Strength Characterisation and Shrinkage Compensation of Lightweight Foamed Concretes

by

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Technical Abstract

The compressive strength and shrinkage behaviour of low-density (800kg/m^3) foamed concrete (FC) were investigated. Foamed concrete is a cementitious material containing a minimum of 20% by volume of mechanically entrained foam. For most applications, an air content between 40 and 80 percent is typical. The production process entails the aeration of a foaming solution to form a stable foam and then the addition of this to cement paste or mortar. The foam bubbles are held within the cement paste until setting, leaving bubble-shaped voids in the hardened material.

Eight foamed concrete mix compositions were tested, three containing primarily ordinary Portland cement (OPC), a further three where a proportion of OPC was replaced by fly ash (FA) and silica fume (SF), and two were half of the OPC was replaced by ground granulated blast-furnace slag (GGBS). These materials develop cementitious properties in the presence of water and ordinary Portland cement, and as waste products from industrial processes are attractive on account of both cost and sustainability considerations.

In addition to these replacements, a further proportion of the OPC was substituted with reactive magnesia (MgO) in each system. MgO of growing interest in the world of cementitious materials. Its behaviour is of particular relevance to foamed concrete as it expands upon hydration. Concrete containing OPC shrinks due to moisture loss as it dries out, and due to Portland cement's reduction in volume through hydration.

Tests were therefore performed to assess how MgO addition would affect the compressive strength of each system of cementitious binders within foamed concrete specimens. Following this, the magnitude of autogenous shrinkage (or expansion) was determined for the OPC and OPC-FA-SF mixes with and without MgO addition. Drying shrinkage is briefly considered for the OPC-GGBS mixes, again with and without the addition of magnesia.

It was found that early strength is reduced approximately in proportion to the amount of Portland cement replaced, regardless of the nature of the replacement. Strength variation between mixes was somewhat lessened after 42 days, as the bulk of the OPC's strength gain had been attained, and the latent hydraulic and pozzolanic activity of the cement replacements had begun to contribute to the strength of the hardened cement paste.

Although many of the mixes exhibited strength much lower than that of FC containing only Portland cement, the strengh-age curves indicated that further strength gain would occur at still greater ages. At 42 days, MgO addition reduces compressive strength in proportion to amount added. Compressive strength in was found to be predicted reasonably well by Hoff's equation, based on specimen density. The OPC and OPC-GGBS mixes obeyed a rule derived by Feret to relate compressive strength to water/cement and air/cement ratios, but the OPC-PFA-SF mixes did not.

Reactive magnesia was found to produce net expansion under sealed conditions. For the Portland cement pastes, the expansion of MgO and the shrinkage of OPC appeared to occur serially: the magnesia's expansion was rapid and short-lived, and was followed by gradual, constant and ongoing shrinkage of the OPC. For the OPC-FA-SF system, there appeared to be some interaction between the combined shrinkage of the three main binders and the expansion of the magnesia. Initial expansions were larger than for the OPC system, and developed more slowly, for equal amounts of MgO addition. Results to date indicate that a greater proportion of this expansion might be retained in the long term, but only continued study will verify this assertion.

Drying shrinkage of the OPC-GGBS system was almost an order of magnitude larger than autogenous shrinkage of the other two systems. Addition of reactive magnesia actually increased drying shrinkage, implying that MgO is far less effective as an expansive agent under these conditions. It is possible that some future compensatory expansion may occur, but again, a longer period of measurement is required before any firm conclusions can be drawn.

Small variations in density were seen to have little effect on compressive strength at the low density of the specimens cast in this work. Void size was found to be independent of cementitious system.

Further work could assess the effect of MgO on autogenous volume change of OPC-GGBS mixes. Alternative methods of obtaining net expansion could also be explored, including cements that produce unusually large ettringite amounts at early ages.

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1 Background and motivation

Concrete is the most-used construction material on Earth: the volume used annually is more than twice that of all other building materials combined [1]. Concrete has many attractive properties, including its inherent fire and corrosion resistance, and its ability to be moulded into practically any shape, but, like any material, its use does have limitations and drawbacks. The manufacture of its principal 'active ingredient', Portland cement, results in the emission of 1 tonne of the greenhouse gas carbon dioxide for every tonne of material produced. In light of this, any material that can offer the same or better properties as ordinary concrete without such an environmental toll is a highly attractive proposition.

As concrete has a low specific strength compared to steel or aluminium, a greater proportion of its strength is employed supporting its self-weight. In structures such as beams and slabs, reducing this self-weight can make construction safer and shorten construction sequences, due to less onerous propping requirements, whilst simultaneously decreasing column and foundation loading. Along with pre-stressed concrete, light-weight concretes (LWC) are one of the dominant means of achieving this reduction. Some of these LWCs use low-density aggregates (which are porous and as such contain a proportion of air by volume) to reduce the concrete's unit weight. An alternative approach is to add gas to the cement paste itself. The gas could be produced by a chemical reaction, for example where finely-divided aluminium powder reacts with a hydration product in the cement paste [2] (in which case the gas produced is hydrogen), or can be held in the mixture by air bubbles, which remain in the mix until the concrete hardens. The latter method, the product of which is called cellular concrete (as the air bubbles form discrete 'cells') or foamed concrete (as the bubbles are delivered to the concrete mix in the form of a foam), is the material considered in this work.

Powers [3] showed that strength of concrete is fundamentally a function of the volume of voids in it. In fact, many porous materials' strengths obey a similar relation of strength and porosity [2]. As LWC densities can vary from 300 - 2000 kgm/^{3}, with concomitant variations in strength, division into three categories has been suggested - see Figure 1. There is considerable industrial interest in improving the strength of those concretes on the border between 'moderate strength' and 'low density', (that is, around 800kg/m^3) in order to utilise them in secondary structural applications. One particular scenario involves a composite lattice girder flooring system, where lattice shear reinforcement is cast into a shallow soffit of high-strength concrete at factory, and the top steel and remaining concrete are added on-site. A low-density concrete, also cast in the factory and filling the space between the precast wormal weight concrete (NWC) and the top of the lattice girders would offer a number of advantages besides the aforementioned reduction in dead load:

- Buckling restraint of lattice chords, allowing a reduction of chord diameter;
- Additional moment resistance and bending stiffness in the temporary case thanks to foamed concrete above the neutral axis, allowing longer unpropped spans and thus more expeditious construction;
- A safer, and level, walking surface for operatives, as the lattice is all but covered.

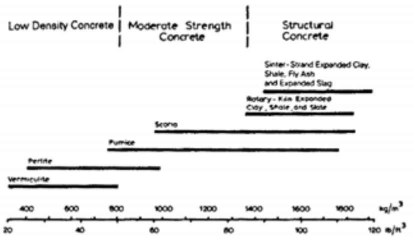


Figure 1: Classifications of oven-dry 28-day density of light-weight concretes and commonly-used low-density aggregates from [2]

Figure 1 suggests three possible lightweight aggregate concretes in the desired density range. Perlite and vermiculite are both minerals that expand prodigiously upon heating into aerated, laminar structures; pumice is found pre-expanded by volcanic activity. All of these aggregates have low strengths in themselves, so an engineer has limited ability to improve the strengths of the concretes they form. These concretes exhibit high to very high shrinkage, and, depending on aggregate size and shape, may not flow well. By contrast, the composition and consequent properties of foamed concrete can be widely customised to meet a specification, and excels with regard to flowability.

2 Foamed Concrete

2.1 Definition, properties and use cases

Foamed concrete (FC) is commonly defined as a cementitious material having a minimum of 20% (by volume) of mechanically entrained foam in the plastic mortar. For most common uses, the air content is typically between 40 and 80 per cent of the total volume [4]. As coarse aggregate is very rarely included, the name is somewhat misleading. The foam's air bubbles do in a sense however perform the `filling' function of coarse aggregate. Fine aggregates are not included in low-density foamed concrete [5], as they would have a propensity to settle, and reduce strength below a useful level because they would decrease the proportion of cement.

Foam addition is accomplished by either the 'inline method', which is only suitable for large pours on sites with volumetric mixing equipment, or by the 'pre-foam method', which is less accurate and cannot produce such large quantities, but is practicable in a laboratory without undue difficulty. A foam generator produces a stable foam that is then added to cement paste or mortar. The mixing action of the concrete mixer is relied upon to blend the mortar and foam.

Foamed concrete does not require compaction, is self-levelling, and can be pumped to significant distances and heights. At time of placement, the advantages of FC on the project schedule are therefore similar to those of self-compacting concrete: productivity is increased and noise and vibration are largely eliminated in the absence of compaction equipment. The foam requires a small volume of surfactant, an ample supply of water and compressed air, all of which are less expensive and easier to transport to site than substantial quantities of aggregate. From a sustainability point of view, removing the need to quarry and process aggregates saves considerable energy, as does the elimination of compaction equipment from the embodied energy of the process. Foamed concrete is a good insulator of both sound and heat: its thermal conductivity is 3-30 times smaller than that of NWC [2,5].

Current usage of foamed concrete includes, but is not limited to:

- Large-scale filling of disused underground spaces;
- Rapid highway trench reinstatement;
- Backfill behind bridge abutments;
- Sandwich wall panels [6];

- Various domestic and industrial sound insulation, heat insulation, and fire protection applications;

- Soil stabilisation on embankment slopes.

2.2 Existing research

Numerous studies have reported on the compressive strength of various foamed concrete mixes [7{12], although few consider densities as low as 800kg/m^3. Kearsley and others have found that strength is primarily a function of dry density, and little affected by the type of cementitious material used [13] (see Section 3.1). Shrinkage in foamed concrete is known to be a substantial problem, as cement content and water/cement ratio are both high. In NWC, the aggregates locally restrain shrinkage [14], but without aggregates, foamed concrete has the propensity to shrink between 4 and 10 times as much as it dries [4]. Lim et al. [9] have suggested that, contrary to ordinary concrete, foamed concrete exhibits an increase in strength when water/cement ratio is increased from 0.6 to 0.8, although such an increase in water content is likely to have an adverse effect on drying shrinkage.

In large-scale pours of FC, it is unlikely that anything but the outer layer of concrete is able to dry out, so the central portion of a foamed concrete mass will be effectively sealed off from the outside environment Moreover, in many applications, foamed concrete will be enclosed on all sides by other impermeable materials, for instance in an underground void or between normal-weight concrete slabs. It is therefore most appropriate to consider the behaviour of the material under conditions where it cannot exchange moisture with its surroundings. Shrinkage under these conditions is known as autogenous shrinkage, and although drying shrinkage has been investigated to some extent [15], autogenous shrinkage has not been studied thus far. Jones [16] found that drying shrinkage is highest at low densities (that is, large air contents) and at high Portland cement contents for foamed concretes. There is no literature currently available that considers techniques to compensate for either type of shrinkage.

Fire resistance has been found to be at least as good as regular concrete, as there are a great number of air-solid interfaces for radiative heat transfer to traverse, and because thermal cracking is reduced without the presence of aggregates of varying thermal expansion coeffecients [12].

Foamed concrete's high cement content means that the heat evolution per unit volume is large, and this, coupled with the insulating effect of the foam's air bubbles, means that temperatures within the first day can vary quite rapidly in cast specimens [17]. These variations set up steep temperature gradients, which could lead to through-depth cracking as hydration generates heat, and voiding as cooling causes shrinkage. There is evidence that substitution of cement for other cementitious materials serves to reduce the peak heat of hydration [8], an effect already exploited in normal weight concrete.

Extensive research has been conducted into how Recycled Secondary Aggregates (RSA) could be used to further reduce the cost of manufacture of this material, whilst simultaneously reducing its embodied carbon [15, 18]. These aggregates come from a variety of sources (eg. demolition fines, foundry sand, crumb rubber) and have particles between 0.1 and 3 millimetres in size, so function as a substitute for traditionally-sourced fine aggregates.

2.3 Laing O'Rourke's specification

This work was sponsored by Laing O'Rourke (LO'R), whose target foamed concrete properties are as follows:

1. Density < 800 kg/m^3
2. Long-term strength > 4MPa
3. Void size < 0.5mm
4. Lightly expansive □ 0:5% = 5000□10$^{□6}$
5. > 25% long-term strength after 20 hours at 20℃
6. Closed voids for low water absorption

2.4 Reseach objective

The aim of this work is to investigate how the binder systems' hydration reactions and their interactions affect compressive strength and volume changes under sealed-curing conditions (autogenous shrinkage). A potential use of reactive magnesia as a means of compensating for any shrinkage observed will then be investigated.

3 Theory

Before we can look in detail at the experiments undertaken, let us consider each of the cementitious materials that will be employed.

3.1 Materials

Ordinary Portland Cement (CEM I 52.5N) can be thought of as the basic `active ingredient 'in all concrete. Often referred simply as OPC, it consists of various calcium silicates and aluminates, plus other minor components. The calcium aluminates are responsible for the initial setting of the paste. The calcium silicates undergo a complex hydration/hydrolysis reaction in the presence of water to produce a compound of approximate composition $(CaO)_3(SiO_2)_2(H_2O)_3$, usually referred to as C-S-H. This reaction continues for many years after initial placement, albeit at an ever-decreasing rate, as the outside of cement particles have reacted, but the less-accessible centres remain unreacted, and it is this which accounts for concrete's prolonged yet gradual strength gain with time. Calcium Hydroxide, $Ca(OH)_2$, is released during the reaction, and is responsible for the pore water's alkalinity, and will participate in reactions with the aforementioned Calcium and silicon compounds.

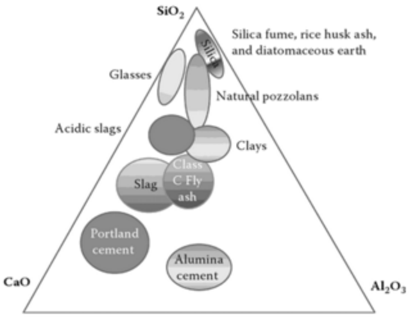


Figure 2: A schematic of the proportions of the three main compounds in OPC, GGBS, FA and SF, from [1]

Until quite recently, Portland cement was regarded as the major cementitious material, with other possibilities available but considered inferior. However, as accessibility and understanding increase, the use of alternative materials is becoming viable in light of both reduced cost - both to the environment and to a project budget - and of desirable improvements to fresh properties, strength, and durability. Four of these were used in this work: fly fsh, ground granulated blast-furnace slag, silica fume and reactive magnesia. With the exception of magnesia, these materials are all composed of three main compounds in different proportions (Figure 2).

Fly ash, (FA) also known as Pulverised Fuel Ash, is a natural pozzolana, that is, a material that has little or no cementitious value itself, but can react with calcium hydroxide to form compounds with cementitious properties. The ash consists of very fine spherical particles of ash precipitated from the chimneys of coal-fired power plants. Physical and chemical properties of fly ash are quite variable, as they depend on the combustion temperature and the nature of the coal being burnt. Because $Ca(OH)_2$ must be present for the cementitious properties of FA to be realised, strength contribution is delayed, and the rate of this is partly dependent on the rate of reaction of the OPC. It may therefore take a year for the OPC-FA system to attain strength parity with OPC alone, although the strength will continue to increase after this time. A cement paste is most strengthened in the long term by replacement of 25% of the OPC with FA, and by 20% in the medium term [19]. Shrinkage behaviour is not thought to be affected by FA content [2]. Inclusion of fly ash improves workability at constant water content, partly due to the 'ball-bearing effect' of particles passing easily over each other on account of their spherical shape, but mostly because the small, charged particles adhere to the surface of the larger cement grains, preventing them from flocculating. Above around 20% cement replacement, no further workability improvement takes place, as all cement grains are already covered [20]. Fly ash inclusion has been reported to significantly reduce the peak temperature arising from exothermic hydration reactions [17, 18].

Ground granulated blast furnace slag (GGBS) is a quenched and then finely ground silicate melt that has been separated from molten iron in a blast furnace. It is rich in silica and alumina, and thus has latent hydraulic and sometimes fully-hydraulic properties, dependent on its lime content. Because GGBS's CaO content is lower than that of OPC, it relies on the action of $Ca(OH)_2$ from the hydration of OPC to begin hyrdration. This means that the initial rate of reaction is very slow, and that strength gain continues over a long period. This means that the release of heat is slowed, and thus the peak temperature in concrete containing GGBS is lowered. Because alkali solubility and thus rate of reaction increase as temperature rises, the centre of a large concrete block will gain strength quicker due to OPC's heat output and the concrete's insulating effect. This strength gain will not be reflected in smaller cubes. 50% replacement of cement by mass is generally thought to result in the greatest long-term strength [21]. Shrinkage of concrete containing GGBS may be initially greater that in regular concrete, but overall shrinkage is not adversely affected [2].

Table 1: A summary of cementitious materials used in this work

Material	Specific gravity	Particle size (μm) [2]
Portland cement [22]	3.1	3 - 45
Fly ash [23]	2.4 [24]	1 - 35
Silica fume [25]	2.2 [26]	0.03 - 0.3
GGBS [27]	2.9 [2]	< 45
Magnesia	3.6 [28]	< 45 [29]

Both GGBS and FA retard the initial set of the concrete by around 30 minutes [2], which could be of some benefit for pumping foamed concrete over long distances. Both of these materials aid in particle packing on account of their fineness, and so reduce the size of capillary voids, which has the effect of reducing permeability.

Silica fume (SF) is a highly reactive pozzolana produced as a by-product in the manufacture of silicon alloys. It consists of extremely fine particles of amorphous SiO_2. Two thirds of the SF present typically reacts within 3 days; very little strength gain is seen after 56 days [30]. In concretes, Silica Fume contributes to high early strength by two mechanisms: (i) pozzolanic reaction with calcium hydroxide, rapidly producing C-S-H, (ii) greatly improved packing of particles against the faces of aggregates, where high porosity is normal and a known source of weakness [2]. The early-age strengthening effect is therefore expected to be less dramatic than in NWC, as without aggregate, only (i) applies. Shrinkage can be 10-20% greater than in regular concrete [30].

Magnesium Oxide (MgO) is a key component in an emerging family of cements which are capable of delivering improved technical and environmental performance over Portland cement. Its most reactive form is also known as light-burned or caustic-calcined magnesia, and has the highest specific surface area of all forms. Reactive magnesia is most often manufactured by thermal decomposition of magnesite or other magnesium-containing minerals at 700 - 1000 ℃. This temperature, being far lower than that required to produce Portland cement clinker, means that MgO carries less embodied energy. Global reserves of magnesite are rich, and moreover, magnesium-based industrial by-products are available for utilisation [31], making the excellent sustainability credentials of this material clear. On contact with water, magnesia transforms to brucite, $Mg(OH)_2$. This is a similar reaction to the hydration of calcium oxide to make $Ca(OH)_2$, in that both reactions yeild products that are less dense, and therefore larger, than the reactants. Whilst CaO begins to react within hours of initial placement, providing the characteristic 'bump' seen in Figure 3, magnesia's reaction rate depends on its specific surface and crystallinity [32], and may take place more slowly.

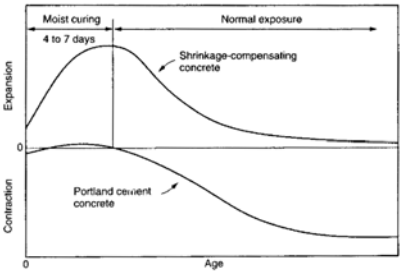


Figure 3: Typical shrinkage compensation behaviour (from [2])

3.2 Mix design

The design of the mixes was done on the basis of a fixed density - that is, the total mass of solids and liquids in a unit volume. The target dry density for all samples mixed in this work was 800kg/m^3, as given by the LO'R performance specification above. The cement content can be inferred from the chosen water/cement ratio, as there is no aggregate, and the ratio of their densities is known. Water/cement ratios of between 0.4 and 0.6 are typical for foamed concrete, but 0.5 was selected, as the most common choice of industry and researchers alike [33].

Since we have only water, cementitious material (here only OPC) and foam are in the mix, and assuming the foam has zero density (as reccommended by The Concrete Society's Good Concrete Guide 7 [5]), we have

$$D = w + c \tag{1}$$

but

$$w = 0.5c \tag{2}$$

so

$$c = \frac{D}{1.5} \quad \text{and} \quad w = \frac{D}{3}$$

We then find f, the foam volume in litres needed to fill the remainder of the unit volume:

$$f = 1000 - \left(\frac{c}{3.1} + \frac{w}{1.0} \right) \tag{3}$$

Where c is the mass of cement clinker in kg, w is the mass of water in kg, and D is the desired density in kg/m^3. 3.1 and 1.0 are the specific gravities of cement and water.

A similar procedure can be carried out for more complex mixes with cement replacement, as long as the ratio of masses of this material and cement are known. Then, (1) is augmented with more terms on the left hand side, and (2) is replicated for each non-cement ingredient.

There is, however, a complication: due to wide variation in chemical composition, the amount of water required to achieve a certain level of hydration is different for each binder material, and information on this water demand is not easily available. This effect is taken into account in European standards by the K-value concept [24,34]. Kearsley and Wainwright describe this as a 'cementing effeciency' [13]. Although in reality many factors govern the strength contribution of cementitious materials, it is necessary to develop a simple rationale for preliminary mix design which gives a constant value of cementing efficiency for each material. This is the approach taken by EN 206-1 to ensure that concrete containing these additions is sufficiently strong and durable, so, whilst not constituting a comprehensive model of strength contribution, is to some extent representative of empirical experience.

For all concrete, there is therefore something of a 'double baseline' for minimum water/(cementitious material) ratio: water must be sufficient both for full hydration and for sufficient flowability, as increasing water content increases the ease with which the mixture's particles can flow past each other. Two further constraints exist for foamed concrete: an overly wet mix will cause foam collapse, whereas too dry a mix will prevent the foam from blending fully with the cement paste.

Table 2: Mix compositions, expressed as a percentage (by weight) of total cementitious material

Mix	OPC (kg/m^3)	OPC %	FA %	SF %	GGBS %	MgO %
FC6a	533	100	-	-	-	0
FC6b	501	94	-	-	-	6
FC6c	469	88	-	-	-	12
FC7a	400	70	20	10	-	0
FC7b	367	64	20	10	-	6
FC7c	296	58	20	10	-	12
FC8a	286	50	-	-	50	0
FC8c	206	38	-	-	50	12

Table 2 shows the percentage by mass of the various ingredients in each of the 8 experimental foamed concrete batches produced. These were chosen to investigate how MgO addition affected the strength and shrinkage of three different cementitious systems: OPC alone (FC6-), OPC/PFA/SF (FC7-), and OPC-GGBS (FC8-). The proportions of fly ash, and silica fume and ground granulated blast furnace slag were selected with reference to the findings of Dubovoy [21] and Odler [19]. The latter two mix families are expected to be rather weak initially compared to the FC6- mixes, with more gradual strength gain giving competing strengths after 28 days. The air content varied between 53% and 60% by volume, depending on the proportions of each material, as their densities are rather different, (see Table 3.1).

3.3 Predicted strength

Several authors have proposed formulae relating compressive strength to porosity [35], but porosity is a difficult value to correctly estimate, or to measure outside of a laboratory, as it depends on degree of hydration. Hoff [7] assumes an average proportion of water bound by hydration by cement, and thus gives an single strength-density relationship for foamed concrete:

$$\frac{\square_y}{\square_o} = \square \frac{d_c}{1+k} \square_b \square \frac{1+0{:}2p_c}{p_c\square_w} \square_b \qquad (4)$$

where $\square_y$ is the predicted strength at the overall concrete density d_c, $\square_o$ is the theoretical strength of zero-porosity concrete, k is the water-cement ratio (by mass), p_c is the specific gravity of cement, and $\square_w$ is the unit weight of water. b is an empirical constant. The strength of zero-porosity concrete is difficult to define, but has been used as another experimentally-derived parameter [35]. This equation essentially links strength to density and water/cement ratio. Hoff gives values of the two parameters for cements of different strengths, and at our target density these predict compressive strengths between 3.8 and 8.2 N/mm^2. This relation by definition implies no effect of cement type on strength.

4 Experimental method

4.1 Foam production

Central to FC manufacture is how the foam is produced. A dry foam generator was selected (Figure 4), which feeds compressed air and a commercially available foaming agent solution through a venturi system to form a stable foam similar in both appearance and behaviour to shaving foam (Figure 5). This agent is a surfactant, that is, a solution of chemicals that alter the surface energy of an air-water interface, thereby facilitating the formation of air bubbles. Protein agents are preferable to available synthetic products, especially in lower-density foams, as they result in a stronger final product [5]. The surfactant was mixed with water in a ratio of 1:25 by volume.

Figure 4: Propump Engineering Ltd's JFG200 foam generator.

Figure 5: Freshly produced foam.

4.2 Mixing and casting

An overview of the entire foam concrete manufacturing process is given in Figure 8. It was found that using a inclined-drum mixer such as is often seen on construction sites (Figure 6) gave the most effective mixing action, on account of its fairly gentle folding action. Vertical-axis lab mixers stir rather than fold, which tends to collapse the foam and leave it sitting on top of the cement paste unmixed - see Appendix B for earlier and less successful mixing methods.

Mould release oil is thought to affect the properties of the concrete [4], and adheres strongly to steel surfaces [8]. The material's very low early strength makes the cubes difficult to demould without damage [5], so standard steel moulds are unsuitable for production of cube samples. Instead, single-use expanded polystyrene (EP) moulds (Figure 7) were selected, as they are simply peeled off just prior to testing, whilst helping to protect the specimens and keep them moist. In addition, their insulating property helps to more realistically model the conditions found in the bulk of a large foamed concrete pour. It should be noted that these moulds are unlikely to be fully compliant with BS EN 12390-1 [36]. For the casting of shrinkage prisms, possible impact on strength is not relevant, so regular steel moulds were used.

Figure 6: The cement mixer used.

Figure 7: Foamed concrete at time of pouring, before floating.

All mix components were weighed out to the nearest 10 g, and then the dry ingredients were mixed for 1-2 minutes until fully blended. The measured water volume was then gradually added whilst the mixer was running. The mixer was periodically stopped to scrape unmixed powders from the sides and mixing blades. This procedure continued until homogeneity. The foam generator was then started, adding the predetermined volume of foam to the running mixer via containers of a known volume. A measurement was made of the foam density, by comparing such a container's full and empty mass, and gave values of 71 - 95 kg/m^3.

For each mix, twelve 100 x 100 x 100 mm cubes and three 500 x 500 x 100 mm shrinkage prisms were cast. The polystyrene cube moulds and steel shrinkage-prism moulds were filled with a single layer of FC. The moulds were not vibrated or compacted, but each was gently tapped a few times on its base to allow air trapped against sharp corners to escape. The top surfaces were skimmed and smoothed off with a trowel, and then the plastic density was measured by comparing the weight of empty and full moulds.

Casting and curing procedures in BS EN 12390-2 [37] were followed when relevant, and where there no established methodology was available for foamed concrete specifically. In particular, the shrinkage samples were demoulded after 24 hours, which was found to be the age where specimen strength was great enough, yet mould adhesion had not reached a troubling level. As mentioned above, the EP moulds were removed from the cubes just prior to testing.

Finally, the cubes were labelled, and then sealed-cured in polymer bags, in a room of temperature 19 ± 2 ℃ and 50 ±10 % relative humidity.

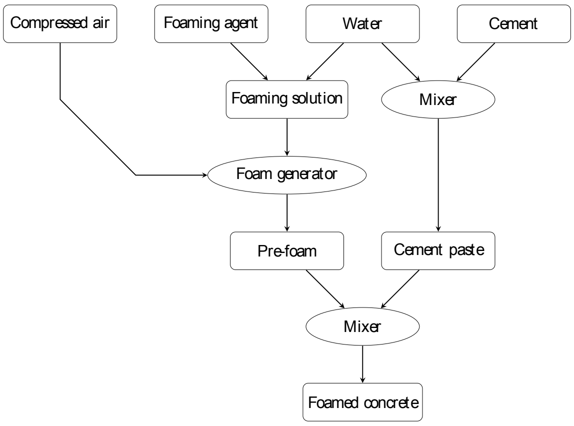


Figure 8: The processes carried out to manufacture foamed concrete.

4.3 Tests on fresh properties

4.3.1 Plastic density

During blending and casting, the mechanical action inevitably causes some volume loss, as bubbles collapse or coalesce. Dry density is reported to be 50 - 200 kg/m^3 less than that wet density as the material desorbs some mix water [5, 8], although smaller changes were seen in this study. As the degree of densification that will occur during mixing is difficult to predict, so the foam volume calculated using Equation 3 often proved insufficient. Once the foam and cement paste were blended to homogeneity, the density was checked by weighing 1 litre of the mixture. A target mass of 825 - 850 g was found to yield a dry density in the right region - although a variation of 50 kg/m^3 or more throughout the batch was still found. If the mass was greater than 850 grams, more foam was added, and the measurement repeated. A tolerance on plastic density was set at ±50 kg/m3 of the target value, which is typical of industry practice for foamed concrete production [8].

4.3.2 Slump flow

There is no standard flowability test for Foamed Concrete, and whilst fresh properties are not the focus of this work, it was deemed important to gain a comparison of how well the different mixes flowed when fresh. Ease of pumping over long distances is an attractive feature of foamed concrete that should be retained in any viable mix design.

A plethora of techniques and equipment exist to characterise many aspects of flow behaviour. Here, the slump-flow test (BS EN 12350-8 [38]) was selected for reasons of equipment availability and ease of execution. It is an attractive test because it could be easily carried out on site as a similar exercise to a slump test for normal weight concrete (see Figure 9) - although no inference of likely hardened properties could be drawn. The test is typically used for self-compacting concrete (SCC), but because of the similarities in both materials' fresh behaviour, it has been applied to foamed concrete [15]. In this test, a slump test cone's contents spread out into a thin disk (Figure 10), and the diameter of this spread is measured as well as the time taken for the material to spread to diameter of 500mm (known as the t_{500} time). The spread diameter is categorised as one of three slump-flow classes, each more flowable than the last, and the result is an indication of the 'filling ability' of the material. The t_{500} time is placed in one of two viscosity classes, as this time gives an indication of flow speed and viscosity.

In literature for self-compacting concrete, slump-flow class SF1 is appropriate for casting by a pump-injection system, whereas SF2 is suitable for many normal applications [39]. In light of this, SF1 is considered adequate for foamed concrete, whilst SF2 is ideal. Foamed concrete of slump-flow class SF3 could be considered for mix refinement with a view to decreasing the water content, as this may prove to be an unnecessary amount of flowability for most uses. VS1/VF1, the lower viscosity class, indicates very good filling ability and good self-levelling capability, and is desirable for foamed concrete, which is often pumped long distances. It is worth noting that the distance FC is to be pumped over will dramatically impact the degree of flowability required.

Figure 9: The slump cone and base plate used for the slump-flow test. Note the inscribed circle for measuring t_{500} time.

Figure 10: The result of a slump-flow test: a circular disk of material.

4.4 Tests on hardened properties

4.4.1 Compressive strength

Three cubes were tested using a Controls C4600 2000 kN servo-hydraulic compression frame at a loading rate of 3000 N/s, in accordance with BS EN 12390-3 [40] at 1, 7, 28 and 56 days. Three cubes per mix composition were tested at each age. Because of the density variance in each batch, an effort was made to test cubes of different densities at each age in order to find a representative strength for the batch overall.

4.4.2 Shrinkage

After demoulding, the shrinkage speciemns were then completely covered with aluminium foil tape within a few hours of demoulding, which had the effect of sealing them (Figure 11), thereby enforcing autogenous shrinkage conditions. A measurement of the sample length was taken relative to a reference bar (Figure 12), and this first reading taken at 1 day gave the original length for calculation of shrinkage strain. Measurements were taken daily to begin with, and then with gradually reducing frequency as the rate of length changed decreased. The mass was measured with approximately every other shrinkage measurement, to ensure the moisture loss from the supposedly-sealed specimens was not excessive.

On two occasions, it was not possible to seal the prisms soon enough after demoulding. This gave a serendipitous opportunity to compare the drying shrinkage of two mixes (see Section 5.5).

Figure 11: A shrinkage prism covered in foil tape. Note the protruding end pins.

Figure 12: Shrinkage measurement frame, reference bar and displacement gauge.

5 Results and discussion

5.1 Slump flow tests

Referring to the definitions given in Section 4.3.2, all the mixes in Table 3 can be seen to have adequate flowability or better. All t_{500} times were less than half a second, at which point the start- and stop-time errors become as large as the duration to be measured. As all these times were substantially less than two seconds, the viscosity falls into class VS1/VF1, indicating that the flow speed is satisfactorily high. Both of these findings generally agree with the experience of pouring the mixes into moulds (see Figure 7).

One trend that is clear from the mixes' slump flow classes is that greater substitution of OPC for other materials tends to decrease flowability. It would appear that the very small particles in silica fume's high demand for water to wet their very large surface had the most profound effect on this property. Fly ash's reputed ability to improve flowability as mentioned in Section 3.1 was not observed in this study. The addition of foam to the cementitious paste appears to have the effect of regulating flowability: stiffer pastes were thinned whilst the thinnest pastes were made somewhat more viscous.

Firm conclusions should not be drawn from the single tests performed, as flowability might vary within one batch, and may not be replicated on production of the same batch at another time. The impact of composition on flow properties could be usefully further explored, as could the effect of adding an equal foam volume to cementitious pastes with a range of initial flowabilities.

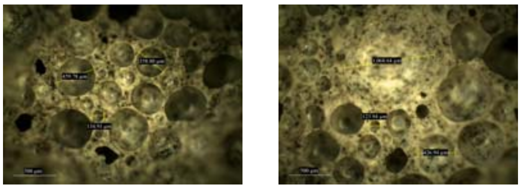
Table 3: Slump-flow test - diameters and classes.

Mix	Slump flow (mm)	Slump-flow class
FC6	809	SF3
FC6b	814	SF3
FC6c	701	SF2
FC7a	575	SF1
FC7b	612	SF1
FC7c	710	SF2
FC8a	669	SF2
FC8c	652	SF2

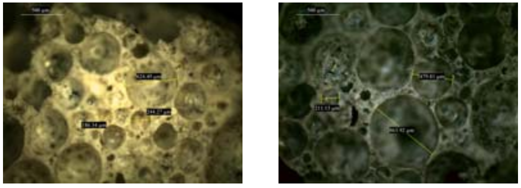
5.2 Void structure

Figure 13 shows that the bubble structure is relatively unaffected by the cement paste composition. Very few voids larger than 1mm (such as in Figure 13(h)), and none below 100μm were found, with a median diameter of around 500μm. This is in line with values in the literature [2,5]. Figure 13 (d) & (e) show a more signs of foam collapse and coalescence than the other mixes. For the vast majority of observed voids, however, the dividing walls of hardened cement paste appear to be smooth and unbroken.

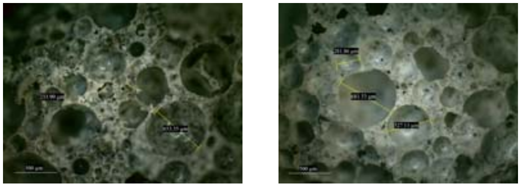
With a few exceptions, bubbles were observed to be uniformly spread and quite uniform in size throughout the cubes. There was little evidence of bubbles rising to the top surface before setting had completed.



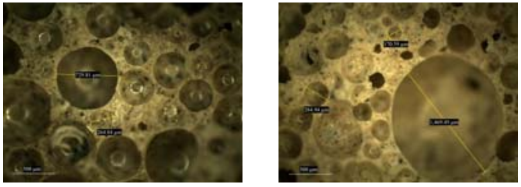
(a) FC6a (b) FC6b



(c) FC6c (d) FC7a



(e) FC7b (f) FC7c



(g) FC8a (h) FC8c

Figure 13: Light microscope images of the 8 mixes' void structures.

5.3 Compressive strength

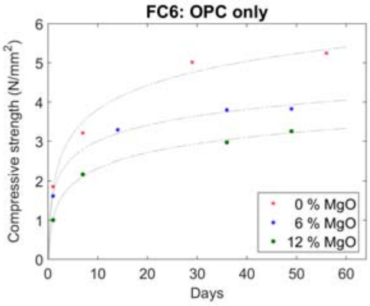


Figure 14: The strength development of FC6a, FC6b and FC6c.

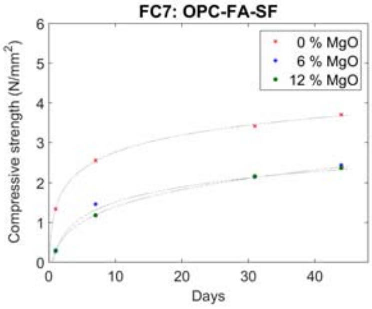


Figure 15: The strength development of FC7, FC7b and FC7c.

The compressive strength test results are shown in detail in Figures 14, 15 and 25, and summarised in Figure 17. As the long-term strengths were measured across a range of a few days, a value of 42-day strength was interpolated for each mix to facilitate comparison

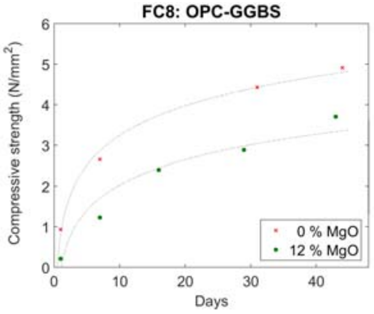


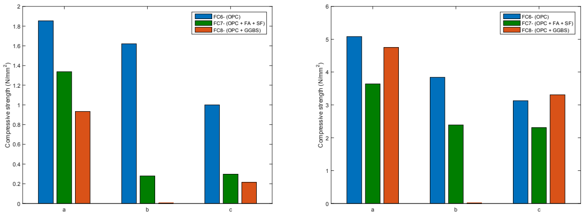
Figure 16: The strength development of FC8a and FC8c.

between them. The error on these values is small, as by this age the strength gain of all mixes was quite slow and relatively close to linear.

In general, the pure OPC mixes showed the greatest strength at all ages. Initially, OPC-GGBS mixes were weak, but the gradients of the strength-age lines indicate that significant further strength gain will occur past two months as it would in ordinary concrete. The long-term strength of both mixes containing GGBS will therefore surpass that of those containing only OPC, again in line with expected performance in NWC [2]. Strength gain was slower for OPC-FA-SF, and although the rate is less than that for the FC8- mixes, it is clear that greater strengths can be expected after a longer period of ageing. It is clear that silica fume's well-documented ability to increase strength, especially at early age, was insufficient to counteract the weakening effect of only adding 20 % of fly ash.

Jones suggests that 56 days is a more appropriate age for assessing the 'long term' compressive strength of foamed concrete than the standard 28 days for NWC [4]; arguments could be made in light of the slow strength for the use of strength values at even greater ages. The specification of strength at a greater age would widen the options available to a foamed concrete supplier regarding mix composition.

The variability of strengths is very large at 1 day: the weakest mix is just over one-tenth of the strength of the strongest. At 42 days, the weakest has improved to half the strength, clearly demonstrating the slow-acting nature of the present pozzolanic and latent hydraulic materials.



(a) 1 day

(b) 42 days

Figure 17: The compressive strength of all 8 mixes at (a) 1 day and (b) 42 days.

5.3.1 Strength impact of cement replacement

Figure 18 shows how the strength of tested foamed concrete cubes varies as increasing cement replacement takes place. Now, four different replacement materials were employed across the whole variety of mixes, but it can be seen that the strength variation at one day can be partially explained by simply considering what proportion of OPC was replaced by any of these (R^2 of 0.66). This indicates that, to some extent, when FC is young, anything other than OPC in the mix will act to decrease the mix's strength to a similar degree. However, only the vaguest correlation can be seen at 42 days, by which time the differing characters of each cementitious material are more fully expressed.

5.3.2 Strength impact of MgO addition

Instead of examining the impact of any cement replacement on the cubes' compressive strength, we can consider how the reactive magnesia's presence affected the strength of each mix family. Figure 19a shows that the early strength declines substantially with the addition of MgO, and that the worst-affected is the OPC-FA-SF system, which retains only one-fifth of its

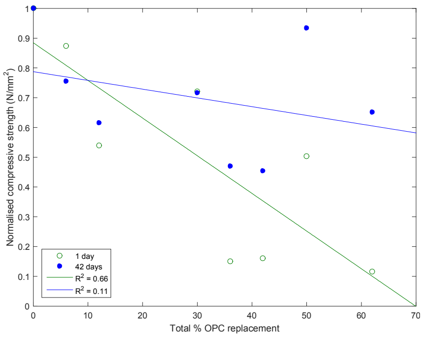


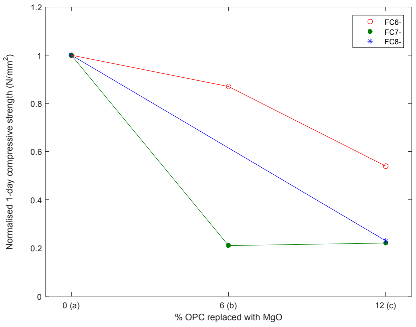
Figure 18: Effect of OPC replacement on short- and long-term compressive strength.

base strength. Figure 19b shows that in the longer term all systems' strengths are much less sensitive to MgO addition, and that this addition affects each system approximately equally.

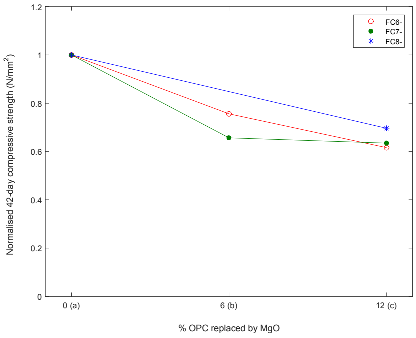
These plots, alongside Figures 17 and 18 above indicate that early strength is primarily linked to Portland cement content (other present ingredients acting to a lesser extent), whilst longer-term strength is less variable and more consistently governed by MgO addition.

5.3.3 Effect of density on strength

Although density was as far as possible fixed in this work, some variation still occurred - but we can use this to our advantage to investigate how strength varies with density at low density. Hoff's equation's predictions (4) certainly gave strengths in the correct region, but it can be seen that cementitious system has a significant bearing on compressive strength, especially in the short term. At 42 days, the range of strengths was 3.1 - 5.1 N/mm^2 for OPC mixes and 2.3 - 4.8 N/mm^2 for the others. Many of these strengths are below Hoff's range of 3.8 - 8.2 N/mm^2. Hoff used 28-day compressive strength to derive his parameters, but in a more recent work, Kearsely and Wainwright cast foamed concrete specimens at several OPC and FA proportions and tested their



(a) 1 day



(b) 42 days

Figure 19: Compressive strengths of the three mix types at (a) 1 day and (b) 42 days, plotted against MgO as a percentage of total cementitious material. Each line has been normalised to strength of the 0% MgO mix of that type.

strength at one year [35]. The best fit for their data was with values of 188N/mm^2 and 3.1 for $\square_o$ and b respectively. Using these values on the highest and lowest average mix dry densities of FC6-8 (821 and 735 kg/m^3) predicts a strength between 2.9 and 4.1 N/mm^2, which is a good but slightly narrow reflection of the actual compressive strengths at only forty-two days. Perhaps the similarity of predicted and actual strengths for this present work would be reduced if compressive strength could be tested after many more months of ageing. A clear weakness of this is equation, therefore, is its failure to take into account the strengthening effect of concrete's ageing. In spite of this, as a first approximation, Kearsley and Wainwright's parameter values will offer a prediction of what we might call medium term strength to within perhaps a factor of two.

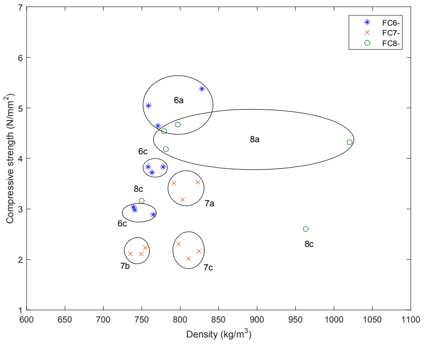


Figure 20: The unclear effect of density on 28-day strength for the mixes studied.

At first glance, Figure 20 might seem to suggest a very steep strength-density relationship, but on closer inspection, the addition of MgO is the main cause of the strength change. Within each mix, strength varies very little with density - although this statement has limited validity as in most cases the range of densities is small. Power's general relation of cube strength to gel/space ratio for cement pastes (Figure 21) holds that strength increases with the cube of gel/space ratio. Inspection of this figure reveals that the limited increase of strength with density

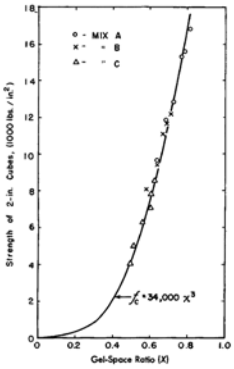


Figure 21: The general cement paste porosity - strength relation, from [3].

observed in the specimens should not be surprising, as the gradient of the curve is very low at low gel-space ratios (ie. high void content). Therefore, high void content and thus low density leads not only to low compressive strength, but also to low change in strength with respect to change in porosity. (Incidentally, the gel-space ratios for our mixes of 0.19 - 0.28 predict compressive strengths for our mixes of 1.5 - 4.4 N/mm^2, into which range most samples' 28-day strengths fit. This relation then appears to be about as valid as that of Hoff, and of Kearsley and Wainwright.)

René Feret established a rule in 1896 that takes a different approach to Hoff, by forming a void/cement parameter

$$\frac{w+a}{c}$$

where w, a and c represent the volume of water, air and cement in the mix, and relating this parameter to strength:

$$S = K\left(\frac{c}{c+w+a}\right)^{n} = K\left(1+\frac{w+a}{c}\right)^{-n} \qquad (5)$$

Where K and n are empirical constants ($n \approx 2$ for NWC). Lim found that this equation explained well the impact of water and air content on strength for various foamed concrete compositions containing ordinary Portland cement and sand [9]. Figure 20 shows their data points and fitted curve together with the data from this investigation. The FC6- and FC8- mixes both lie quite close to the power-law line found in [9], implying that their strength is largely governed by Feret's parameter, whereas the FC7- mixes' strengths seem to be almost unaffected by change in this parameter. It would therefore seem that factors other than air/cement and water/cement ratios primarily control the strength of the OPC-FA-SF system. Feret's rule therefore shows that many, but not all, foamed concrete compositions' strengths are governed by his parameter, which in turn implies that strength is reduced by increasing air/cement or water/cement ratio.

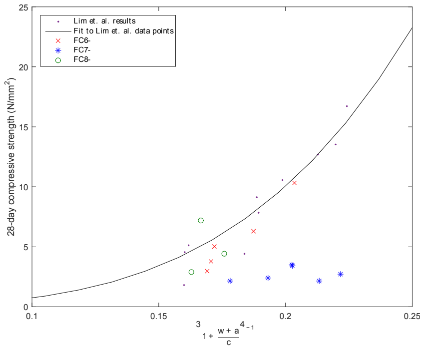


Figure 22: A comparison of the strength-porosity relationship for mixes in this work, and from Tam et. al. [9], with the power-law relation from that work

5.4 Autogenous shrinkage

Figures 23 and 24 show the autogenous shrinkage of OPC and OPC-FA-SF mixes respectively. Table 4 summarises the expansive behaviour of the four shrinkage-compensated mixes. Without any MgO addition, autogenous shrinkage after one month is 7 - 10 times greater than the

40×10^{-6} typically experienced by normal weight concrete [41]. By comparison with the characteristic shrinkage curve for uncompensated concrete in Figure 3, it can be assumed that some additional future shrinkage will occur. The slight volume gain that this figure indicates to occur within the first week was observed for FC6a, but it was by comparison only slight and short-lived, perhaps implying that the FC's void structure absorbs small and short-term volume changes.

For the OPC mixes, it would appear that the reactive magnesia's expansive action and the autogenous shrinkage of ordinary Portland cement occur somewhat independently of each other, as after around 7 days, the rates of shrinkage for all three samples was very similar. The magnesia, whilst only having the effect of reducing strength in the short term, was very reactive in terms of producing expansion in the same period. The expansion attained by addition of MgO is non-linear: the first 6 % addition yields 763×10^{-6} of compensation, whereas the second 6 % generates just over a third of this amount.

For the OPC-FA-SF mixes, autogenous shrinkage without compensation is somewhat less than for OPC. It appears that the PFA or SF interact with the magnesia in some way, as the same proportions produce very different expansion rates and magnitudes in the two systems. It is notable that maximum expansion is reached a full 2 - 3 weeks after the same state in FC6b and FC6c. Conversely to the FC6- mixes, the second 6 % of MgO addition generates almost twice as much expansion as the first, again suggesting some interaction with one of the cementitious materials.

Table 4: Analysis of expansion.

Mix	Maximum Expansion	Long-term expansion	Expansion retention
FC6b	710	85	12%
FC6c	1141	372	33%
FC7b	649	195	30%
FC7c	1459	1397	96%

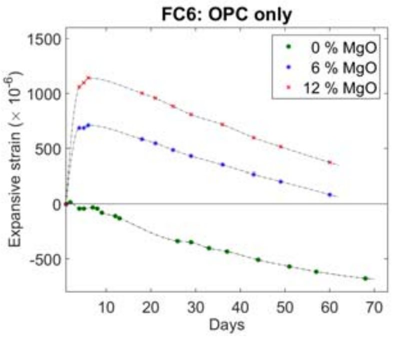


Figure 23: Autogenous shrinkage of OPC mixes.

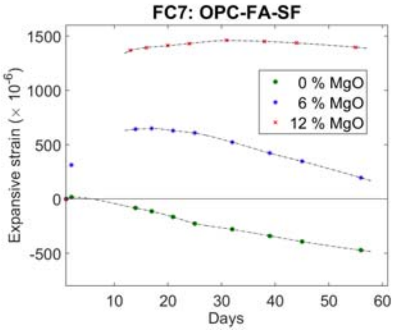


Figure 24: Autogenous shrinkage of OPC/FA/SF mixes. The lines for FC7a&b are truncated, because time constraints prevented any shrinkage readings being taken before 14 days, and any joining line causes the rate of expansion to seem slow compared to the FC6- mixes. Instead, it is likely that both mix families experienced similar rates of expansion.

5.5 Drying shrinkage

Figure 25 shows drying shrinkage for both OPC-GGBS mixes, and indicates that composition has an effect on both shrinkage rate and magnitude. Strangely FC8c was seen to shrink more and more quickly than its equivalent mix without reactive magnesia - the opposite effect to that seen under sealed conditions. The shrinkage rate might therefore depend predominantly on availability of free water, with this effect outweighing any expansive activity of MgO. Due to the relatively short measurement duration, the final drying shrinkage strains are unknown, but the discrepancy may decrease with time, as FC8a is still undergoing further shrinkage, and the final reading for FC8c at 53 days could indicate that some expansion is beginning to occur. In any case, the shrinkage magnitudes at 42 days are similar to those seen by Jones at similarly low densities [16], and are almost an order of magnitude larger tan those seen under sealed conditions.

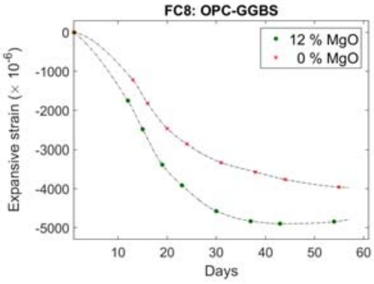


Figure 25: Drying shrinkage of OPC/ GGBS mixes.

Given the large difference in magnitude between drying and autogenous shrinkage (which represent opposite extremes of boundary permeability), and the varying effect of MgO under the two conditions, further work should be performed to better understand (i) what level of permeability is typical at the boundaries of a concrete pour and (ii) what volume changes will occur in foamed concrete under conditions of intermediate permeability.

5.6 Observations of quality

There was very little indication of segregation of bubbles and paste either at the time of casting - where bubbles rising would be seen on the top surface whilst skimming - or when samples were compression-tested after they had hardened - where bubble segregation is visible on the inside of the cube. Although local inhomogeneities and defects were present in some cubes, such as those in Figures 26(a) and (b), there was no discernible trend of these affecting compressive strength.

(a) (b)

Figure 26: One defect seen in a small number of cubes: air gaps near the tops of the cubes. Note the surface finish is the negative of expanded polystyrene. This did not appear to adversely affect strength.

6 Conclusions

Concrete with a cement content far lower than that of FC6a will have a far greater compressive strength, because at a simplistic level, any aggregate is stronger than an air void. In light of this, and because Portland cement is relatively costly and aggregate is comparatively inexpensive, the use of foamed concrete is not necessarily an economical approach for simple bulk applications. The material excels where some or all of low density, pumpability, ability to fill voids, and thermal insulation are important requirements, and as such should be considered a specialist material. For applications demanding a light-weight fill, however, the compressive strengths found in this work indicate that foamed concrete can compete with light-weight aggregate concretes on strength, whilst offering far superior flow properties.

The experiments undertaken have revealed the principles briefly outlined below.

1. Density variation within a foamed concrete batch has minimal impact on compressive strength. Void sizes are not affected by mix composition.
2. Substitution of other materials for OPC has an adverse effect on FC's flowability.
3. Substituting MgO for OPC reduces strength in approximate proportion to amount added.
4. Foamed concrete containing only OPC, water and foam is the benchmark for strength at low densities and at early ages. Of the three mix families investigated, the OPC-PFA-SF-MgO (FC7-) mixes always exhibit the lowest strength. The OPC-GGBS system has low early strength, but equals or exceeds OPC alone at greater ages.
5. Reactive magnesia expands rapidly under sealed conditions and in an OPC-only cement system, but may worsen drying shrinkage in an OPC-GGBS system. OPC's normal shrinkage still occurs following the magnesia's expansion.
6. Replacing some Portalnd cement with fly ash and silica fume reduces autogenous shrinkage. When MgO is added, larger expansions occur in this system, with greater retention of the expansion attained. The expansion is significantly slower, however.

7 Further work

Before commercial use of any of the experimental foamed concrete mix compositions studied in this work, tests must be performed on many additional properties, including:

- Degree of reinforcement bond and passivation;
- Durability, assessing both permeability and resistance to chemical attack;
- Fire resistance.

Development of design codes would also be essential in order ensure usage is appropriate and safe.

As mentioned in Section 5.1, work could very usefully be done to relate the flowability of foamed concrete to its composition. Because of the promise of the GGBS mixes in terms of long-term strength, additional mixes could be cast with some silica fume to increase early strength to a more acceptable level. It has been reported [5] that many superplasticisers are unsuitable for use in foamed concrete, as they react with chemicals in the foaming agent. Because a decrease in water-cement ratio would increase strength, there would be great value in finding a superplasticiser compatible with fresh foam in order to maintain flowability in mixes with reduced water content. Future research could identify chemicals safe for use with foaming agents and their effect on flow properties.

In addition to the work necessary to further the findings of this report, investigations could readily proceed into new areas, for example the use of shrinkage-compensating cements whose expansion is driven by the formation of larger-than-normal quantities of ettringite [2].

8 Acknowledgements

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A Specification compliance

Although the findings from the above investigations are valuable in their own right, it remains to evaluate the performance of each foamed concrete mix composition against the specification provided by Laing O'Rourke in Section 2.3. This evaluation is summarised in Table 5 below. Here follows brief observations regarding each of the stipulations.

Specification point 1, requiring density to be less than or equal to 800 kg/m^3, was not met by all mixes, but the average density of all cubes of a given composition was never more than 3 % distant from the target value. Most individual cubes were within the $\pm$ 50 kg/m^3 range typically allowed in industry [4].

Specification point 2, requiring a long-term strength in excess of 4 N/mm^2, was easily met by FC6a and FC8a, and almost met by FC6b and FC7a. It is likely that these two compositions, with the possible addition of FC8c (or a mix with less MgO), would exceed the target strength at an age greater than 48 days.

Specification point 3, requiring void sizes under 0.5 mm, was not convincingly met by any of the mixes, as can be seen in Figure 13. Median void size, however, is likely close to 0.5 mm. Void size could be decreased by reconfiguring the foam generator to produce a dense foam, or perhaps by using a different foaming agent entirely. No research has been found to suggest that strength is linked to void size, but only to proportion of voids, that is, porosity. At constant void volume, smaller voids will be surrounded by thinner walls and allow straighter load paths, whereas larger bubbles will have thicker, stronger walls at the expense of more tortuous load paths. Further investigation will be needed to understand both how void size can be controlled, and how it might affect compressive strength and other properties.

All mix compositions fell well short of meeting specification point 4, which called for 5000 micro-strain of expansion. Even FC8a, the mix where the greatest expansion was seen, only produced around a third of the desired expansion - and it is uncertain what proportion of this amount would be retained after more complete hydration (and consequent further shrinkage) of the Portland cement. It should be noted that this composition did not offer sufficient compressive strength either at 1 day or in the long term, so even if sufficient expansion was obtained through a greater substitution of MgO for OPC, the resulting compressive strength of this composition would be unusably low.

Specification point 5, demanding a 1-day compressive strength above 1 N/mm^2, was easily met by all three OPC mixes as well as FC7a. This result is testimony to the early strength contribution of silica fume to a mix, when not disturbed by the addition of MgO. The condition was almost met by FC8a, but the other three mixes fell well short. It can be seen clearly that high percentages of Portland Cement are the most reliable way to obtain strength at the very early ages demanded by precasting. If early strength as high as 1 N/mm^2 is not certainly required, a lower value should be specified as this will allow the use of mixes with increased substitution of OPC for supplementary cementitious materials. The three principal benefits of this are (i) reduced cost due to exploitation of waste materials, (ii) reduced carbon emissions associated with manufacture and (iii) the possibility of greater long-term strength.

Specification point 6, regarding void interconnectivity, was not examined beyond the microscopy work shown in Figure 13. The indication from these images is that voids are well-separated by walls of hardened cement paste. However, in a small number of cases, fractures in these walls can be seen, for example in Figure 13(d). These fractures would significantly increase transport of moisture and deleterious species through a specimen, because in their absence diffusion through the hardened cement paste wall itself must occur.

Table 5: A review of which mix compositions satisfied which specification points. Percentages indicate the proportion of the specified property attained.

Specification point	1	2	3	4	5	6
FC6	X (781)	X 127 %	-	-ve	X 185 %	-
FC6b	X (766)	96 %	-	2 %	87 %	-
FC6c	X (748)	78 %	-	7 %	54 %	-
FC7a	(821)	91 %	-	-ve	72 %	-
FC7b	X (735)	60 %	-	4 %	15 %	-
FC7c	(812)	58 %	-	28 %	16 %	-
FC8a	(803)	X 119 %	-	-ve	93 %	-
FC8c	X (794)	83 %	-	-ve	22 %	-

Table 5 shows that foamed concrete at 800 kg/m^3 cannot meet all of the stipulated specification points at once. Addition of magnesia to elicit even a fraction of the desired expansion will result in inadequate short-term strength, with no guarantee of sufficient compressive strength at a later time.

B Superseded mixing methods

The mixes featured in this report begin their names with the numeral 6 because a series of trial mixes were cast in preparation for the main experimental effort discussed above. These trials allowed the author to find the most effective method of combining pre-foam and cement paste.

The first method employed involved simply placing the pre-foam on top of the already-mixed cement paste in a standard laboratory pan-type mixer (Figure 27), and then mixing until homogeneity was achieved. However, as the foam was more than an order of magnitude less dense than the cement paste, and the mixer's vertical vanes do little to promote layer inter-mixing, foam collapse and coalescence accompanied pervasive segregation. Figure 28 shows a cube cast from materials mixed in this manner. The very poor surface finish is due to an early attempt to line an ordinary cube mould with domestic 'cling film' in order to prevent adhesion in line with recommendations from Jones and The Concrete Society [4, 5].

The second superseded method replaced the ineffective mixing action of the aforementioned equipment with a drill-mounted 'whisk' ordinarily used for mixing small quantities of paint and plaster (Figure 27). This technique was quite effective, but was also very slow when working on larger batches. Because of the length of time taken to mix, some foam collapse again occurred.

The mixer in Figure 6 was eventually employed because its motion caused inter-layer mixing by shearing (as material underneath caught on the vanes) and by free-fall.

Figure 27: The pan-type mixer used in earlier batches. This pan was also used with the pictured drill-mounted 'whisk' attachment.

Figure 28: A poor-quality cube from an early mix attempt. Note over-density, segregation (larger bubbles visible closer to the top), crevices and rounded corners due to intruding 'cling film'.

C Risk Assessment Retrospective

The start-of-project risk assessment (RA) quite accurately reflects the generality of risks encountered. The project risks could be divided into three categories: (i) those that did not materialise, as they had been correctly anticipated; (ii) those that did materialise and where more specific identification could have been done and (iii) additional risks that were discovered and which had not been taken into account at all, necessitating new precautions.

In the first category, was the risk of use of electrical equipment including mixers and a drill for the whisk attachment mentioned in Appendix B. These were used as intended, and thus there was no mishap. Similarly, the lab technicians go to great lengths to keep the laboratory environment as clear of clutter as possible, so there was indeed little possibility of tripping, as identified in the original RA.

In category (ii), the inhalation of hazardous substances was made less likely than imagined by the use of the installed dust extraction tube. This was fortunate, as it had not been anticipated how much dust the mixer pictured in Figure 6 would expel before water addition. Knowledge of this in advance might have led to the sourcing of a cover to retain all airborne dust inside the drum (in practice, a rubber floor mat was used to good effect). Another specifc ergonomic risk encountered was the movement of shrinkage samples from the casting laboratory to a constant-temperature room. These were relatively heavy and unwieldy, and yet too delicate to transport by a trolley, which would vibrate whilst travelling over rough floors. Prior knowledge of this might have led to installation of equipment to maintain a constant temperature in the casting laboratory.

A completely unexpected danger fitting into category (iii) was the release of an irritating mist when the mixer above was rinsed out with water. This was surprising, as rinsing was only carried out when as much cementitious material as possible had already been wiped from the internal surfaces. The mist most probably consisted of fine particles of hardened cement paste amongst droplets of water vapour, and irritated the nose and throat only briefly. Once this effect had been discovered, a dust mask and goggles were worn when rinsing, and no further discomfort was experienced.

Risk assessments attempt to anticipate every risk associated with an activity, and prevent or mitigate the occurrence of any damage before it can occur. It is recommended that future risk assessments of this type should not only build upon the original RA and the notes above: 'risk interviews' should additionally be conducted with at least one student and one technician who both work regularly in the relevant laboratory spaces. Their knowledge of real-world conditions and practices could enable identification of risks that might be hard to imagine prior to starting work.