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Heat of hydration in foamed concrete: Effect of mix constituents and plastic density

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Abstract

Foamed concrete is a versatile material that can be utilised in a wide range of construction projects, although the majority of it is consumed in high volume void filling applications. The advantages of foamed concrete are its high flowability, low self-weight, minimal consumption of primary aggregate, controlled low strength and excellent thermal insulation properties. However, in applications with high volume to surface area ratios, the relatively high Portland cement contents often used in foamed concrete, together with its high thermal insulating capacity, can lead to significant core temperature rises due to heat of hydration. This paper describes a laboratory study of the (i) temperature development of low-density (600 to 1200 kg/m^3) foamed concrete with Portland cement contents between 300 and 600 kg/m^3, (ii) influence of mix parameters on the temperature profiles, (iii) effect on cube strength, (iv) use of fly ash to ameliorate the problem and (v) provides a method to estimate temperature rise.

Keywords: Temperature; Hydration; Mixture proportioning; Compressive strength; Foamed concrete

1. Introduction

Foamed concrete has found increasingly widespread use in high volume void fill applications, especially when access is problematic, including sealing redundant sewerage pipes, wells, cellars, basements, mines, storage tanks, tunnels and subways [1–4]. Its key attributes are high flowability, self-compacting nature, minimal dimensional changes (compared to conventional granular fill) and low density [3,5,6]. Furthermore, with foamed concrete, there is a reduced demand on primary aggregates (thereby enhancing sustainability), since no coarse aggregate is required in its production and the fine aggregate fraction can be partially or fully replaced with recycled or secondary materials, e.g. demolition arisings fines, fly ash, as well as air itself [7]. Given that most high volume void fills do not have particular strength requirements, foamed concretes with densities in the order of 500 to 600 kg/m^3 or even lower can be used, which produce strengths of around 0.5–1.0 N/mm^2 for Portland cement (PC) contents of 300 kg/m^3 [5].

In addition to void fills, foamed concrete is also beginning to be used in a range of lightweight, semi-structural applications, e.g. bridge abutments, floor and roof screeding, road sub-bases, bridge arch infills etc., where higher strengths are usually required [3,8–11]. To achieve these strengths, plastic densities typically around 1600 kg/m^3 are required [12], but there are advantages in using lower density mixes, e.g. 1000 to 1200 kg/m^3, however, these typically require higher PC contents, up to 600 kg/m^3. It should be noted that the use of water-reducing chemical admixtures in foamed concrete to reduce the water/cement (w/c) ratio tend to cause instability in the foam and consequently are not normally used. In addition, the unusual phase nature of foamed concrete means that small changes in the w/c ratio do not influence strength in the way expected for normal weight concrete. Thus, plastic density is normally the way in which strength is controlled, if specified.

Foamed concrete has excellent thermal insulation properties and a typical thermal conductivity between 0.23 and 0.42 W/mK at 1000 to 1200 kg/m^3 dry densities [5]. However, in applications with high volume to surface area ratios, this,

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combined with relatively high PC contents, can lead to significant core temperature rises due to heat of hydration. If core/surface thermal gradients are large enough, cracking may occur, adversely affecting the concrete performance [13,14] and in extreme cases, may cause some dehydration of the plastic concrete. Furthermore, core temperatures may be retained for a greater period of time in foamed than in normal weight concrete. Whilst these issues have been addressed for normal weight concrete sections, little or no systematic work has been carried out with foamed concrete.

This paper reports the findings of a laboratory-based study that examined the temperature profiles that can develop in foamed concrete due to cement hydration and their effect on cube strength. The use of fly ash to reduce these temperature rises was investigated. In addition, it was assessed whether characteristics of the temperature profiles and strengths can be estimated.

2. Experimental details

2.1. Programme of work

The laboratory investigation considered self-flowing foamed concretes, i.e. spread greater than 200 mm, when tested to the controlled low-strength material (CLSM) method [15], with plastic densities of 600 to 1200 kg/m^3, as these represent common densities used by industry. Where the influence of cement type was considered, fixed water contents were employed. However, because of the high cement contents, a small dosage of superplasticiser was used to disperse the particles in the base mix (i.e. prior to incorporation of the foam).

Temperature profiles of test specimens, subjected to near-adiabatic conditions in an insulated hot-box, were measured. In addition, equivalent cube strengths were calculated from tests on 100 mm diameter cores obtained from the hot-box cured (HBC) samples and compared with strengths of 100 mm cubes from the same batch but sealed-cured at 20±2 °C (reference samples).

2.2. Materials and mix proportions

The cements tested were Portland cement (denoted PC) to BS EN 197-1 [16] and combinations of PC with fine fly ash (denoted FA_f) to BS EN 450 [17] at 20%, 25% and 30% by mass (CII-V and CIV-V to BS 8500-2 [18]). A deliberately high total cement content of up to 600 kg/m^3 was considered, reflecting the maximum quantity likely to be used in foamed concrete and hence, the probable 'worst case'.

The types of fine aggregates used comprised sand (Category G_F85 to BS EN 12620 [19], but with particles >2 mm removed by sieving) and coarse fly ash (denoted FA_c) to BS 3892-2 [20]. A commercially available synthetic surfactant was used in the study (clear, golden liquid with pH=7.5 and specific gravity=1.05 g/cm^3, as supplied by the manufacturers). The chemical and physical properties of the cements and fine aggregate types are summarised in Table 1, whilst the mix constituent proportions of the foamed concretes, derived using the method described by Jones and McCarthy [12], are given in Table 2.

Table 1
Properties of mix constituents used

Property	Cements		Fine aggregates	
	PC [a]	FA_f	Sand	FA_c
Main oxide composition, % by mass				
CaO	64.6	2.5	1.5	2.7
SiO_2	21.0	51.1	78.5	50.2
Al_2O_3	4.9	32.8	10.5	31.3
Fe_2O_3	2.6	4.7	3.0	4.0
MgO	1.2	–	0.9	0.3
SO_3	3.3	0.6	0.1	1.0
K_2O	0.7	1.4	1.6	1.2
Na_2O	0.1	–	2.0	0.2
TiO_2	–	1.6	0.5	1.4
Physical properties				
Fineness, m^2/kg	405	7.2 [b]	– [c]	26.5 [b]
Loss on ignition, % by mass	1.4	5.0	–	7.5
Particle density, kg/m^3	3140	2270	2630 [d]	2070
Water absorption [e], % by mass	–	–	0.9	–

[a] PC phase composition: C_3S=53.0%, C_2S=21.0%, C_3A=8.5% and C_4AF=8.0%.
[b] 45 μm sieve retention, % by mass.
[c] Sand conforming to category G_F85 according to BS EN 12620.
[d] Saturated surface dry density.
[e] From laboratory dried at 20±2 °C to saturated surface dry.

2.3. Preparation of test specimens

Foamed concrete was produced in a rotary drum mixer (free-falling action) following the mixing sequence described by Kearsley [21]. Once a homogeneous base mix was obtained, the preformed foam was prepared (60 g of surfactant per litre of water foamed to a density of 50±5 kg/m^3 in a foam generator), added to the base mix and combined until uniformly distributed and incorporated. The plastic density of the foamed concrete was then measured in accordance with BS EN 12350-6 [22] and values within ±50 kg/m^3 of the target density accepted, which is typical of the tolerance used by industry [23]. If the density was higher, additional foam was prepared and added incrementally until a density within the accepted range was achieved. Mixes with densities lower than the range of acceptable values, i.e. where excess foam was added, were discarded and repeated.

The foamed concrete was sampled in accordance with BS EN 12350-1 [24], poured into the moulds (lined with domestic kitchen plastic cling film) and finished by steel float. The exposed as-cast surface of the specimens was immediately covered with cling film to minimise water loss. The test samples were monitored visually for any bleeding or instability, but in no cases was this evident. Samples undergoing near-adiabatic temperature cycles were then placed in the insulated hot-boxes for testing, within 10 min of completion of mixing. The reference samples were demoulded after 24 h and sealed-cured, i.e. wrapped in cling film and stored in sealed plastic bags at 20±2 °C until testing.

Table 2
Mix proportions of foamed concrete mixes tested

Plastic density [a], kg/m^3		Cement content [b], kg/m^3 (% by mass)		Fine aggregate content [b], kg/m^3		Water content [b], kg/m^3	w/c ratio		Actual/calc. foam [d]
Target	Actual	PC	FA_f	Sand	FA_c		Calc.	Actual [c]	
a) Influence of cement type									
1000	1010	600	– (0)	210	–	190	0.32	0.32	1.02
	980	480	120 (20)					0.32	1.04
	995	450	150 (25)					0.32	1.07
	1025	420	180 (30)					0.33	1.16
1200	1205	600	– (0)	410	–	190	0.32	0.32	1.03
	1220	480	120 (20)					0.32	1.06
	1190	450	150 (25)					0.33	1.13
	1230	420	180 (30)					0.33	1.24
b) Influence of fine aggregate type									
1000	990	300	– (0)	550	–	150	0.50	0.50	0.99
	1030	210	90 (30)					0.53	1.47
	975	300	– (0)	–	365	335 [e]	0.50	0.50	1.13
	1015	210	90 (30)					0.53	1.60
c) Influence of target plastic density									
600	610				85	215		0.57	1.35
800	785	300	–	–	215	285	0.55	0.56	1.21
1000	1020				345	355		0.56	1.17
600	595				85	215		0.58	1.46
800	815	210	90 (30)	–	215	285	0.55	0.57	1.28
1000	1025				345	355		0.57	1.25

[a] Values reported to the nearest 5 kg/m^3. Acceptable variability ±50 kg/m^3 of the target value [23].
[b] Per cubic meter of foamed concrete.
[c] These ratios include any additional free water resulting from foam collapse.
[d] These ratios indicate the degree of foam/mix instability, i.e. ratio nearest to 1.00 is the most stable.
[e] The mass of the FA_c was included in the w/c ratio calculation as a simple way of ensuring that sufficient water was present to 'wet' the high surface area of these particles.

2.4. Test procedures

2.4.1. Foam/mix stability

The stability of the test mixes was assessed by comparing (i) the calculated and actual quantities of foam required to achieve a plastic density within 50 kg/m^3 of the design value and (ii) the calculated and actual w/c ratios [25]. In addition, segregation measurements on hardened concrete were made by quantifying the difference in oven-dry densities between 25 mm slices taken from the top and bottom of a standard 100 mm diameter and 300 mm length cylinder.

2.4.2. Temperature development in a hot-box (nearly adiabatic heat cycle)

Temperature development during hydration was monitored by placing a 165 mm cube foamed concrete sample in an insulated timber hot-box (with 150 mm thickness expanded polystyrene). A Type K thermocouple was pushed into the centre of the test specimen (see Fig. 1). Temperature was recorded at 15 min intervals and the data were used to determine peak temperature and maximum rate of temperature rise and decline. The area between the temperature curves (curves starting at 20± 2 °C and 0 h) and a horizontal axis at datum temperature (assumed for all mixes in this case to be-12 °C [26]) was calculated and the equivalent maturity age of 21,505 (28 days at 20 °C) and 43,010 °C h (56 days at 20 °C) established for each mix. Comparison of data was made on equivalent placing temperature (ambient = 20 ± 2 °C at 0 h). One sample was tested for each mix. (Note: Isothermal hydration tests using conduction calorimetry could not be carried out as the foam could not be incorporated in the testing apparatus without disintegrating/collapsing).

2.4.3. Compressive strength

Compressive strength was measured to BS EN 12390-3 [27] on 100 mm cube reference (sealed-cured) samples, with tests carried out (two for each test age and mix) at 28 and 56 days. Additional strength measurements were made on cores, as described in BS EN 12504-1 [28], taken from the HBC specimens. These were tested at equivalent maturity ages of 28 and 56 days. The 165 mm long and 55 mm diameter cores were taken horizontally and then cut by diamond saw to produce two test specimens with a length/diameter ratio of 1.5. The equivalent cube compressive strength was then calculated using Eq. (1) [28].

$$\text{Equivalent cube strength} = \frac{D}{1.5+\frac{1}{\lambda}} \times \text{Measured compressive strength of core, N/mm}^2 \tag{1}$$

where

D 2.5 for cores drilled horizontally
λ length/diameter ratio of core sample

It should be noted that heat shock was avoided by reducing the test specimens' temperatures to near ambient before testing.

3. Foam/mix stability

The actual to calculated foam and actual w/c ratios (resulting from additional free water from the collapse of foam) for the test mixes are given in Table 2. It was found that, when FA was used, the actual amount of foam required to achieve the target plastic density was higher than the calculated quantity, due to foam collapse during mixing. The reasons for this are somewhat unclear but foam stability is likely to be affected by surface charges, 'free' water content [25] and residual active carbon in the FA [29]. The additional 'free' water contents resulting from foam collapse corresponded to an increase in 'actual' w/c ratios of up to 0.03, which has minimal effect on strength [30]. For a given fine aggregate type and cement type and content, the greatest increases in actual w/c ratios were noted at decreasing concrete densities. Segregation measurements were carried out on the hardened foamed concrete as described earlier and indicated that all test mixes were stable, i.e. densities did not vary more than 50 kg/m^3 compared to the mean value.

4. Temperature profiles

Samples of the temperature curves obtained from the foamed concretes subjected to near-adiabatic heat cycles are shown in Figs. 2 and 3, whilst a range of characteristics obtained from the temperature profiles is summarised in Table 3.

4.1. Effect of cement content

As can be seen in Table 3 and Fig. 2, peak temperatures of between 62 and 82 °C were observed on the 1000 kg/m^3 sand foamed concretes with 600 kg/m^3 PC or PC/FA_f content. These temperatures were reached at between 8.25 and 13.25 h from test initiation, whilst the greatest rates of temperature rise ranged from 8 to 20 °C/h. On the other hand, the temperatures of the 300 kg/m^3 cement content and 1000 kg/m^3 density sand foamed conretes tested did not exceed 50 °C (see Table 3 and Fig. 3). This represents a reduction in peak values of between 26% and 40% compared to the 600 kg/m^3 cement content concretes, for a given cement combination. Furthermore, the lower cement content mixes exhibited significantly slower rates of temperature rise (66% to 78% lower) and a retardation of between 1.25 and 3.00 h in achieving the peak value.

4.2. Effect of cement combinations

In line with normal weight concrete [31], the replacement of PC with fine fly ash had a significant influence on the temperature profiles of the foamed concretes. As can be seen from Fig. 2 and Table 3, the peak temperature of the 1000 kg/m^3 PC reference mix with 600 kg/m^3 cement content and sand fine aggregate reduced by 7%, 17% and 24% with additions of 20%, 25% and 30% FA_f, respectively. The rates of temperature rise decreased correspondingly from 20 °C/h for PC to 14, 9 and 8 °C/h, respectively, for PC/FA_f combinations used and the peaks were noted with a retardation of 3.25, 3.75 and 5.00 h compared to PC. As would be expected, there was a general correlation between FA_f addition levels (% by mass of PC) and (i) reduction (% of PC reference) of peak temperature and (ii) retardation (hours) of peak temperature, showing the effectiveness of fly ash in reducing heat of hydration even in foamed concrete.

At lower cement contents (i.e. 300 kg/m^3), the reduction and retardation of peak values and decrease in rate of temperature rise observed with FA_f addition were significantly lower than those at 600 kg/m^3 cement contents (see Table 3). At 30% FA_f level, the peak values of sand foamed concretes were only 6% lower than the PC mix (compared with 24% at 600 kg/m^3 cement contents), retarded by 3.25 h (compared with 5.00 h) and the maximum rate of rise was 1.3 times smaller (compared with 2.5 times).

Overall, the behaviour of foamed concrete in terms of temperature development due to cement hydration/pozzolanic reaction broadly followed the patterns of normal weight concrete, in terms of FA_f addition [14,31]. The retardation of and reduction in peak temperatures observed are attributed to the dilution of PC with FA_f and the established slower reactions of PC/FA_f concretes. In addition, the dilution of PC causes a

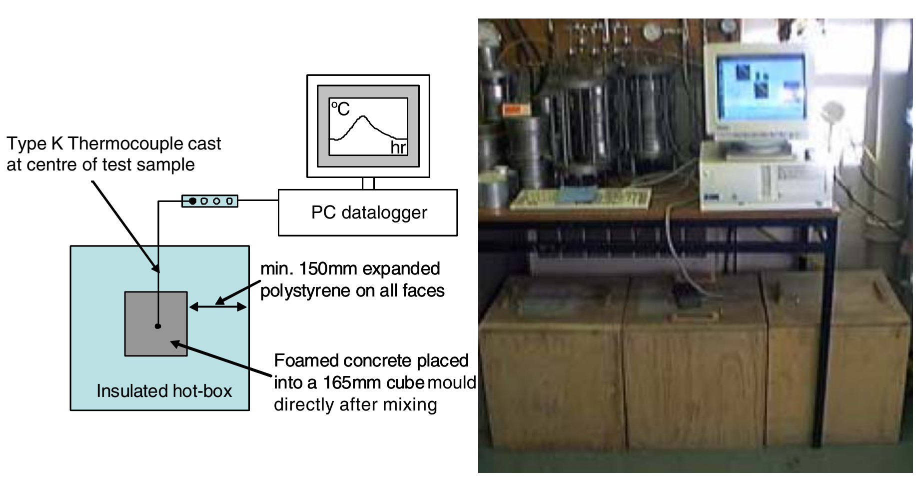

Fig. 1. Schematic layout and illustration of the hot-box test apparatus.

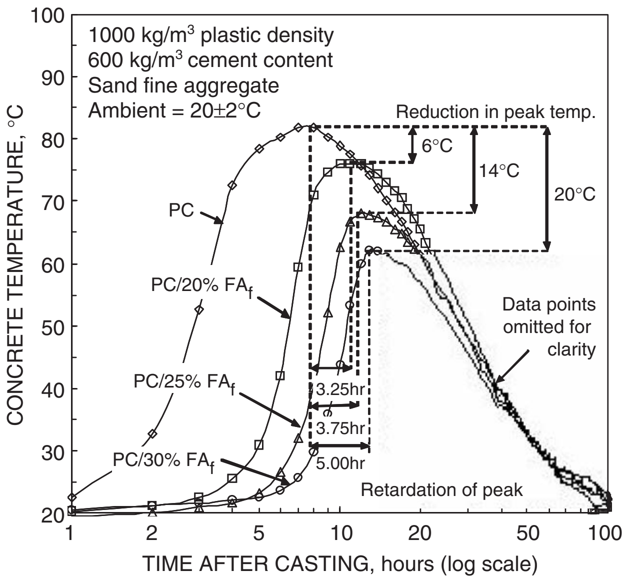

Fig. 2. Influence of FA_f addition to temperature development of 1000 kg/m^3 foamed concretes.

can be seen in Table 2), a greater amount of energy would be required to raise a unit mass of water through a unit change in temperature and hence, the peak temperatures and heat evolution achieved with FA_c were lower [33,36].

In line with the observations in Section 4.2, the peak temperature of PC concrete with FA_c fine aggregate (46 °C) reduced by 26% with 30% FA_f addition (34 °C) and this was noted with a retardation of 2.25 h. However, the temperature development of the PC/30% FA_f mix with FA_c was even lower, possibly reflecting more limited Portland cement hydration and/or pozzolanic reactions due to reduced availability of lime, when fine and coarse FA (hence high concentration of aluminosilicates in solution) are used simultaneously in these mixes [32]. In addition, the restricted hydration of PC particles in the early stages of reaction may be attributed to the adsorption of water onto the large surface area of the FA reduction in the Ca^{2+} concentration in the pore solution, thereby delaying the CH and CSH nucleation and crystallisation, prolonging the dormant period and ultimately retarding hydration [32].

Trials with ground granulated blastfurnace slag (GGBS) were also carried out, which indicated that GGBS can have similar effects to the temperature profiles as FA_f. However, the PC/GGBS combination foamed concretes exhibited difficulties with foam incorporation during mixing, foam bubble coalescence and post-construction foam/mortar segregation and, as a result, this cement combination was not examined further.

4.3. Effect of fine aggregate type

The influence of fine aggregate type on the temperature profiles of foamed concretes was examined on a small range of mixes (sand and FA_c fine aggregate types, 1000 kg/m^3 plastic density, 300 kg/m^3 PC and PC/30% FA_f content, w/c ratio of 0.50), as can be seen in Fig. 3 and Table 3.

The total replacement of sand with FA_c on 1000 kg/m^3 mixes led to a reduction in peak temperature of 3 and 12 °C on the PC and PC/30% FA_f concretes, respectively, and an offset of the temperature curve (i.e. retardation) compared to the sand mixes of up to 4.50 h. This effect of fine aggregate type on temperature profiles is probably due to a combination of factors. As FA_c has been found to have little or no contribution to heat generation during the early (up to 72 h) stages of reaction [33], the reduction in peak temperatures noted with FA_c (for both PC and PC/30% FA_f cement types) is probably due to the significant differences in specific heat capacity of the mix constituents of the two fine aggregate type concretes [13]. Indeed, the specific heat of quartz (740 J/K kg) is very similar to that of FA (800–900 J/K kg) but significantly lower than that of water (4190 J/K kg) [33–35]. As a result, when sand is replaced with FA_c and higher quantities of water are present (from mix proportioning and foam instability as

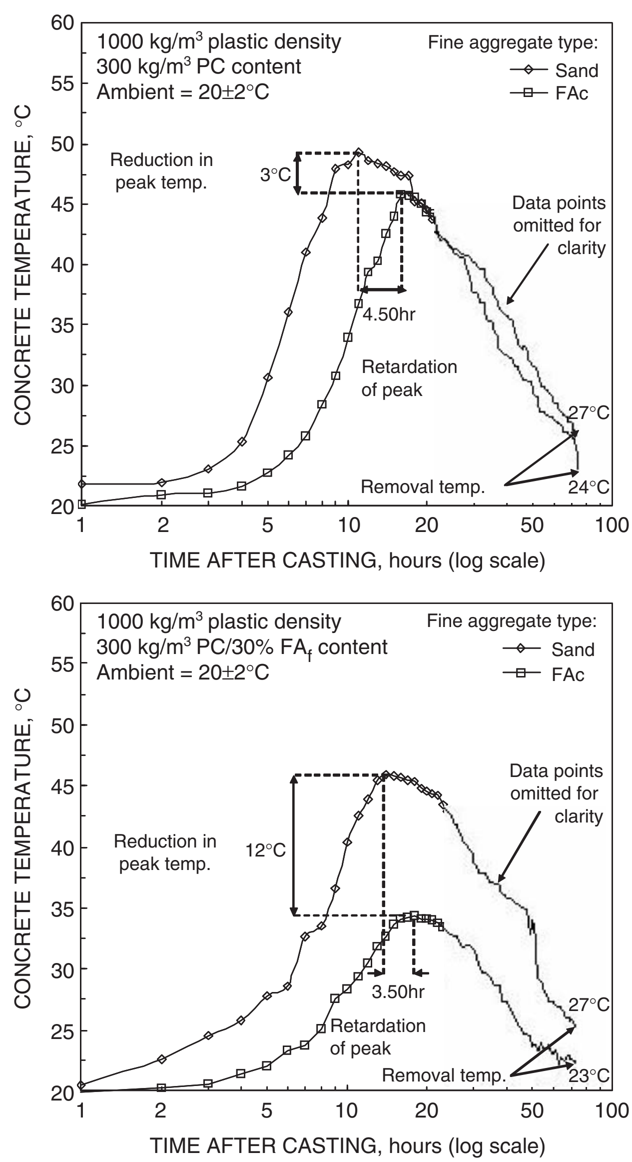

Fig. 3. Influence of sand and FA_c fine aggregate types on temperature development of 1000 kg/m^3 foamed concretes with (a) PC and (b) PC/30% FA_f cement combinations.

Table 3
Influence of cement, fine aggregate type and density on temperature cycles of foamed concretes

Target pl. density, kg/m^3	Fine aggr. type	Cement content, kg/m^3	Cement combination (% by mass)	Peak temp.[a], °C	Time to reach peak temp., h	Max. rate of rise, °C/h	Maturity at 28 days[b], °C h	Equivalent maturity	
								28 days	56 days
a) Influence of cement type									
1000	Sand	600[c]	PC	82	8.25	20	26,165	21.9	49.9
			PC/20% FA_f	76	11.50	14	25,235	23.1	51.1
			PC/25% FA_f	68	12.00	9	25,100	23.3	51.3
			PC/30% FA_f	62	13.25	8	24,865	23.6	51.6
1200	Sand	600[c]	PC	80	9.75	18	26,010	22.1	50.1
			PC/20% FA_f	79	11.00	15	25,630	22.6	50.6
			PC/25% FA_f	77	14.50	14	25,605	22.7	50.7
			PC/30% FA_f	75	15.50	11	25,545	22.7	50.7
b) Influence of fine aggregate type									
1000	Sand	300	PC	49	11.25	4	24,115	24.6	52.6
			PC/30% FA_f	46	14.50	3	24,060	24.7	52.7
	FA_c	300	PC	46	15.75	3	24,045	24.7	52.7
			PC/30% FA_f	34	18.00	1	23,470	25.4	53.4
c) Influence of target plastic density									
600				48	13.50	4	24,320	24.3	52.3
800	FA_c	300	PC	53	9.00	10	24,374	24.4	52.4
1000				45	16.25	4	25,448	25.4	53.4
600				40	13.75	4	22,922	22.9	50.9
800	FA_c	300	PC/30% FA_f	42	16.00	6	24,761	24.8	52.8
1000				35	17.25	4	24,064	24.1	52.1

[a] Ambient temperature=20±2 °C.
[b] Maturity measured from a datum of −12 °C [26], compared with 21,505 °C h at 20 °C.
[c] Total cement content of 600 kg/m^3 is considered the 'worst case' in this study.

particles, thereby restricting its access to the PC grains (a form of 'self-desiccation').

4.4. Effect of plastic density

For a given cement combination and content, it might be expected that the lower density foamed concretes with greater air contents (and hence, enhanced thermal insulating capacity) would result in a higher temperature rise [36], in the same way that insulation applied externally to fresh concrete (e.g. plywood, as opposed to steel, formwork) has been found to increase temperature development for a given cement content [37,38]. Whilst these trends were observed between 600 and 1000 kg/m^3 mixes with 300 kg/m^3 cement contents (see Table 3 and Fig. 4), the performance of the 800 kg/m^3 concretes was not in line with the above ranking. Similarly, such differences in peak temperatures were rather unclear between 1000 and 1200 kg/m^3 concretes with 600 kg/m^3 cement contents.

This, therefore, indicates that, in agreement with the observations in Section 4.3 on the influence of fine aggregate type, the effect of foamed concrete plastic density on temperature profiles is also a result of a combination of factors. More specifically, in addition to the thermal insulating capacity [37,38], the significant differences in specific heat of the individual mix constituents in a unit volume of foamed concrete would also contribute to the trends in peak temperatures and profiles obtained [13,33,36]. It would, therefore, appear that in some cases the influence of thermal insulating capacity is more dominant than the influence of specific heat, e.g. between the 600 and 1000 kg/m^3 concretes, and vice versa, e.g. between the 600 and 800 kg/m^3, between the 800 and 1000 kg/m^3 and between the 1000 and 1200 kg/m^3 concretes.

Another factor influencing the temperature development of the different density foamed concretes is microstructure. It is possible that higher rates of heat loss (hence lower peak temperatures) occur through the formation of convection currents in the lower density concretes, as these exhibit a more 'open' and interconnected microstructure than higher density mixes of the same mix constituents. This is, indeed, reflected in increasing water vapour permeability rates with decreasing concrete densities, as can be seen in Fig. 5 [39]. However, given that the laboratory specimens were subjected to a nearly adiabatic heat cycle in the sealed hot-boxes, it is likely that there was little or no heat convection. The influence of this effect would perhaps be more significant in full-scale pours, where heat can be conducted in the environment. Clearly, further work is required in this area.

4.5. Core/surface differential and risk of thermal cracking

Despite the replacement of PC by up to 30% by mass FA_f, the majority of the HBC foamed concretes exhibited temperature rises in excess of 20 °C above ambient (i.e. peak temperature >40 °C). These results could translate into on-site core/surface differential >20 °C, assuming (i) that the temperature of the foamed concrete surface would be near ambient and (ii) that of the core was similar to that recorded on the HBC specimens. In normal weight concrete, such a temperature

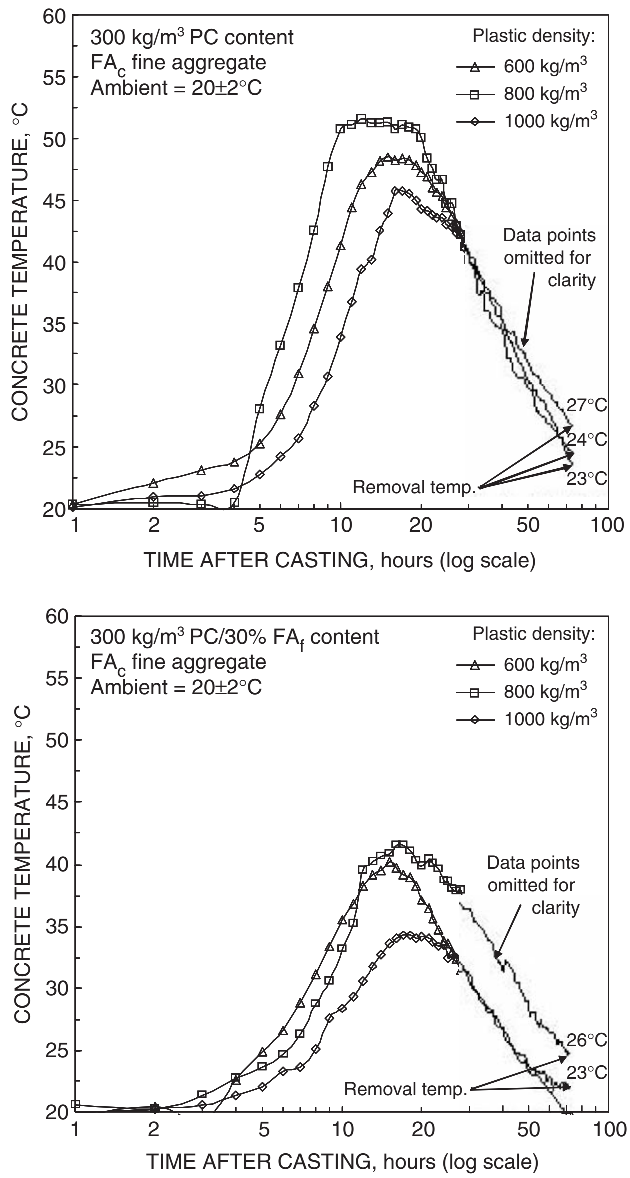

Fig. 4. Influence of plastic density on temperature profiles of foamed concrete.

differential could result in internal cracks during the heating cycle and external cracks on the cooling cycle [37]. Although, to the authors' knowledge, the tensile strain capacity of foamed concrete has not been established, there is a need to examine the effect of these high temperatures, sustained for a significant period of time, and potential of thermal crack formation on full-scale foamed concrete production. This effect could be exacerbated by the large drying shrinkage strain that also occurs with foamed concrete [39].

4.6. Theoretical risk of delayed ettringite formation

The concrete temperature development profile during hydration is the most important parameter in determining susceptibility to delayed ettringite formation (DEF) [40]. This can occur when the temperature is >65 °C and is sustained for more than 12 h [41,42]. The data in Table 3 and Figs. 2 and 3 therefore suggest that there is a theoretical risk of DEF in foamed concrete when high cement contents (in this case 600 kg/m^3, required for semi-structural applications) are used, as temperatures >65 °C were sustained for up to 14 and 16 h by PC and PC/FA$_f$ foamed concretes, respectively.

There are, however, a number of additional factors that influence the risk of expansion due to DEF. These include (i) concrete composition, i.e. aggregate type and grading, use of cement combinations, air content/porosity and chemical composition of the cement (particularly Na_2Oeq and SO_3), and (ii) exposure conditions, i.e. presence of sufficient moisture and ambient temperature [40–42].

Using the threshold values given by the Building Research Establishment [40] in this study, the Na_2Oeq was 0.56%, and SO_3 was 3.3% i.e. placing the foamed concrete in the 'low risk' category. This risk of cracking is also potentially reduced by the large porosity of the foamed concrete, however, it was not possible within the scope of the study to allow sufficient time to determine whether this could be ruled out. For this reason it is recommended that further work is carried out over the longer period to determine whether the use of FA and/or the porosity of foamed concrete are sufficient to remove any risk of DEF-induced cracking in foamed concrete.

5. Influence of heat development rate on foamed concrete maturity

The aim of this part of the work was to address whether self-generated heat in large pours would preferentially enhance the strength development of mixes containing FA, given the well established acceleratory effect that elevated curing temperatures have on the pozzolanic reaction [26]. The effect of temperature development on the maturity of the 600 kg/m^3 cement content PC and PC/FA$_f$ foamed concretes is examined in Table 3. As can be seen, the contribution of the temperature cycle to maturity ranged between 3360 and 4660 °C h for the 1000 kg/m^3 and between 4040 and 4505 °C h for the 1200 kg/m^3 density concretes, which is an increase of maturity of up to 22%, compared with specimens not subjected to nearly adiabatic cycles. In addition, foamed concrete maturity at a given test age reduced by between 2% and 5% with the addition of FA$_f$ and this effect was greater at increasing FA$_f$ levels and on the lower density (1000 kg/m^3) mixes. As a result, PC and PC/FA$_f$ foamed concretes reached equivalent 28 day maturity (21,505 °C h) at 22 days and at between 23 and 24 days, respectively. The corresponding equivalent 56 day (43,010 °C h) maturity was achieved at 50 days and at between 51 and 52 days.

Similarly, the contribution of the temperature cycles to the maturity of the 300 kg/m^3 cement content and 1000 kg/m^3 density foamed concretes led to an advancement of equivalent maturity by around 3 days (up to 2610 °C h). In addition, the difference in 28 day maturity of the PC and PC/30% FA$_f$ concretes ranged from 55 to 575 °C h, whilst the 28 day maturity of the FA$_c$ fine aggregate mixes was up to 585 °C h lower than the sand foamed concretes.

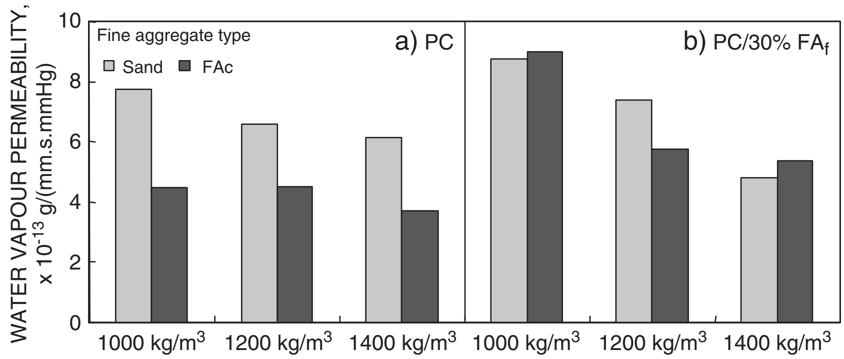

Fig. 5. Influence of plastic density on water vapour permeability indices of 300 kg/m^3 cement content foamed concretes.

Overall, however, it is recognised that further work on the influence of datum temperature (measured, rather than the assumed −12 °C, which is suitable for a specific range of peak temperatures [26]) on foamed concrete maturity is required, as this may vary, given high peak temperatures reached with these mixes.

6. Influence of heat development rate on hot-box cured (HBC) cube strengths

It is well established that, while short periods of high temperature curing can enhance early strength development in concrete, prolonged exposure can have an adverse effect [26]. Temperature rise due to heat of hydration in mass concrete and hot-box curing (HBC) of concretes in nearly adiabatic conditions have an analogous effect [43]. In order to assess the effect of HBC on the strength of foamed concrete, cores were extracted from specimens subjected to nearly adiabatic temperature cycles and tested for strength at equivalent 28 and 56 day maturities. The equivalent cube HBC strengths are compared with those measured on reference sealed-cured (at 20±2 °C) specimens in Table 4.

As can be seen, the equivalent 28 day maturity strengths (calculated from cores) of 1000 and 1200 kg/m^3 PC HBC foamed concretes (peak values around 80 °C) were 14% and 19% lower, respectively, than those of sealed-cured specimens. A number of factors could have contributed to this trend, including the rapid rate of hydration preventing the hydration products from diffusing away from the cement particles and distributing uniformly in the paste/mortar matrix and partial dehydration of the concrete whilst cement hydration is on-going [13,26]. In addition, loss of free water due to incomplete sealing in the hot-box, coring for equivalent cube strengths and disruption of bubble structure at high temperatures, leading to effects in the nature of the bubble wall (expansion) and subsequent microcracks [44] may have also contributed to strength losses. However, this was beyond the scope of this work and there was insufficient data to quantify the effect of these parameters individually.

In contrast to normal weight concrete, where curing at elevated temperatures can accelerate the pozzolanic reaction [45] and enhance concrete strength development [43,46], the majority of the PC/FA_f HBC foamed concretes with 600 kg/m^3 cement content exhibited reduced strengths, compared to sealed-cured specimens, by up to 2.0 and 2.7 times at 28 and 56 days, respectively. Similar trends were observed on the 300 kg/m^3 cement content concretes, with reductions in strength, compared to equivalent sealed-cured specimens, of up to 30% noted on the PC and PC/30% FA_f HBC mixes. The differences in trends between normal weight (NWC) and foamed concretes may be attributed to the effect of high temperatures distorting the bubble structures of foamed concrete [44]. In addition, it may be due to some form of 'self-desiccation' and the formation of a hard, impermeable shell around the PC particles (in the presence of large quantities of FA), which would have an adverse effect on continued hydration, as noted previously.

7. Estimation of temperature rise in foamed concrete

As discussed previously, temperature development in foamed concrete due to heat of hydration is affected by a wide range of parameters. In addition to cement content and type, which are dominant factors in NWC, fine aggregate type and plastic density, for example, were also found to influence the temperature development due to heat of hydration behaviour of foamed concrete. Although the range of foamed concretes considered in this study was not sufficient for the development of a temperature/heat of hydration prediction model for foamed concrete, recommendations on mix constituent selection can be made in order to minimise temperature development in high volume foamed concrete applications. Overall, the use of FA_f is recommended as addition to PC and, in semi-structural applications, where higher strengths are required, FA_c fine aggregate and higher foamed concrete density are recommended. Finally, trial tests are suggested to ensure that, with the proposed mix constituents, the design strength is achieved, whilst temperature rise from ambient in hot-box tests does not exceed 20 °C.

As a general rule of thumb, however, for the PC mixes with sand fine aggregate tested in this study, a simple prediction approach of a 10 °C rise in temperature from ambient per 100 kg of PC per m^3 of concrete under near-adiabatic conditions could be applied for foamed concrete in near-adiabatic conditions. This approach, which is slightly lower than the prediction approach of a 12 °C rise in temperature from ambient per 100 kg of PC per m^3 of normal

Table 4
Influence of cement type on 28 and 56 day sealed-cured and hot-box cured (HBC) equivalent maturity 100 mm cube strengths of 1000 and 1200 kg/m^3 foamed concretes

Target pl. density, kg/m^3	Fine aggr. type	Cement Content, kg/m^3	Cement combination (% by mass)	100 mm sealed-cured cube strength, N/mm^2		100 mm HBC cube equiv. maturity strength [a], N/mm^2		Peak temp. [b], °C
				28 day	56 day	28 day	56 day	
1000	Sand	600	PC	5.8	5.9	5.0	5.2	82
			PC/20% FA_f	3.9	5.8	2.2	3.5	76
			PC/25% FA_f	3.6	5.5	2.9	3.0	68
			PC/30% FA_f	3.5	4.4	2.1	2.5	62
1200	Sand	600	PC	6.8	7.7	5.5	5.7	80
			PC/20% FA_f	4.7	8.0	2.3	3.0	79
			PC/25% FA_f	4.5	6.5	3.8	5.2	77
			PC/30% FA_f	4.3	5.5	7.2	9.3	75
1000	FA_c [c]	300	PC	3.9	6.7	3.4	5.3	46
			PC/30% FA_f	1.4	1.8	1.0	1.4	34

[a] Maturity measured from a datum of −12 °C [26].
[b] Ambient temperature = 20±2 °C.
[c] HBC strengths of equivalent sand fine aggregate concretes are not reported, as the 55 mm dia cores crumbled/disintegrated during extraction.

weight concrete in adiabatic conditions [26], could also be applied conservatively to PC/FA_f cement combination and FA_c fine aggregate foamed concretes.

8. Conclusions

This study has shown that free-flowing, low density (thermally insulating) foamed concretes used in large volume semi-structural applications could potentially result in significant temperature development due to heat of hydration. Indeed, rises in temperature of between 29 and 62 °C from ambient (i.e. 20 ± 2 °C in this study), at rates of rise up to 20 °C/h, were observed on a range of PC and sand foamed concretes subjected to near-adiabatic temperature cycles. Assuming that rises in temperature of this magnitude could be achieved in the cores of large foamed concrete pours, the resulting core/surface differentials could exceed the strain capacity of foamed concrete, thereby causing thermal cracks to form (although the risk of this did not form part of this study).

As expected, the reduction in cement content from 600 to 300 kg/m^3 helped reduce significantly the temperature development (40% decrease in peak value) in foamed concrete during cement hydration. Further reductions in temperature were also achieved with the addition of FA_f to PC at levels in excess of 20% by mass. More specifically, reductions in (i) peak values by up to 24%, (ii) rates of rise (up to 2.5 times lower) and (iii) retardation in achieving the maximum temperature by up to 5 h were observed with PC/FA_f combinations. Similar trends, although on a smaller scale, were obtained with the total replacement of sand with FA_c, with a greater impact noted with the simultaneous use of fine (as addition to PC) and coarse (as sand replacement) fly ashes.

Although the temperature cycles led to an advancement in foamed concrete maturity by up to 6 days, these had an adverse effect on foamed concrete strength (at equivalent maturity). Indeed, the HBC strengths of the majority of specimens (both PC and PC/FA_f combinations) were up to 2.7 times lower than those sealed-cured at 20 ± 2 °C until testing.

Given that the temperature development in foamed concrete was found to be affected by a greater number of parameters than normal weight concrete, existing temperature prediction models could not be used with this material. Whilst this study has focussed on the influence of foamed concrete mix design on temperature development, further work on a wider range of foamed concretes at full-scale would be required before such a prediction model could be developed.

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