdot}18} \quad (3)$$

$$\text{FA}_{\text{coarse}} \text{ fine aggregate: } E = 0{\cdot}99 f_c^{0{\cdot}67} \quad (4)$$

where E is the static modulus of elasticity (kN/mm^2) and f_c is the 100 mm cube strength (sealed-cured) (N/mm^2).

As with tensile strength, for a given compressive strength, the FA_{coarse} specimens exhibited lower E-values than the sand fine aggregate concretes. The relationships between E-values and compressive strengths are also compared in Table 4. The ranking of E-value/f_c ratios for the three types of concrete was foamed (both sand and FA_{coarse} mixes), LWC and NWC in increasing order of values, with NWC exhibiting values up to four times higher than equivalent strength foamed concretes. This has considerable implications for the use of foamed concrete in flexural applications, as deflections could be expected to be much higher, given a particular load and section geometry. Taken together with the lower tensile strength, direct substitution of foamed concrete for normal weight concrete of the same grade would not give similar structural performance.

Accelerated carbonation resistance

Resistance to carbonation was determined to see whether foamed concrete could be reinforced with carbon steel and exposed to outdoor, sheltered environments. An accelerated approach to this testing was adopted, using an enriched CO_2 method.[27] As there are concerns regarding accelerated methodologies, natural exposure tests have also been initiated. However, the results of these are not expected for at least five years.

Carbonation resistance was measured for test mixes 17 to 20 on 100 mm × 100 mm × 510 mm prism specimens placed in a $4 \pm 0{\cdot}5\%$ CO_2 atmosphere at $55 \pm 5\%$ relative humidity, the results of which are given in Fig. 6. As might be expected for a vesicular material with a high vapour diffusivity, all the foamed concrete mixes had high rates of carbonation, with the deepest level of carbonation penetration (23 mm after 15 weeks exposure) noted on 1400 kg/m^3 sand concretes. The 1800 kg/m^3 FA_{coarse} concretes exhibited greater carbonation depths than the equivalent density, sand fine aggregate concretes, however, at 1400 kg/m^3 the ranking order was reversed, although the differences between the two concretes were small. These results show that a great deal of care should be exercised if conventionally reinforced foamed concrete is to be used in exposed environments, where carbonation-induced corrosion could occur, and supports a similar conclusion for lightweight aggregate foamed concrete.[28]

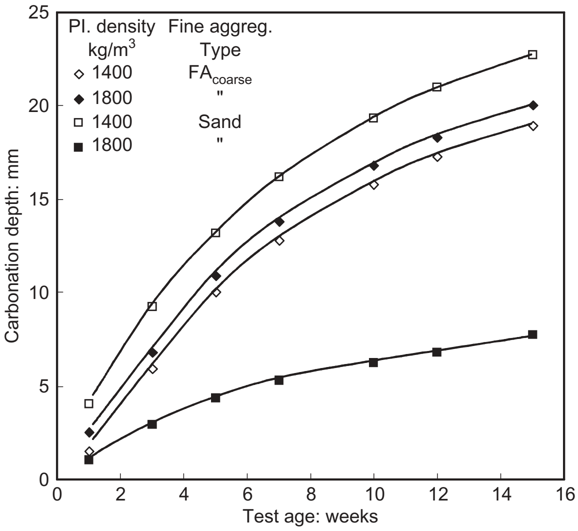

Fig. 6. Effect of FA_{coarse} as a sand fine aggregate replacement on carbonation resistance (mixes 17–20)

Application of polypropylene fibres

Given the high drying shrinkage strains and relatively low tensile strength and elastic modulus of the foamed concretes, consideration was given to whether the use of fibres could offset this performance. A number of fibre types were considered but it was felt that conventional steel and glass fibre were too rigid to easily 'sit' in a material with relatively thin walls of solid mortar between the bubbles. Thus, relatively more flexible polypropylene fibres were utilised.

One type of proprietary polypropylene fibre (19·2 mm long at 0·25 and 0·50% by mix volume), primarily designed to reduce shrinkage cracking in slabs, was tested. The effect of this on the engineering properties of 1400 and 1600 kg/m^3 FA_{coarse} foamed concretes (mixes 21, 22)[29] is summarised in Table 5. Overall, the compressive, flexural strengths (tested to BS EN 12390-5)[30] and E-values increased with the addition of fibres, with the most marked increases noted at 0·50% rate and 1400 kg/m^3 density. More specifically, the 28 day compressive and flexural strengths at this density were up to 52 and 58% higher than the reference respectively. Benefits were also noted on the E-values of the foamed concrete specimens, which now approximated the strength/E-value relationship of the LWC mixes in Fig. 5.

In all cases, the introduction of this type of fibre significantly reduced the mix workability. Higher fibre contents were also tried, but the mix workability decreased even more substantially and hence, the 0·50% fibre content was considered the upper optimum addi-

Table 5. Influence of polypropylene fibre addition on engineering properties of foamed concrete (mixes 21, 22)

Target plastic density: kg/m^3	Actual plastic density: kg/m^3	Fibre content: % mix volume[a]	28 day compressive strength[b]: N/mm^2	f_t/f_c ratio	E/f_c ratio
1400	1405	0	21	0·09	285
	1395	0·25	25	0·10	350
	1420	0·50	32	0·09	438
1600	1620	0	26	0·07	290
	1605	0·25	33	0·07	395
	1580	0·50	38	0·06	413

[a] 0·50% was the highest fibre content considered due to the adverse effect on mix rheology.
[b] Sealed-cured, 100 mm cube strength.

tion rate, in terms of a trade-off between workability lost and performance improvement.

Pilot load/deflection tests on full-scale beam elements

In order to assess the behaviour of foamed concrete in a more practical way, full-scale reinforced beams (200 mm × 300 mm × 2000 mm) were designed in accordance with BS 8110,[13] assuming a design load of 6·8 kN/m and an imposed load of 3·0 kN/m. The performance of two 1400 and 1600 kg/m^3 FA_{coarse} foamed concrete sections (mixes 23, 24)[29] was compared with a 25 N/mm^2 NWC beam, as can be seen in Table 6. In all cases, the beams were similarly reinforced with 2 × 8 mm diameter high yield carbon steel main reinforcement at 25 mm cover depth (i.e. assuming mild exposure) with mild steel links at 200 mm c/c and loaded at the third points and tested to failure, as shown schematically in Fig. 7. The load/deflection performance and crack initiation patterns of the three beam specimens are given in Figs 8 and 9, respectively.

As expected, given the relative stiffness of the materials, the deflections noted at the design load for the 1400 and 1600 kg/m^3 foamed concrete beams (3·0 and

Table 6. Comparative third point load/deflection behaviour of reinforced beams (mixes 23, 24)

Concrete type/beam mass[a]	At design load	At first visible crack		At failure	
	Deflection	Load	Deflection	Load	Deflection
FA_{coarse}, 1400 kg/m^3 170 kg	3·0 mm	14·7 kN	3·4 mm	48·6 kN	19·0 mm
	Normal, tensile failure (slightly brittle) with concrete failing before steel.				
FA_{coarse}, 1600 kg/m^3 190 kg	1·5 mm	14·9 kN	1·8 mm	47·1 kN	12·0 mm
	Tensile failure, more brittle than 1400 kg/m^3 beam specimen.				
NWC, 2370 kg/m^3 285 kg	0·8 mm	29·4 kN	3·0 mm	49·1 kN	8·4 mm
	Normal, tensile failure, with concrete failing before steel reinforcement.				

[a] The calculated beam mass does not include that of the reinforcement, the latter being the same in all three elements.

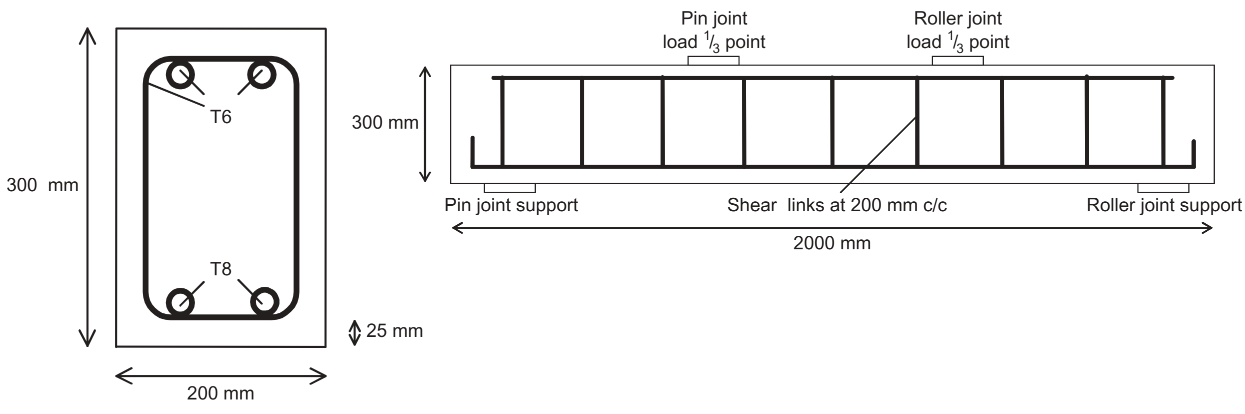

Fig. 7. Detail of reinforced beam element and loading arrangement

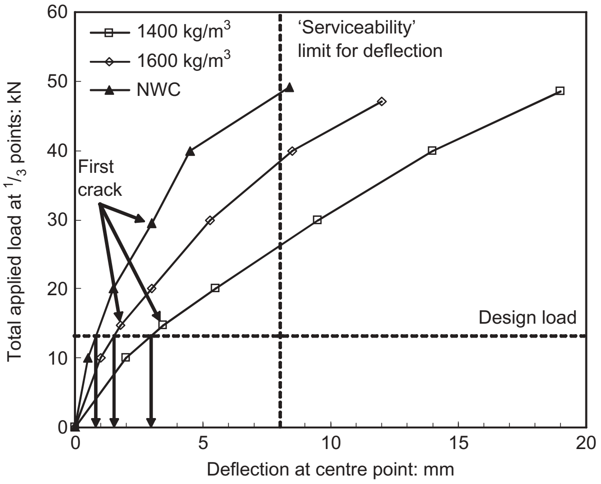

Fig. 8. Load deflection of 1400 and 1600 kg/m³ foamed concrete and NWC beams (mixes 23, 24). (Note: in making these comparisons, it is recognised that the short-term deflections observed in this study have been compared with the BS 8110[13] limit for deflection, which includes the effects of final, i.e. 30 year, drying shrinkage and creep strains.)

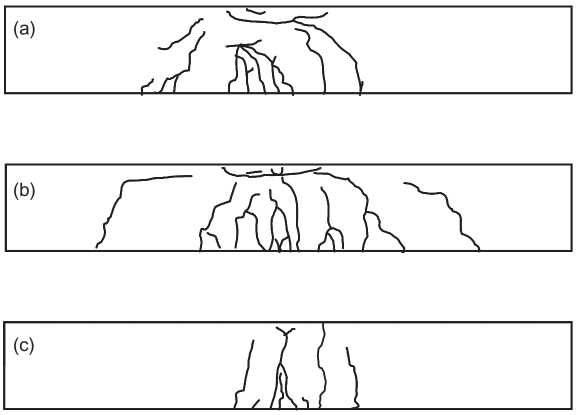

Fig. 9. Crack mapping patterns at failure load of (a) 1400 and (b) 1600 kg/m³ foamed concrete and (c) NWC beams

1·5 mm respectively) were higher than that for the NWC test specimen (0·8 mm). However, all are well within the serviceability limit (*l*/250) of BS 8110[13] and Eurocode 2[31] for deflections becoming noticeable in members that are visible (i.e. in this case 2000/250 = 8 mm). There were no visible cracks on any test specimens at the design load. In making these comparisons, it should be recognised that the short-term deflections observed in this study have been compared with the BS 8110[13] limit for deflection, which includes the effects of final, namely 30-year, drying shrinkage and creep strains. In addition, since the deflection, for a given design moment, is a function of the span, the performance observed can only be considered to apply for beams of around 2 m length or those with a span/effective depth ratio in the order of 6·4. However, it should be noted that these were pilot tests with a small number of elements and, whereas the foamed concrete did behave satisfactorily, there is a need for further work to evaluate long-term behaviour.

The loads at which the first visible cracks (>0·3 mm) appeared on the foamed concrete beams exceeded the design load but were half of that noted for NWC, even though the deflections at first crack of all three beams were comparable.

In all cases, the failure mode was of a tensile nature with the ultimate load at failure being similar in both the foamed FA_{coarse} and NW concrete beams. The deflections at failure of the foamed concrete beams, however, were considerably larger than that of NWC (with the highest value noted on the 1400 kg/m³ specimen), reflecting the lower stiffness and slightly more brittle behaviour of the material.

As regards the crack mapping patterns of the foamed concrete beams (see Fig. 9), both exhibited more flexural cracks, well distributed over a greater length, than on the NWC section. A horizontal crack appeared on the 1400 kg/m³ beam between the two load points at 40 mm distance from the compression face, suggesting slightly more brittle failure,[19] although this was neither sudden nor explosive in nature. The brittleness was more notable on the 1600 kg/m³ element, which failed at a slightly lower load than the 1400 kg/m³ beam. A concrete wedge approximately consisting of the top 50 mm of the compression face between the two load points broke away. As noted above, the addition of fibres, or perhaps additional tensile reinforcement, could offset this behaviour but further tests could not be carried out within the scope of this project.

Following failure, the beams were broken open and no evidence of localised crushing around the reinforcing bar ribs was observed (again in line with previous observations),[19] indicating that minimal or no bond slip had occurred.

Fire resistance issues

Fire resistance is a complex issue (e.g. ranging from the ability to support loads during and after a fire, to significantly reducing heat transfer) and, although it was not considered in this study, the literature[32–34] reports generally good behaviour for foamed concrete. The material has been found to be incombustible, and in a test on 100 mm thick foamed concrete slabs, fire resistance of 2·5 and 3·75 h at 1250 and 930 kg/m³ oven dry densities respectively was observed. Furthermore, there was less strength loss proportionally than normal weight concrete, particularly at lower densities.

Concluding remarks

This study has shown that the use of fly ash in foamed concrete, either as a cement or as a fine aggregate replacement can greatly improve its properties.

More specifically, fine FA had a beneficial effect on significantly reducing heat of hydration, which is an important issue, given the high thermal insulation characteristics of the material. Although the drying shrinkage strains of foamed concrete were high, as would be expected in a concrete with a large paste-phase volume, these were reduced by up to 35% at 1400 kg/m^3 plastic density, when substituting PC with 30% FA_{fine}.

On the other hand, the results demonstrate that sealed-cured 100 mm cube strengths in excess of 25 N/mm^2 at 1400 kg/m^3 plastic density can only be achieved when FA_{coarse} is used instead of sand, although it is recommended that 56 days is a more appropriate design age. In addition to significantly improving compressive strengths, the tensile strengths and E-values of FA_{coarse} concretes were enhanced by the addition of polypropylene fibres, but at some loss of workability.

There are further potential gains to be made by employing fine and coarse FA together, using particle size and chemical optimisation. However, given the high particle surface areas involved with high volume of fly ash in the mixes, advances will be necessary in compatible surfactants and superplasticisers to enable lower water/cement ratios to be used and, thereby, achieve higher compressive strengths at plastic densities lower than 1400 kg/m^3. Such a chemical admixture would also enable the utilisation of fibres without the adverse impact on workability.

Preliminary tests on full-scale conventionally reinforced foamed concrete beams indicated satisfactory load behaviour with similar failure mode to equivalent 25 N/mm^2 normal weight concrete elements. However, the deflections at failure of the 30 to 40% lighter FA_{coarse} sections were up to 2·3 times greater than that of the NWC beam. Given the relatively poor carbonation resistance of the foamed concretes, the use of carbon steel should be carefully considered in reinforced sections. Indeed, the material seems far more suited to fibre-reinforced composite reinforcement, although this was beyond the scope of the present study. Further work is also necessary to look at cyclic loading, crack propagation and situations where the shear capacity of the concrete itself is important.

A consideration of unit cost of foamed and normal weight (NWC) concretes alone does not provide a meaningful comparison of the overall use of the materials. The free-flowing and self-compacting nature of foamed concrete gives similar benefits to self-compacting concrete (SCC), that is, it aids productivity and minimises noise and vibration during placement and compaction. In addition, since the material is typically foamed on site, 1 m^3 of base mix can produce up to 6 m^3 of foamed concrete, thereby reducing the number of truck movements to produce a given volume of material, with concomitant environmental benefits. It has been estimated, however, from informal discussions with producers, that the unit volume cost of foamed concrete is approximately 1·3 times that of NWC and similar to SCC. Finally, the use of FA_{fine} as a cement and the replacement of primary sand fine aggregate with FA_{coarse} also make a significant contribution to more sustainable concrete production.

Overall, the research reported demonstrates that the use of foamed concrete in structural applications is a realistic proposition although it is unlikely that a direct substitution for normal weight concrete should be attempted. In addition, a more innovative approach should be taken to application and reinforcement materials and methods.

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Discussion contributions on this paper should reach the editor by 1 August 2005