Technical Abstract

Foamed concrete (FC) is a widely used form of low-density concrete commonly defined as 'a cementitious material having a minimum of 20 per cent by volume of mechanically entrained foam in the plastic mortar or grout'. The introduction of stable voids within the hardened cement paste or mortar reduces the density of the product and removes the need for aggregate fill. These voids are formed by the addition of an aerated surfactant solution.

Developed from Portland cement (PC) concrete, foamed concrete is PC-based with possible partial substitutions of supplementary cementitious materials (SCMs). However compared to normal aggregate concrete (NAC), foamed PC concrete (FPC) uses a similar amount of PC per volume of final material. PC and concrete derived from it constitute the largest volume of manufactured material in the world and such are a significant source of carbon dioxide. Therefore, FPC does not have an environmental advantage over NAC. With the subject of the environmental effect of concrete and PC usage being seriously considered around the world, the development of alternative alkali-activated (AA) binders is on the rise.

Alkali-activation is used to promote or initiate the cementitious properties of binders such as ground granulated blast furnace slag (GGBS) or fly ash (FA). AA FA as a foamed concrete binder has proved successful, with the requirement for heat curing to accelerate strength development. This experimental work focuses on the development of a foamed alkali-activated GGBS concrete (FGC) with curing at ambient temperature.

A target dry density of 700 kg/m^3 was established and two foaming agents, one protein-based and one synthetic were used. The complex chemical interactions involved in alkali-activated materials can pose compatibility issues with the foam. Compatibility tests were performed for both foaming agents and each activator used in this work. The majority of the highly alkaline sodium-based activators were incompatible with the protein foam. Therefore, this foaming agent was not used in the experiments beyond the initial mixes.

Two stages of mixes were performed in this investigation. The initial set included FPC and FGC mixes to allow (i) comparison of the early strengths of FGC with FPC and (ii) to find the

optimum activator(s) in terms of ease of mixing, safety and environmental reasons. These mixes highlighted a number of issues with FGC. Long setting times, up to 5 days, were exhibited, in line with those shown for non-foamed AA concretes. Flash setting for the sodium carbonate-activated mixes was observed with the activated GGBS slurry thickening during mixing, preventing slump flow tests being perfomed. Lastly, high shrinkage of the cbe specimens was observed upon demoulding, indicating that a significant amount of autogenous shrinkage occured in the initial curing days. As a result of these initial mixes, along with safety and environmental considerations, sodium carbonate, at a concentration of 5% Na_2O per weight of GGBS, was identified as the optimum activator.

The main mixes characterised the strength and sealed shrinkage behaviour of sodium carbonate-activated GGBS foamed concrete, investigating the effects of the activator state and the effects of the addition of MgO with varying water/binder contents. The basic FGC mix exhibited compressive strengths comparative to FPC and sealed shrinkage significantly higher than FPC. The addition of a liquid rather than powder activator increased flash setting effects, increasing the sealed shrinkage and reducing compressive strengths significantly due to poor mix homogeneity. Flash setting affected all the main mixes to some extent, resulting in the specimens being of activated-GGBS held by the foam matrix rather than a homogeneous material. This gave very low compressive strengths to all but two mixes and prevented slump flow tests. These two mixes were shown to obey Féret's rule relating compressive strength to the water/binder and air/binder ratios. High shrinkage behaviour was observed for all of the FGC mixes, with minimal effect from the addition of MgO as an expansive agent. The medium reactive MgO was shown to increase sealed shrinkage and give higher compressive strengths, closer to those of FPC.

Overall, two FGC mixes exhibited compressive strengths comparative to FPC, with the addition of medium reactive MgO giving a compressive strength-age curve that indicated further strength gain above that of FPC could occur at greater ages. However, both these mixes exhibited high autogenous shrinkage, associated with the hydration of the alkali-activated system. With further research to reduce flash setting and to understand the shrinkage mechanisms more fully, sodium carbonate-activated GGBS has the potential to become a viable replacement for PC as the binder system for foamed concrete.

Acknowledgements

The author would like to thank Prof. Abir Al-Tabbaa and C. Litina for attentive supervision and continuous support through this project; F. Jin, A. Abdalqader and W.Y. Lau for their advice and technical support; M. Touhey, P. McLaren and C. Knight for laboratory assistance; ProPump Engineering Ltd for the supply of consumables and advice; J. Davies and R. Davies for editorial guidance, and G. Beckham and F. Jin for photography assistance.

Abbreviations

AA – Alkali-activated

FA – Fly ash

FGC – Foamed alkali-activated GGBS concrete

FPC – Foamed Portland cement concrete

GGBS – Ground granulated blast furnace cement

MgO – Magnesium oxide

MgO_M – Medium reactivity MgO (92/200)

MgO_H – High reactivity MgO (N50)

Na_2CO_3 – Sodium carbonate

NaOH – Sodium hydroxide

Na_2SiO_3 – Sodium silicate

NAC – Normal aggregate concrete

PC – Portland cement

RH – Relative humidity

SMC – Supplementary cementitious material

w/b – water/binder ratio

w/c – water/cement ratio

1 Introduction

1.1 Background and Motivation

The development of Portland cement (PC) in the nineteenth century is considered one of the most important technical advances in the history of humanity [1]. This is evident by concrete being used twice as much around the globe as the total of all other building materials including wood, steel, plastic and aluminium [2]. The many uses of concrete have led to development of numerous types of cement and concrete mix designs. Though traditionally thought of as purely a structural component due to its compressive strength capacity, concrete can also have insulation or aesthetic uses. One such growing area of interest is that of low-density concretes, in particular foamed concretes (FC).

Foamed concrete is a widely used form of lightweight concrete consisting of a binder, water, air and sometimes sand. The air bubbles are mechanically formed and form a minimum 20% of the volume of the material. This differentiates it from air-entrained concrete, containing less volume of air, and aerated concrete, containing chemically formed voids. The introduction of stable voids within the hardened cement paste or mortar reduces the density of the product and removes the need to use aggregate fill. The preformed foam is produced by passing a diluted surfactant through a foam generator before being added to the cementitious slurry in a quantity that produces the desired density.

Foamed concrete is highly flowable, self-levelling and can be pumped. These properties make it useful for filling voids or trench reinstatement. It requires no compaction, easing installation, and has low thermal conductivity, useful for insulation purposes. FC densities can vary from 1800 kg/m^3 (structural applications) to 300 kg/m^3 (insulation applications), with the general trend of decreasing strength with decreasing density. Other properties can be varied widely to meet the requirements and needs of the application.

Foamed PC concrete (FPC) can be a more energy efficient option than using normal aggregate concrete (NAC) for non-structural applications. The production of FPC does not require quarrying for aggregate or expensive compaction equipment. In addition, there can be added benefits from the nature of foamed concrete, such as decreased thermal

conductivity. The thermal conductivity of FPC can be between 3 and 20 times less than that of NAC [3] [4]. However, compared to NAC, FPC uses a similar mass of cement per volume of concrete. PC and concrete derived from it constitute the largest volume of manufactured material in the world and, as such, are a significant source of carbon dioxide. Therefore, FPC does not have an environmental advantage over aggregate concrete. The subject of the environmental effect of concrete and PC usage is being seriously considered around the world due to the increasing global dependence on it for construction. The environmental considerations not only include the high-energy consumption of PC production but also the large consumption of natural resources and the mass disposal of demolition waste.

Various measures have been proposed, and some implemented, to reduce the energy consumption in the life of PC and concrete. These include improving the energy efficiency of the PC production process, using renewable energy sources or replacing regular aggregate with recycled materials from demolition waste [5]. One measure that has been developed in recent years, and is still the subject of significant research, is the use of alternative cementitious materials in the place of the PC binder. This can be through partial substitution or complete replacement with a range of supplementary cementitious materials (SCMs) such as ground granulated blast furnace slag (GGBS) or fly ash (FA).

Complete substitution of PC in concrete mixes with GGBS, a by-product from the steel industry, can significantly reduce the energy footprint of concrete. GGBS is a latent hydraulic material, requiring the presence of an alkali to accelerate cementitious properties. Therefore, such materials are called alkali-activated (AA) concretes (though not technically concrete as there is no PC present, these materials are still referred to as concretes). In addition to the environmental benefits, AA concretes can offer superior properties over PC concretes in terms of potentially increased strength, and fire and chemical resistance. One drawback, however, is their propensity to shrink to a greater extent than equivalent PC based concretes. Both autogenous (due to hydration of the binder) and drying (due to loss of moisture to the environment) shrinkage are affected [6].

The research areas of foamed concrete and alkali-activated concretes are individually extensive and continue to grow. The convergence of these areas of research is currently very small and therefore the motivation for this project is to broaden the understanding and potential use of an alkali-activated binder to create foamed concrete.

1.2 Aims and Objectives

The overall aim of this research is to develop a foamed alkali-activated GGBS concrete (FGC). The objectives of this research are to:

1) Trial a number of alkali-activated foamed GGBS concrete mixes using different alkali-activators to find an activator that is suitable in terms of practicality, economy and environmental benefit.
2) Assess the strength and sealed shrinkage of alkali-activated foamed GGBS concrete using this optimum activator in both powder and liquid activator state.
3) Investigate the performance of the alkali-activated foamed GGBS concrete with the addition of magnesia as an expansive agent to combat any observed shrinkage.

In addition to the above objectives, the project sponsor, Laing O'Rourke, provided an ideal specification for foamed concrete. The alkali-activated foamed GGBS concretes developed in this work will be assessed against these criteria:

1) Density < 800kg/m^3
2) Strength > 4MPa
3) Void size < 0.5mm
4) Lightly expansive ~0.5%
5) Early strength > 25% of long term strength after 20hrs at 20^{O}C
6) Closed voids for low water absorption

2 Literature Review

2.1 Foamed Concrete

2.1.1 Definition, Properties and Uses

Foamed concrete is generally defined as 'a cementitious material having a minimum of 20 per cent by volume of mechanically entrained foam in the plastic mortar or grout' [3]. For most common uses, the typical air content is between 40 and 80 per cent of the total volume [7]. This allows for densities to be as low as 300 kg/m^3 [3].

Foamed concrete can come under two different classes of concrete, lightweight concrete and air-containing concrete. Firstly, the defining criterion for lightweight concretes is dry density, with values ranging from 300 kg/m^3 up to 2000 kg/m^3 [8]. They include no-fines concrete (Figure 1a), foamed concrete (Figure 1b), aerated concrete (Figure 1c) and lightweight aggregate concrete. Foamed concrete is one of the few not to contain any coarse aggregate, only fine sands. Extremely light versions will not contain sand so technically the product is more accurately described as a foamed mortar [9]. In addition, foamed concrete is distinct from aerated concrete in that the bubbles are mechanically formed rather than being introduced by a chemical reaction. Out of the four types of lightweight concretes, foamed concrete exhibits the lowest strengths [8].

(a) No-fines concrete [8] **(b) Foamed concrete** **(c) Autoclave-aerated concrete [8]**

Figure 1: Types of lightweight concrete

Secondly, air-containing concretes have air trapped in the hardened cement paste or mortar. This category includes air-entrained concrete, autoclave-aerated concrete and foamed concrete. Foamed concrete is distinct in this group because of the proportion of air incorporated in the mortar and the method of trapping the air. Air-entrained concrete is formed through the mechanical mixing of a concrete mix containing an air-entraining

admixture. The shearing action traps air and the air-entraining admixture stabilises these bubbles. Through this method approximately 4-7% air by volume of concrete can be incorporated [10]. Autoclave-aerated concrete is formed through the chemical reaction of a gas-forming agent, such as aluminium powder, during the mixing process before being autoclaved at very high temperatures [11] [12]. This form of concrete can be up to 80% air [13]. Foamed concrete, on the other hand, contains above 20% air by volume and this air is incorporated through mechanical means as a preformed foam.

The properties of the foam used for foamed concrete are very important to the final product, in particular the strength [9]. Typically, the density of the foam is between 40 and 100 kg/m^3. Dry foam, formed by forcing compressed air through a foaming agent within a mixing chamber, is used to produce PC with densities lower than 1100 kg/m^3 [9]. This foam is extremely stable and similar in appearance to shaving foam.

Foamed concretes exhibit high shrinkages, up to 10 times greater than NAC [14] due to the absences of aggregate that would normally restrain it. Magnesium oxide (MgO), or magnesia, can be used to reducing this shrinkage. Research by Wright [15] showed that the addition of MgO reduced the sealed shrinkage of FPC through its expansive nature but increased the drying shrinkage of foamed concretes with partial GGBS substitutions.

For foamed concrete, strength is not always the most important parameter and, depending on the application, other properties such as thermal conductivity can be critical [4]. Low strengths may even be a requirement for temporary applications of foamed concrete. These other properties give rise to the varied uses of FC including but not limited to:

- Trench reinstatement – replacing traditional granular fill materials
- Void filling e.g. old sewers, basements, storage tanks
- Road bases – reduced settlements because of light weight

2.1.2 Strength Predictions

Whilst, the low strengths of foamed concrete have been acknowledged and well documented [14], it is useful to be able to predict the strength. Several formulae have been

proposed relating the compressive strength of concrete to porosity [16]. The porosity of concrete is difficult to estimate, or measure outside of a laboratory, because it depends on the degree of hydration. Hoff [17] concluded that there is a single strength-density relationship for FPC that can be expressed in terms of the water/cement (w/c) ratio and the density. He assumed an average ratio of the water bound by hydration in the cement of 0.2 and thus giving the following equation for FPC:

$$\frac{\sigma_y}{\sigma_0} = (\frac{d_c}{1+k})^b (\frac{1+0.2\rho_c}{\rho_c \gamma_w})^b \quad (1)$$

where σ_y is the compressive strength, σ_0 is the theoretical strength at zero porosity, k is the w/c ratio, ρ_c is the specific gravity of the cement, d_c is the concrete density, γ_w is the unit weight of water and b is an empirical constant.

The strength of a zero-porosity paste is difficult to define but through experiments can be estimated [16]. This equation only holds true for FPC containing only air, water and PC. Adjustments are required for the inclusion of additional cementitious components.

2.2 Alkali Activation

Alkali activation is a method for increasing the cementitious properties of pozzolanic or latent hydraulic materials. These materials are by-products of industrial processes and form the basis of the 'greenness' of alkali-activated (AA) materials, due to their lower embodied energy. A variety of activator combinations and cementitious materials give a wide range of strengths and other properties such as sulphate resistance.

The binders consist of alumino-silicate minerals activated by highly alkaline metal solutions. The alkaline environment breaks down the Si-O bonds in the binder and these become available for interaction with the alkaline species in the activator to form an 'inorganic polymer' [18]. Common activator types include caustic alkalis (MOH), non-silicate weak acid salts (M_2CO_3, M_2SO_3) and silicates ($M_2O.nSiO_2$) [6]. The most commonly used activator is a sodium silicate solution [19] because of the high compressive strengths it allows compared to other activators, as can be seen in Figure 2. The molar ratio of silica to soda (SiO_2:Na_2O) in sodium silicate can be varied with the addition of sodium hydroxide.

Though the use of alternative binders can reduce the emissions profile of concrete, the introduction of expensive man-made activators can increase it [20]. These activators involve highly energy-intensive processes in addition to posing safety issues because of toxicity and high pH. Therefore, they are not considered sustainable activators for AA concretes. An alternative, more sustainable activator is sodium carbonate (Na_2CO_3). In addition to being naturally occurring, it is less caustic and less harmful to the environment [20]. A number of research papers have investigated sodium carbonate-activated GGBS concretes [21] [22]. Though longer setting times and low early strengths are documented, Atis et al. [22] found that the drying shrinkage of a sodium carbonate-activated GGBS can be close to or even lower that of a PC concrete in addition to higher long-term compressive strengths.

The curing environment for AA materials is critical to strength and microstructure development [23]. Water immersion is not suitable as the activator ions leach out. Sealed curing or in high humidity results in higher strengths with the optimal temperature conditions depend on the nature and reactivity of the binding material [23]. AA fly ash-based materials often require increased temperature curing to acquire good compressive strength [24]. GGBS-based AA materials, however, show no strength difference at higher curing temperatures [24] and demonstrate good strength development with ambient temperature sealed curing [25]. The strength development of AA materials tends to be slower than that of PC concrete, as shown in Figure 2.

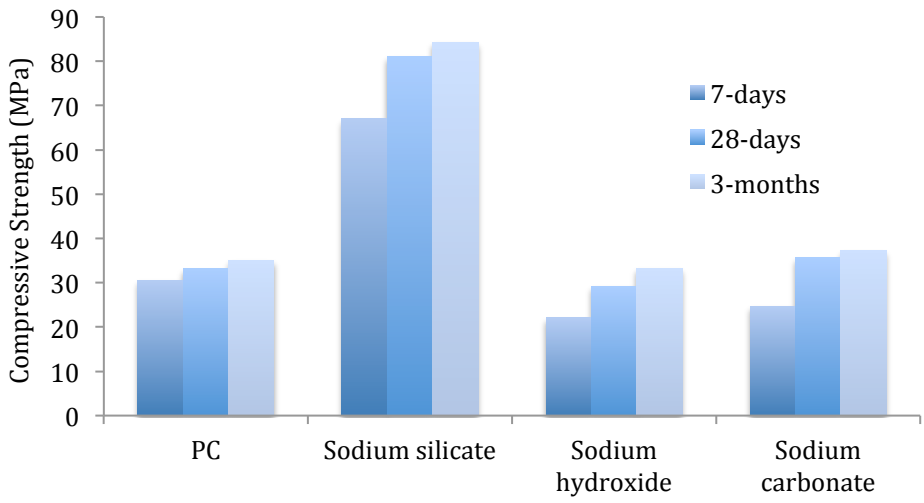


Figure 2: Compressive strengths of PC paste and various alkali-activated GGBS pastes (Data from Atis [22])

One disadvantage to AA materials is the high drying and autogenous shrinkage behaviour [26]. Cincotto et al. found that sodium silicate-activated GGBS could exhibit shrinkage over five times higher than PC concrete [6]. They found that the concentration of the activator played an important part in the amount of shrinkage observed, as shown in Figure 3.

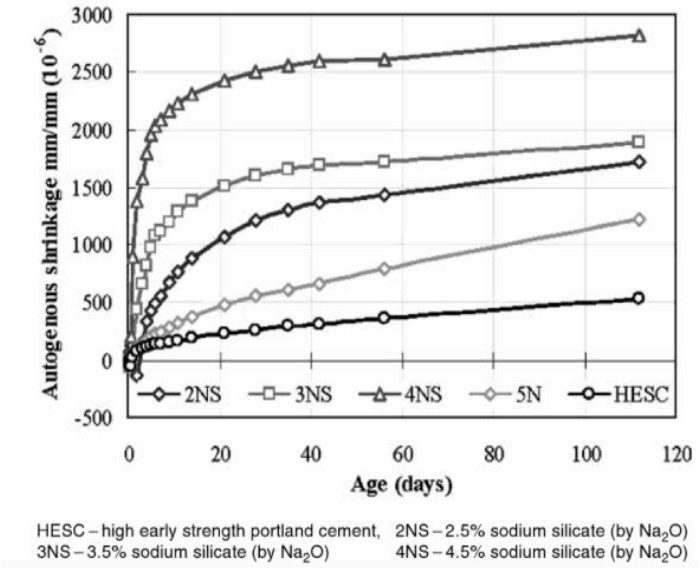


Figure 3: Autogenous shrinkage of PC and sodium silicate-activated GGBS pastes (from Shi et al. [6])

As with PC concretes, the addition of MgO can counteract shrinkage. Shen et al. [27] found that the addition of 10% MgO to sodium silicate-activated GGBS/FA cement meant the drying shrinkage after 14 days reached a steady lower value than without MgO. However, the amount of MgO included in a mix can also have negative effects on shrinkage. Fei and Al-Tabbaa [28] found that compared to a mix with no MgO and depending on the sodium carbonate activator concentration, a 5% addition of MgO reduced drying shrinkage whilst a 10% addition increased it. The relative reactivity of the magnesia also affects shrinkage.

2.3 Foamed Alkali-Activated GGBS Concrete

Foamed alkali-activated GGBS concrete (FGC) is foamed concrete with a fully GGBS binder. An alkali activator or combination of activators is required to promote cementitious behaviour and increase the rate of strength development. It is possible that foamed GGBS concrete could yield higher strengths than FPC for a constant density due to GGBS having a lower relative density than PC. The strength of FC is a function of the porosity, which in turn is related to the volume of air trapped by the foaming agent [16]. Therefore for a given mix

density using a lower relative density binder should allow a reduced volume of air to be used than for FPC [29], increasing the compressive strength.

There are numerous papers concerning foamed concrete and alkali-activated slag separately. However, minimal information is in the public domain about alkali-activated foamed GGBS concretes.

Yang et al. [30] [31] successfully produced foamed GGBS concretes with a view to implementing them in floor heating systems as a thermally insulating material. The mixes used a number of different activator combinations including calcium hydroxide with magnesium nitrate and calcium hydroxide with sodium silicate. High workability was exhibited, partly due to the addition of a high early strength agent at a variety of contents from 0.3 – 1.0% per mass of GGBS. The activator combinations also contributed to this high workability and prevented quick setting of the concrete. The foam used in the FGC was pre-formed from a protein foaming agent to a density of 40 kg/m^3.

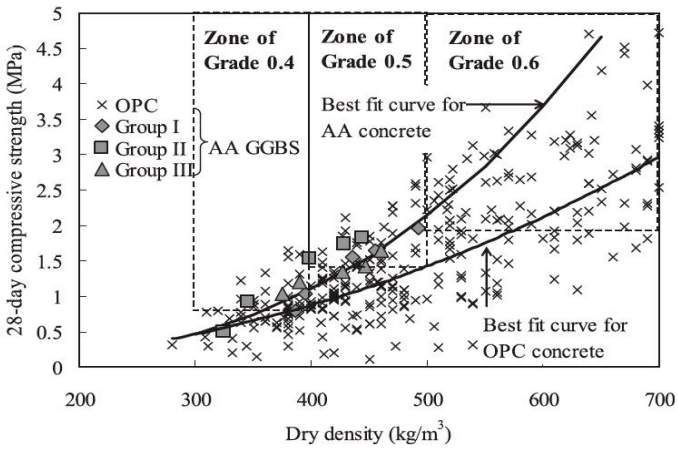


Figure 4: Relationship between dry density and 28-day compressive strength of FPC and FGC from Yang et al. [31]

The results of the FGC mixes gave 7-day strengths varying from 0.69 - 2.15 MPa and 28-day strengths between 0.8 - 3.03 MPa for different dry densities below 500 kg/m^3. The maximum values were for the activator combination of 10% calcium hydroxide with 4% magnesium nitrate. A number of their mixes exhibited compressive strengths greater than that of FPC at similar densities (Figure 4). Their research also involved observing the effect of different water/binder (w/b) ratios on the properties of the FGC. These were varied from 0.4 to 0.5 for the FGC using calcium hydroxide and magnesium nitrate. The effect of the w/b ratio can

be seen in the air-void microstructure in Figure 5. A water/binder ratio of 0.4 was identified as the optimum.

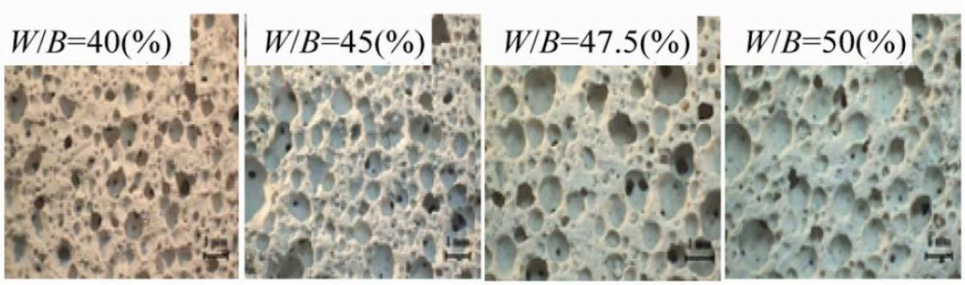


Figure 5: Air-void structure of FGC showing the effect of different w/b ratio (from Yang and Lee [30])

Though the research by Yang showed that FGC could be produced successfully, some issues were highlighted. A reaction between the sodium silicate activator used in some of the mixes and the protein foam lead to defoaming of the fresh concrete. Additions of FA up to 20% increased this defoaming further however also led to increased compressive strength. There is little scientific evidence to explain the defoaming effect of FA [31]. Kearsley and Kovtun [29] also experienced foam stability problems with the use of sodium silicate as the activator. The viscosity of the mixture was affected such that the air was no longer trapped in the paste as noted by Yang et al. [31]. Therefore, there is a need to assess compatibility of activators with the foam during mix design.

Kearsley and Kovtun also observed segregation, with the solids sinking to the bottom of the samples and the foam floating on the top. In addition, their results showed unpredictability in cube density, with some mixes exhibiting an increase in density at demoulding compared to the wet casting density.

2.3.1 Strength Predictions

The equation suggested by Hoff [17] (see Section 2.1.2) for predicting the strength of foamed concrete has been shown to be applicable to FPC containing high percentages of fly ash [16]. However, there is little research about predicting the strengths of FGC. This is likely to be due to the different mechanisms of strength development of GGBS with varying activators along with the complex chemical interaction of the activator, GGBS and foam.

3 Materials and Experimental Method

3.1 Materials

3.1.1 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag (GGBS) is an industrial by-product from iron or steel production. Its composition, a mix of lime, silica and alumina, depends on the raw materials and the type of iron or steel produced. These oxides also form PC but in different proportions. As a latent hydraulic material, GGBS develops strength much slower than PC. The use of an alkali-activator accelerates the strength development significantly such that AA GGBS concretes can reach the same one-day strength as PC concrete [32]. The environmental benefits of using GGBS include significant energy and carbon dioxide emission reductions, whilst conserving natural resources.

The GGBS used in this work was obtained from Hanson, UK. The hydraulic index, as given by Eqn 2, is calculated as 1.6, agreeing with Mantel [33]. His research reported that the hydraulic index should be greater than 1 to achieve good mechanical performance.

$$Hydraulic\ Index = \frac{CaO + MgO + Al_2O_3}{SiO_2} \quad (2)$$

The chemical composition of the GGBS used in this work is given below in Table 1.

Chemical Composition (%)	SiO_2	MgO	CaO	Al_2O_3	Na_2O	K_2O
GGBS	37	8	40	13	0.3	0.6

Table 1: GGBS chemical composition, from supplier datasheets

3.1.2 Alkali Activators

The chemical activators used in this work were sodium silicate powder (with ratio SiO_2:Na_2O = 2, technical grade), sodium hydroxide solution (10M standard solution), anhydrous sodium carbonate (technical grade), calcium hydroxide and magnesium nitrate powders (ACS reagent, 99%). They were sourced from Fisher Scientific and Sigma Aldrich. All the activators were incorporated into the FGC mixes in powder form except for the sodium hydroxide solution and the N5b mix activator (see section 3.2). These were dissolved in the mix water prior to mixing.

3.1.3 Magnesium Oxide (MgO)

Magnesium oxide (MgO), or magnesia, is a key component used to improve concrete's environmental and technical performance. The most reactive form, known as light-burned magnesia, is manufactured by thermal decomposition at 700-1000^{o}C of magnesite, or other minerals such as dolomite or brucite. The physical and chemical properties of reactive MgO can vary significantly depending on the precursor source and calcination history [34].

The magnesium oxides used in this work were obtained from Richard Baker Harrison (UK sourced from China). The chemical compositions for these are given in Table 2.

Chemical Composition (%)	MgO	SiO_2	CaO	R_2O_2	Fe	SO_3	Cl
MgO_M - 92/200	91.5	2	1.6	1	-	-	-
MgO_H - N50	97.7	-	0.5	-	0.02	0.8	0.1

Table 2: Magnesium Oxide chemical compositions, from supplier datasheets

3.1.4 Foam

There are a variety of protein-based or synthetic foaming agents commercially available for use in foamed concrete. Currently, protein foaming agents are preferable as they give a higher strength performance because they generally form smaller voids [29]. However, synthetic foaming agents are easier to handle, cheaper and require less energy to produce foam [3].

In this work, both a synthetic and a protein foaming agent sourced from ProPump Engineering Limited were used.

3.1.5 Additional Materials

The Portland cement used in this experimental work was obtained from Hanson, UK. The chemicals used to perform the magnesia reactivity tests were acetic acid, citric acid and phenolphthalein. These were purchased from Fisher Scientific of Sigma Aldrich.

3.2 Mix Design

The mix designs were based on an ideal fixed density in terms of the total mass of liquids and solids in a unit volume. For this work, a target dry density of 700 kg/m^3 was used to ensure compliance with the Laing O' Rourke specification. The cement content of a basic FPC can be inferred from the chosen w/b ratio and the ratio of the densities of each material. This method can be altered for AA FC by generalising the cement variable to the total binder content (e.g. GGBS + activator). Equations 3 to 6 show this method. Further alterations can be made for more complex mixes with multiple activators or other SCMs, provided that the ratios of these materials to GGBS are known. The w/b ratio used for FPC can vary from 0.4 to 1.24 [14]. However in current AA foamed concrete research, a w/b ratio of between 0.375 and 0.5 [30] [31] is used. This work used a starting w/b ratio of 0.5.

For 1 m^3 of FGC with one activator:

$$D = w + s + a \tag{3}$$

$$w = 0.5(s + a) \tag{4}$$

$$a = Cs \tag{5}$$

$$w = \frac{D}{3}\ , \quad s = \frac{D}{\frac{3}{2}(1 + C)} \quad and \quad a = \frac{D}{\frac{3}{2}(\frac{1 + C}{C})} \tag{6}\ i, ii, iii$$

where w is the mass of water in kg, s is the mass of GGBS in kg, a is the mass of activator in kg, D is the desired density in kg/m^3 and C is the activator content per weight of GGBS.

The volume of foam, f, in litres, to fill the remainder of the unit volume is calculated using Equation 7. The density of foam is considered negligible (as per the Concrete Society [3]).

$$f = 1000 - \left(\frac{s}{\bar{\rho}_s} + \frac{a}{\bar{\rho}_a} + \frac{w}{\bar{\rho}_w}\right) \tag{7}$$

where the specific gravity of each material is denoted by $\bar{\rho}$ and the respective subscript.

There are many factors contributing to the strength of hardened cementitious materials. The complicated and unknown nature of AA GGBS systems and the added complication of foam interaction mean that this simplified mix design method is one that can be used as a starting point for this research. The wide variation in material chemical composition gives varying

water requirement to achieve a certain level of hydration of each activator-binder system. In addition, the air-void characteristics, governed by the type of foaming agent used [9], in tandem with the curing regime, contribute to the strength development of foamed concrete. This simplified method negates the need for a significant amount of experiments and statistical analysis to determine relationships between the properties of the concrete and the properties of the constituent materials.

Two stages of mixes were performed in this investigation. The initial mixes were used firstly to give an idea of FPC strengths with the different foaming agents and secondly as trials for developing an FGC mix. The mix proportions for the initial mixes are summarised in Table 3. Mixes TAA1, TAA2 and TAA3 were based on those by Yang and Lee, and Yang et al. [30] [31] and those numbered TAA5 to TAA9 used different types and amounts of sodium-based alkali activators. The sodium-based activator content is given as a percentage Na_2O per weight of GGBS.

Mix	Foaming Agent	w/b	OPC (kg/m^3)	GGBS (kg/m^3)	OPC (%)	GGBS (%)	Activator
TOPC1	Protein	0.5	467	-	100	-	-
TOPC2	Protein	0.4	500	-	100	-	-
TOPC3b	Synthetic	0.4	500	-	100	-	-
TAA1	Protein	0.5	-	401	-	86	10% $Ca(OH)_2$ + 4% $Mg(NO_3)_2$
TAA2	Protein	0.5	-	401	-	93.7	4.5% $Ca(OH)_2$ + 1.8% $Mg(NO_3)_2$
TAA3	Protein	0.4	-	430	-	86	10% $Ca(OH)_2$ + 4% $Mg(NO_3)_2$
TAA5	Synthetic	0.4	-	450	-	90	5% Na_2SiO_3 + 5% NaOH
TAA6	Synthetic	0.4	-	450	-	90	10% Na_2CO_3
TAA7	Synthetic	0.4	-	475	-	95	5% Na_2CO_3
TAA8	Synthetic	0.4	-	450	-	90	5% Na_2CO_3 + 5% NaOH
TAA9	Synthetic	0.4	-	487.5	-	97.5	7.5% Na_2CO_3

Table 3: Initial mix compositions

The second set of mixes were the main mixes. The main mix proportions, given in Table 4, were decided upon from the results of the initial mixes. Sodium carbonate was chosen as the activator with the effects of the activator state (liquid or solid), along with the effect of the addition of MgO, being investigated in terms of compressive strength and shrinkage behaviour. Again, the sodium-based activator content is given as a percentage Na_2O per weight of GGBS.

Mix	w/b	GGBS (kg/m^3)	GGBS (%)	Na_2CO_3 (%)	MgO_H (%)	MgO_M (%)
N5	0.4	475	95	5	-	-
N5b	0.4	475	95	5*	-	-
N5H5	0.4	450	90	5	5	-
N5M5	0.5	420	90	5	-	5
N5M5b	0.45	434.5	90	5	-	5
N5M5c	0.475	427	90	5	-	5

Table 4: Main mix compositions

* The powder activator was dissolved in the mix water and left until cool to room temperature before mixing.

3.3 Experimental Method

3.3.1.1 Foam Production

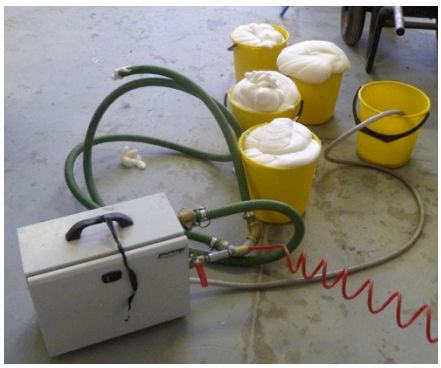


Figure 6: Set up of ProPump Engineering Ltd.'s JFG 200 Foam Generator

The foam for this experimental work was created using a dry foam generator (See Figure 6). Compressed air is fed along with a diluted foaming agent through a venturi system. The appearance and behaviour of the foam depends on the type of foaming agent and machine settings. This work used constant settings and two different foaming agents, one synthetic (Figure 7) and one protein-based (Figure 8). The dilution rate was 1:25 by volume.

Figure 7: Synthetic Foam

Figure 8: Protein foam

3.3.1.2 Foam Compatibility Testing

Foam compatibility tests were performed to assess the suitability of each alkali activator with the foaming agents. The alkali combinations tested were: $Ca(OH)_2$ + $Mg(NO_3)_2$, NaOH, Na_2SiO_3 and Na_2CO_3. Each activator combination was weighed out and dissolved in an appropriate amount of water to give the same ratio as would be used in the initial FGC mixes (Table 3). These were added to 0.25 litres of foam (Figure 9). Photographs were taken at intervals of 1 minute up to a total time of 10 minutes to determining if defoaming had taken place.

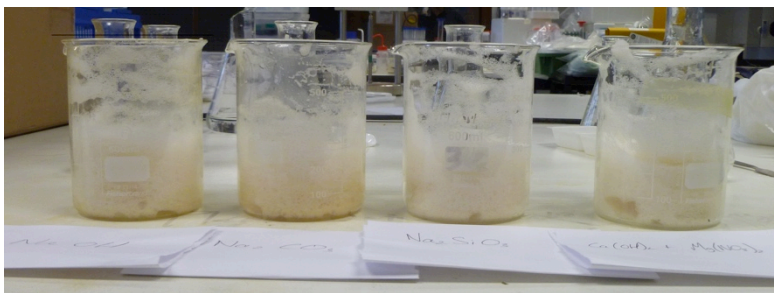


Figure 9: Foam compatibility test set up

3.3.2 Mixing and Casting

An overview of the production process of FGC can be seen in Figure 11. The mixing method was developed by Andrew Wright [15] as part of previous work on FC. An inclined drum mixer (Figure 10) was used due to its capacity and gentle mixing action.

The mix components were weighed out to the nearest 10g and the dry ingredients were mixed in the drum mixer for 1-2 minutes until blended. The measured water and any liquid activator were then added to the mixer while it was running. The mixer was periodically stopped to allow manual scraping of the unmixed powders from inside of the drum. This process was continued until homogeneity was achieved. At this point, the foam generator was started and a predetermined volume of foam was measured into the mixer. The foam density was calculated by comparing a container of known volume when empty and full. This gave values of 50-70 kg/m^3 for the protein foam and 40-50 kg/m^3 for the synthetic foam.

Figure 10: Drum cement mixer

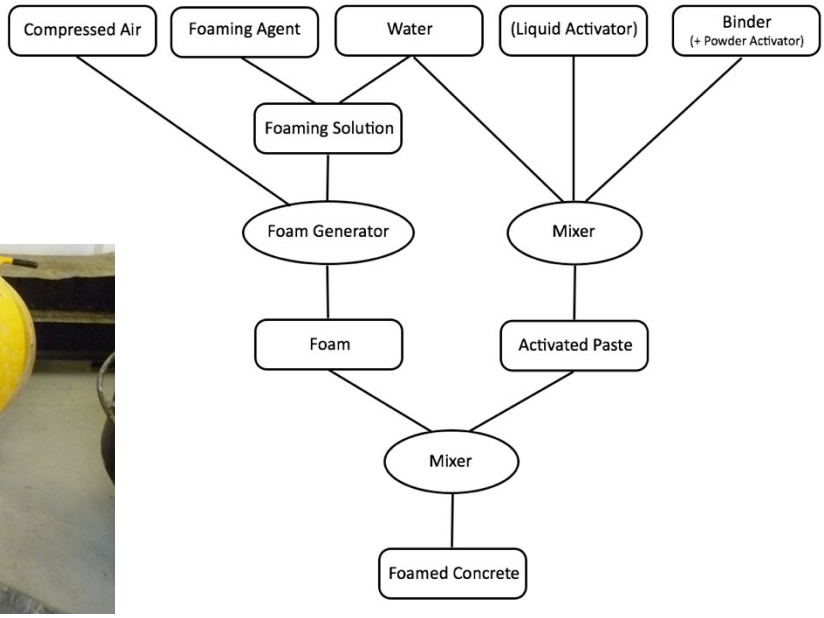


Figure 11: Foamed concrete production process

For the initial mixes, eight 100 x 100 x 100 mm cubes were cast and, for the main testing mixes, ten 100 x 100 x 100 mm cubes and six 40 x 40 x 160 mm shrinkage prisms were cast. The moulds were filled with a single layer of FC and not compacted but gently tapped on their bases to allow trapped air at the sharp corners to escape. The tops of the moulds were smoothed with a trowel before lids were applied to the cubes and the shrinkage moulds covered with a plastic sheet. Finally, the plastic density of the concrete was determined by comparing the weight of empty and full moulds.

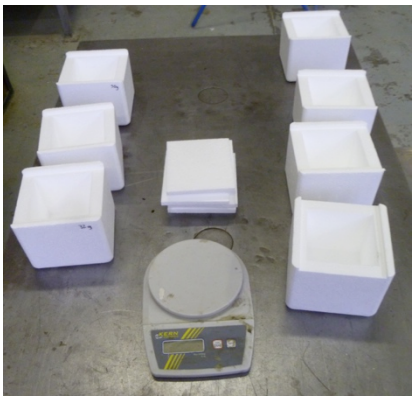


Figure 12: Polystyrene cube moulds

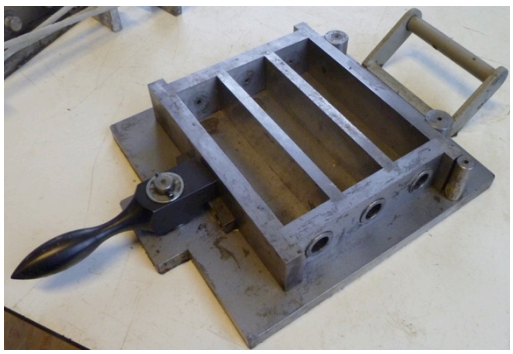


Figure 13: Steel shrinkage prism moulds

As mould release oil can affect the properties of FC [7] and FPC has been found to strongly adhere to steel [35], single-use expanded polystyrene cube moulds were used (Figure 12). In addition, the low early strengths of FC makes cubes difficult to demould without damage [3]

and so the use of polystyrene moulds allows them to be peeled off prior to testing. The insulating properties of the polystyrene also reproduce the conditions found in the main portion of large foamed concrete pours. It should be noted that full compliance with BS EN 12390-1 [36] is unlikely for these moulds. The casting of shrinkage prisms used regular steel moulds (Figure 13) as the possible impact on the strength of the prisms is not relevant.

Where relevant, the casting and curing procedures in BS EN 12390-2 [37] were followed, as no established methodology is currently available for foamed concrete. Cubes and associated shrinkage prisms were demoulded when they were deemed hard enough to handle without damage. This varied between mixes. After demoulding, cubes were labelled and sealed in polymer bags, imposing sealed curing as per industry practice [35]. These bags were placed in a temperature-controlled room at 19 ± 2^{o}C and 50 ± 10% RH.

3.3.3 Tests of Fresh Properties

3.3.3.1 Plastic Density

FPC desorbs between 50 and 200 kg/m^3 of the total mix water [35] making it difficult to design for a specific dry density. Therefore, a target plastic density becomes the design criterion. FGC was expected to exhibit similar values; however smaller changes were seen in this work. In addition, the mechanical action of the mixer can cause foam loss due to collapse or coalescing of bubbles. The volume lost is likely to depend on the integrity of the foaming agent, mixing duration and the chemical interaction between the foam and activated binder. In this work, the mixing time was kept approximately constant for each mix. Therefore, variation in the mix densities is likely to be dependent on the GGBS hydration compounds and interaction of these with the foam. The typical allowable variation in plastic density for FPC is ± 50kg/m^3 [35], increasing to 100 kg/m^3 for higher density mixes [3]. For this work, an allowable variation in plastic density for the initial mixes was chosen at ± 75 kg/m^3 and ± 50 kg/m^3 for the main mixes.

3.3.3.2 Slump Flow Test

There is no standard flowability test for foamed concrete as for NAC. Through the fresh properties of FGC are not the focus of this work, a comparison of the flow of each mix was

deemed important as for a possible commercial use of FGC as the ease of pumping over long distances is important.

There are numerous techniques to characterise flow, with many being applicable to FC. The slump flow test, BS EN 12350-8 [38], was selected as advised by The Concrete Society [3] along with reasons including ease of execution and equipment availability. It is a practical test that can easily be carried out on site in a similar way to a slump test for NAC (Figure 14). The test results in the contents of the slump cone being spread thinly into a disc (Figure 15), and the largest diameter, along with the diameter perpendicular to this, are measured. In addition, the time taken for the material to spread to a diameter of 500mm, known as the t_{500} time, is recorded. The slump-flow diameter allows categorisation into one of three slump-flow classes, giving an indication of the material's filling ability. The t_{500} time can be placed into one of two viscosity classes, giving an indication of flow speed and viscosity.

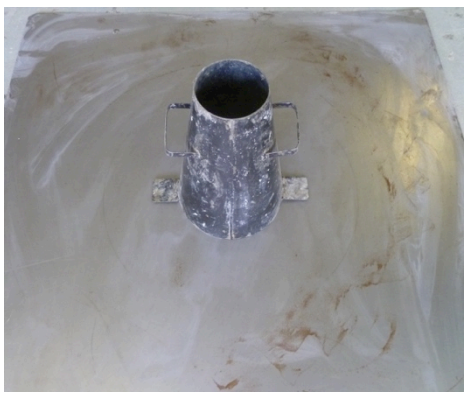


Figure 14: Slump flow test equipment. Note the marked circle for measuring the t_{500} time.

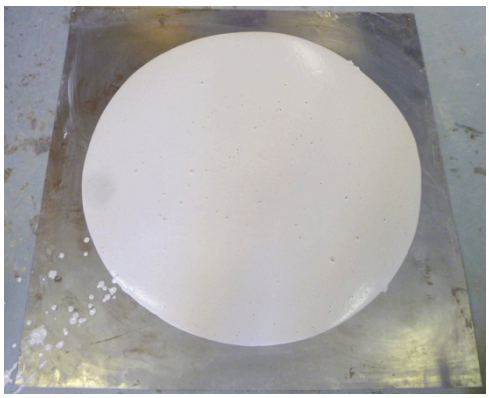


Figure 15: Result of a slump flow test: thin disc of material

In self-compacting concrete literature, the slump-flow classes correspond to a range of common applications. SF1 is suitable for pump-injection systems and SF2 is considered suitable for many normal applications [39]. For this experimental work, SF1 is adequate for foamed concrete and SF2 is considered ideal. Mixes with a slump-flow class of SF3 could be considered for refinement as they exhibit excessive flowability. The viscosity classes are VS1/VF1, indicating good filling ability with self-levelling capabilities, and VS2/VF2 indicating increasing thixotropic effects with increasing flow time. A viscosity class of VS1/VF1 is desirable for foamed concrete to allow long distance pumping. However, it is worth noting that the further foamed concrete is pumped, the higher the degree of flowability that is required.

3.3.4 Tests of Hardened Properties

3.3.4.1 Compressive Strength

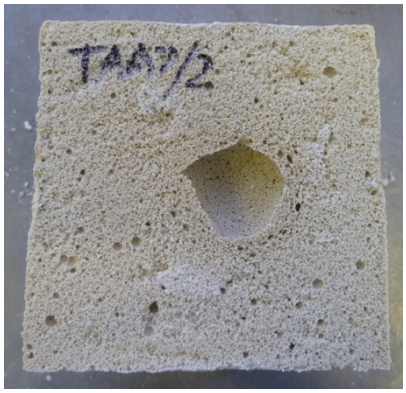


Figure 16: Example of a cube with a hole in the top

Figure 17: Controls C4600 2000kN compression frame

Figure 18: Controls C250kN compression frame

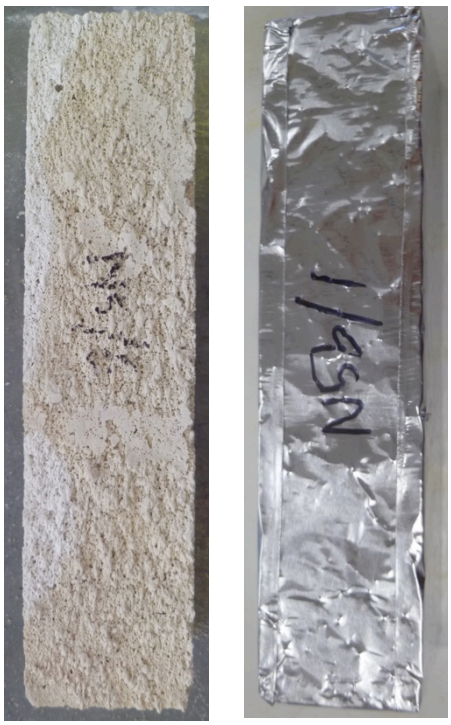
Upon demoulding, the cubes were weighed and the average side lengths measured with digital callipers. For the initial mixes, holes (Figure 16) or missing corners were noted and their volumes estimated for inclusion in the density calculation. The main mixes did not suffer from the same quantity of quality issues as the initial mixes.

A minimum of three cubes were tested at demoulding, 7 and 28 days using either a Controls C4600 2000kN servo-hydraulic frame (Figure 17) or a Controls C250kN frame (Figure 18), depending on equipment availability. The loading rate was set to 3000 N/s, in accordance with BS EN 12390-3 [40]. Cubes were tested in plastic bags to prevent the brittle cubes causing a mess (the bags did not affect the strength measurements). Due to the density variation within each batch, the cubes that were strength tested were chosen with different densities in order to give a representative strength for the batch overall.

3.3.4.2 Sealed Shrinkage

After demoulding, the shrinkage prisms were immediately covered with aluminium foil tape to seal them from the environment, enforcing autogenous conditions (Figure 19). A measurement of the prism length was taken relative to a reference bar (Figure 20) and this

initial length reading used in calculating the shrinkage strain as per BS EN 12617-4 [41]. Daily length measurements were taken, gradually reducing in frequency as the rate of change of the shrinkage decreased.



(a) Before taping (b) After taping up

Figure 19: Shrinkage prism

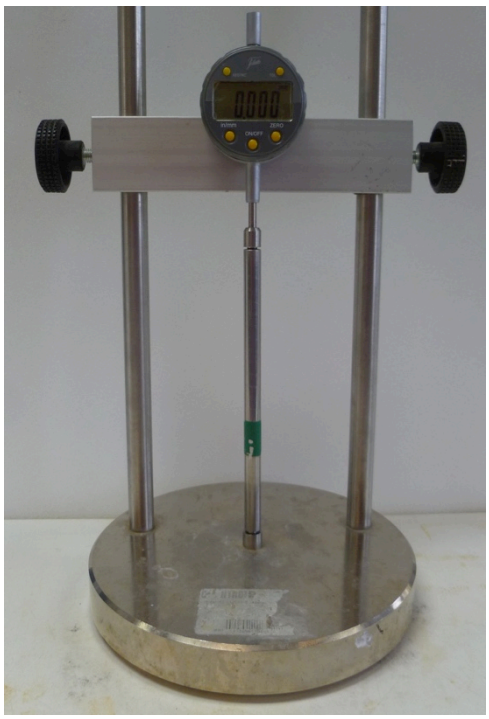


Figure 20: Shrinkage measurement apparatus with reference bar

3.3.5 Magnesia Reactivity Tests

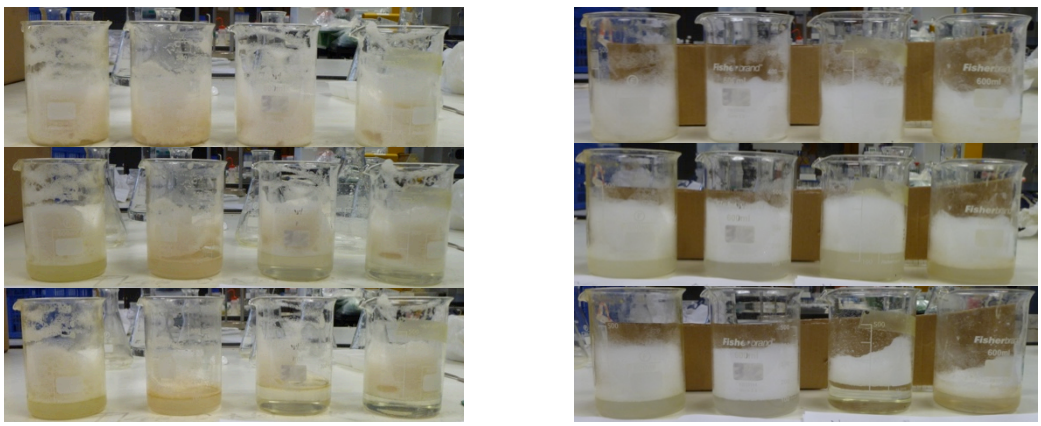
Reactivity tests were performed on both types of magnesia used in this experimental work. The test methods were as per the Acetic Acid Test 1 and Citric Acid Test 2 of research undertaken by Fei Jin [20]. These tests consisted of stirring a small amount of MgO with an acid and indicator. The time taken for the colour change of the indicator, representing neutralisation of the acid, was recorded for each test. The results of the tests from this work were compared to values given by Jin [20].

4 Results and Discussion

4.1 Material Tests

4.1.1 Foam Compatibility Tests

Compatibility between the foaming agents and the proposed alkali-activators was assessed under laboratory conditions. The results, as seen in Figure 21a, show that the protein-based foaming agent was not compatible with sodium carbonate or sodium silicate but was compatible with calcium hydroxide with magnesium nitrate and sodium hydroxide. However, the synthetic foaming agent, as seen in Figure 21b, was not compatible with calcium hydroxide with magnesium nitrate and had slight defoaming with sodium silicate.



(a) **(b)**

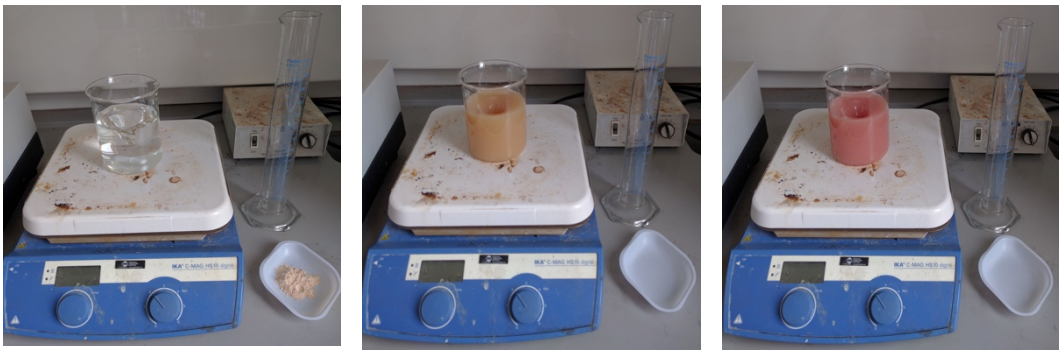
Figure 21: Foam compatibility tests: before, activator added and after 10 mins
NaOH, Na_2CO_3, Na_2SiO_3, $Ca(OH)_2$ + $Mg(NO_3)_2$
(a) Protein Foam (b) Synthetic foam

The foam compatibility test results were used to choose the activators to trial in the initial mixes. The TAA1-3 mixes were completed before the compatibility testing took place and the activator combination used in these mixes, $Ca(OH)_2$ + $Mg(NO_3)_2$, was not considered further due to the extensively long setting time (see section 4.4 for further discussion). For the initial mixes, the synthetic foaming agent was chosen along with varying combinations of sodium carbonate, sodium hydroxide and sodium silicate.

4.1.2 Magnesia Reactivity Tests

The reactivity of magnesia is expressed as the time taken to completely neutralise an acid, causing a colour change of the indicator, as shown in Figure 22. These values are then used to rank various MgOs relative to each other. The shorter the time, the more reactive the

magnesia is. For the same magnesia type, results from tests with different acids are not comparable to each other. The reactivity of magnesia contributes to its effectiveness in alkali-activated materials as an activator or an expansive agent.



(a) Before (b) During (c) After

Figure 22: Magnesia reactivity test [56]

Magnesia Type	Time to colour change (sec)		
	Acetic Acid	Citric Acid	Acetic Acid (as per Jin [20])
MgO_H – N50	<10	<10	<10
MgO_M – 92/200	440	845	550

Table 5: Magnesia reactivity test results

Table 5 gives the results from the reactivity tests of the MgOs used in this work and those found by Jin [20]. The MgO_H is deemed highly reactive because of the very short neutralisation time. The reactivity for the MgO_M in this work is within 20% of the value given by Jin and significantly different to that of the MgO_H. Therefore, it can be classed with medium reactivity. There is an understanding that different batches of the same type of MgO, even from the same plant, can have different properties because of variation in production and source material [20]. This could explain the difference between the results for the acetic acid test on MgO_M given by Jin and the value found in this work.

4.2 Slump Flow Tests

The results of the slump flow tests are given below in Table 6, along with the corresponding slump flow classes. For those tests that could be performed, the spread diameter exceeded 500mm in a time that could not be measured accurately without stopwatch errors being a

significant proportion of the measurement. Therefore, the viscosity class of each mix, according to the t_{500} time, was not taken into account.

Initial Mix	Average Diameter (mm)	Slump Flow Class	Main Mix	Average Diameter (mm)	Slump Flow Class
TOPC1	*809**	*SF3*	**N5**	578	SF1
TOPC2	770	SF3	**N5b**	-	-
TOPC3b	720	SF2	**N5H5**	-	-
TAA1	-**	-	**N5M5**	730	SF2
TAA2	828	SF3	**N5M5b**	-	-
TAA3	803	SF3	**N5M5c**	-	-
TAA5	843	SF3			
TAA6	-	-			
TAA7	720	SF2			
TAA8	-	-			
TAA9	-	-			

*Value taken from Wright [15] due to inadequate quantity of mix to perform a slump flow test

**No value due to error in test execution

Table 6: Slump flow test results for initial and main mixes

For both the initial and main FGC mixes, only half the slump tests were possible due to the problem of flash setting. The formation of specific products by the reaction of the sodium-based activator with GGBS caused mixes to thicken rapidly and become unrepresentative of the initial consistency. All of the main mixes were affected to some extent by flash setting. This phenomenon is not widely documented with the few reported cases attributing it to overdosing with strong alkali activators [42] or a low water content [43]. One possible solution is through continuous mixing to overcome the thickening effects [44]. This was unknown at the time and could not have been implemented without affecting the foam structure. For the mixes with MgO, except N5M5, the high water consumption of the MgO exaggerated the effect of flash setting and thickened the mixes further (see section 4.5.1.2 for further discussion).

In Table 6, the results of TAA7 and N5 should be the same, as they are identical mixes. However, the scaling up of mixes, with additional moulds to fill, increased the time from water addition to the slump flow test. This allowed the flash setting to impact the fluidity of the mix and reduce the slump flow diameter.

Overall, the results of the slump flow tests show that more research into the cause and prevention of flash setting is required to ensure adequate flowability and homogeneity of the final product.

4.3 Void Structure

Figure 24 shows that the void bubble distribution of the FPC (TOPC1) and FGC mixes are approximately even. Analysis of the microscopy images found no voids larger than 1mm, agreeing with values from literature [3].

There is little distinction between the mixes using the protein foam and those using the synthetic foam in terms of the void sizes produced (Table 7 and Figure 23). The FPC mix produced the largest void size and range in void sizes. However, the mean void size was consistent with the FGC mixes. This conflicts with the notion that a protein foaming agent produces smaller bubbles than a synthetic foaming agent, as given by literature [29].

Mix	Largest Void Diameter (mm)	Mean Void Diameter (mm)
TOPC1	0.892	0.335
N5	0.501	0.228
N5b	0.461	0.289
N5H5	0.692	0.333
N5M5	0.783	0.204
N5M5b	0.743	0.301
N5M5c	0.413	0.467

Table 7: Largest and mean void sizes

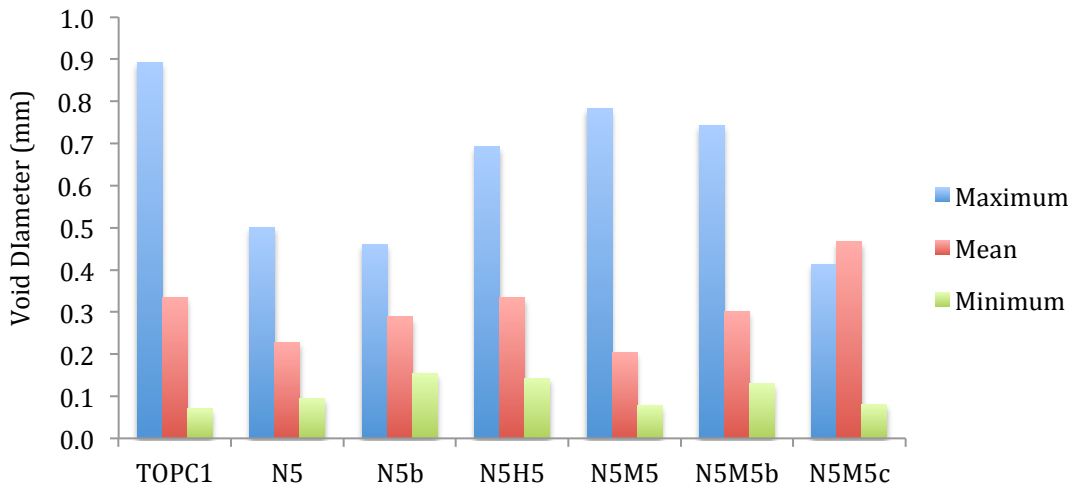
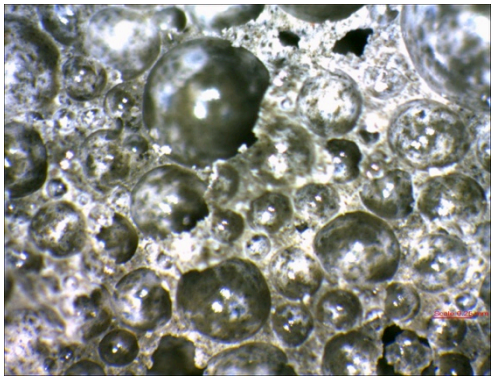
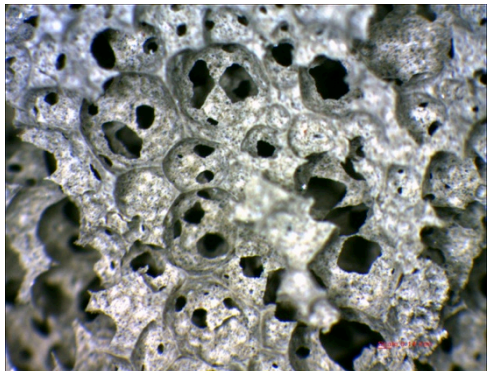


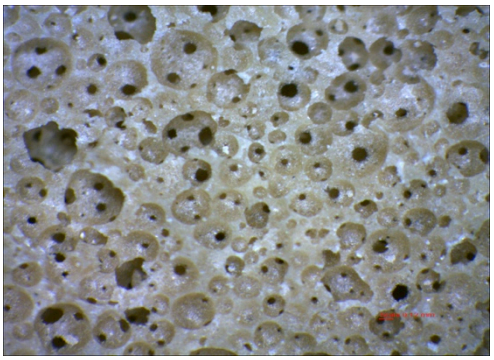
Figure 23: Maximum, minimum and mean void diameters



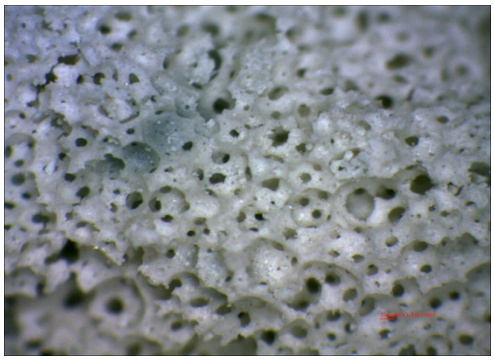
(a) TOPC1



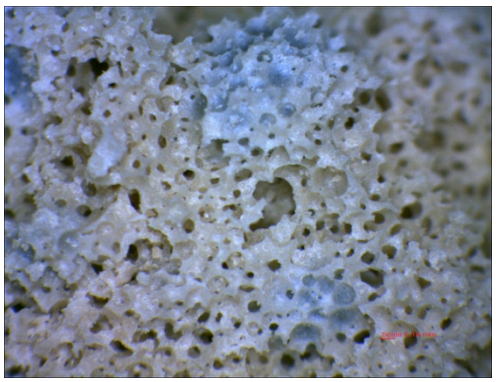
(b) TOPC3b



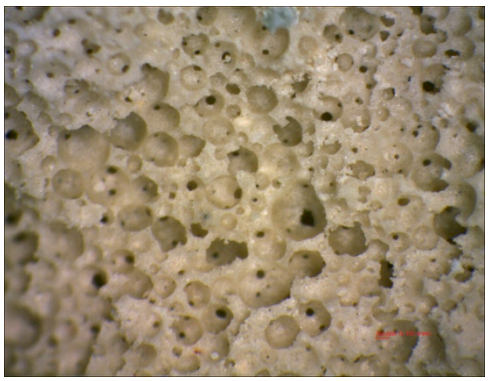
(c) N5



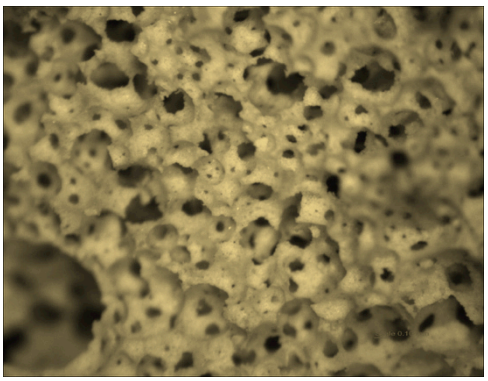
(d) N5b



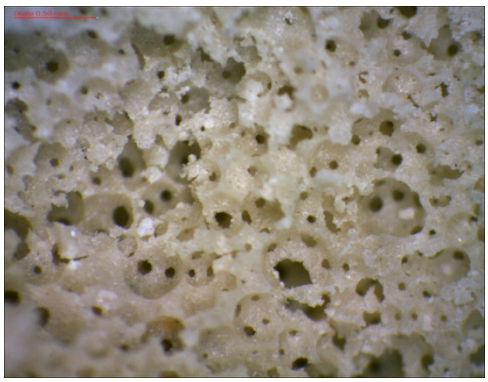
(e) N5H5



(f) N5M5



(g) N5M5b



(h) N5M5c

Figure 24: Optical microscope images of void structures

Note: the scale is not the same for each image

The main distinction between the protein foam and synthetic foam mixes, in terms of the microstructure, is the quality of the hardened paste between the voids. Compared to TOPC1 (Figure 24a), the other mixes (Figure 24b-h) have thinner walls and holes in these dividing walls. This could imply that the chemical interaction between the synthetic foam with the PC or activated GGBS is quite different to that of the protein foaming agent in terms of its stability and characteristics within the cementitious matrix during curing. More research into the chemistry between the activated GGBS and the foam during curing is required to assess the cause of these holes and the impact on the other properties of FGC.

4.4 Initial Mixes

			Demoulding Average		7-day Average	
Mix	Average Wet Density (kg/m^3)	Demoulding day	Dry Density (kg/m^3)	Strength (MPa)	Dry Density (kg/m^3)	Strength (MPa)
TOPC1	733	1	696	1.40	697	2.66
TOPC2	724	1	700	1.50	694	2.63
TOPC3b	580	1	530	0.37	548	0.78
TAA5	695	2	710	1.65	716	2.44
TAA6	746	5	722	2.90	734	3.14
TAA7	763	4	740	1.20	754	2.50
TAA8	617	3	628	0.50	627	0.67
TAA9	744	4	718	2.15	714	3.21

Table 8: Initial mix density and compressive strength results

Figure 25: Top of TAA6 cube

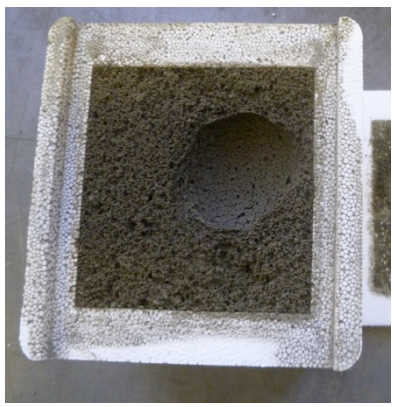


Figure 26: Example of TOPC3b cube with hole in top of cube

Three PC mixes, using the two foaming agents, were performed to give baseline values to which the AA mixes could be initially compared. As can be seen in Table 8, the two PC mixes

using the protein foam agent (TOPC1 & TOPC2) exhibited similar compressive strengths despite the differing w/b ratios (TOPC1 = 0.5, TOPC2 = 0.4). These mixes both gave densities very close to the desired dry density of 700kg/m^3. The mix with the synthetic foam, TOPC3b, showed a significantly lower density, with the chemistry between the synthetic foaming agent and PC being part of the cause. When handling the synthetic foam, it was observed that it was not as susceptible to defoaming through mechanical motion as the protein foam. The mechanical action of the mixer may have increased the air that was incorporated in the mix rather than breaking down the foam. The low strength of this mix may also be explained by an incompatibility between PC and the foaming agent in addition to the large holes caused by the foam coalescing (Figure 26) during curing acting as initial flaws for failure. Water was observed to seep out of the base of the moulds during initial curing. This seepage was attributed to the foam being broken down, allowing the bubbles to coalesce, rather than there being surplus water in the mix design.

The TAA1, TAA2 and TAA3 mixes do not appear in Table 9 as they did not set for a significant amount of time, >50 days, with the TAA3 cubes not able to be demoulded for twice as long, >100 days. Only the TAA2 cubes gave compressive strengths at demoulding, due to the other mix specimens squashing in the test apparatus with no value registering. Though Yang et al. [30] [31] successfully used the same activator proportions for FGC, their work used lower design densities at less than 500 kg/m^3. Therefore, it is possible that this activator combination is suitable for FGC but only at low densities.

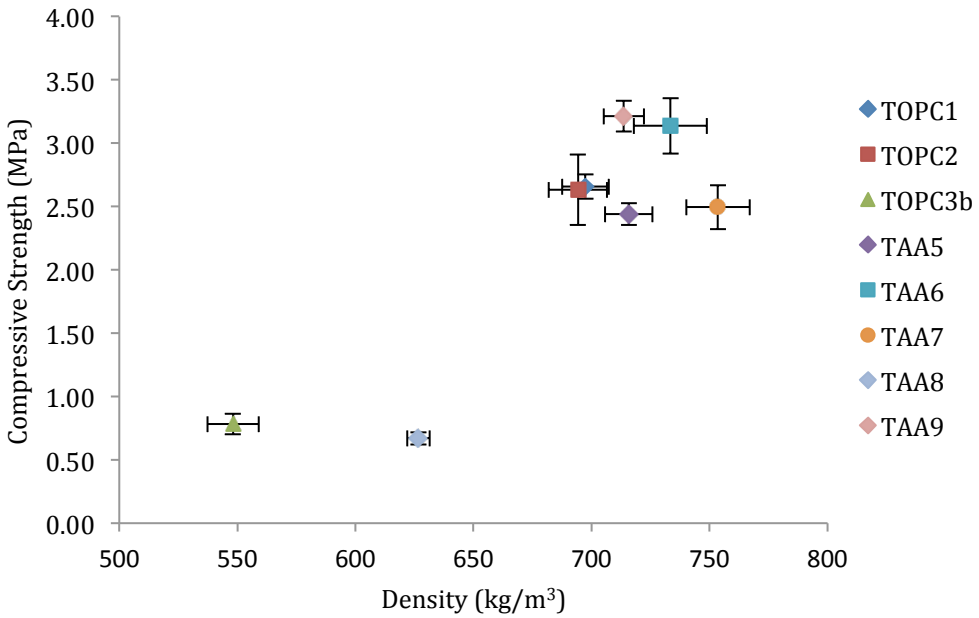


Figure 27: Initial mixes strength vs. density at 7-days

The majority of the sodium-based activators (TAA5-7, 9) produced mixes with good quality cubes (Figure 25) and compressive strengths that are comparable to the FPC mixes (Figure 27). The TAA8 mix used a combination of sodium carbonate and sodium hydroxide producing very weak and brittle specimens. This mix exhibited significant shrinkage in all dimensions while in the cube moulds (Figure 28). Sodium hydroxide was also used in combination with sodium silicate for TAA5, exhibiting very little shrinkage at the sides of the cubes and some vertically, as shown in Figure 29. TAA5 also had compressive strengths comparable to the other FGC mixes. The sodium hydroxide in combination with the sodium carbonate could be presumed to have reacted or created hydration products that interacted differently with the foam.

Figure 28: TAA8 cube with high shrinkage

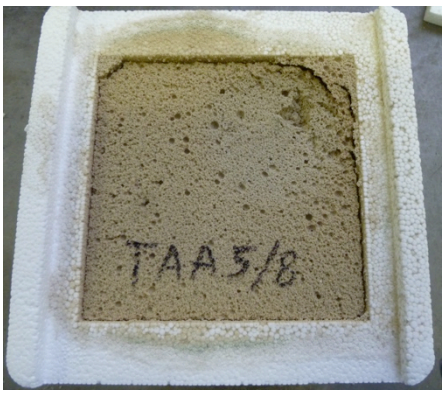


Figure 29: TAA5 cube with some shrinkage

The failure mechanisms of FC do not conform to the same mechanisms as NAC. The majority of the cubes exhibited a close to vertical crack failure mechanism as show by Figure 30a. Some mixes, such as TAA6, showed a failure mechanism as shown in Figure 30b. Here the majority of the cracks are vertical but the inner portion of the cube is stronger than the outer 'shell' which cracks off in large flat pieces. The weaker mixes with compressive strengths less than 1MPa, TOPC3b and TAA8, showed cracks angled away from vertical. Generally, the cubes fractured into a few larger pieces with small fragments from the failure interfaces falling off as the test progressed. Where there were holes in the tops of the cubes due to poor casting or coalesced bubbles, they instigated compression failure.

(a) (b)

Figure 30: Compression test failure mechanisms

An interesting observation was made during compression testing of the mixes with sodium-based activators of the development of a green colour within the cubes, as shown in Figure 31. This is attributed to a complex oxidation state of sulphide sulphur compounds during slag hydration. The colouring disappears upon exposure to direct sunlight and air, becoming light grey or white [45]. The different activator combinations produced different green patterns.

(a) TAA5 (b) TAA6 (c) TAA7

Figure 31: Different patterns of green colour development

The overall outcome of the initial mixes was the choice of sodium carbonate as the activator for the main mixes. Though it is acknowledged that there are longer setting times, sodium carbonate is superior to sodium hydroxide or sodium silicate in terms of safety, economic and environmental considerations [28]. In addition, high initial shrinkage and chemical incompatibility arose in initial testing for the other activator combinations. The concentration for sodium carbonate was chosen as 5% Na_2O per weight of GGBS. This was because the higher concentrations exhibited quicker flash setting and though casting of the cubes was completed satisfactorily, this would not be possible with an increased number of cube and shrinkage moulds to fill.

4.5 Main Mixes

A process of trial and error was used in developing the sodium carbonate-activated foamed GGBS concrete. The requirement for long-term compression tests lead to the ease of mixing and compressive strength at demoulding being taken as indicators to formulate the following mix compositions.

4.5.1 Compressive Strength

			Demoulding Average		7-day Average		28-day Average	
Mix	**w/b**	**Demoulding day**	**Dry Density (kg/m^3)**	**Strength (MPa)**	**Dry Density (kg/m^3)**	**Strength (MPa)**	**Dry Density (kg/m^3)**	**Strength (MPa)**
TOPC1	0.5	1	696	1.40	697	2.66	697	3.57
N5	0.4	4	642	1.67	652	2.07	655	2.95
N5b	0.4	3	649	0.42	667	0.60	669	0.75
N5H5	0.4	3	552	0.24	565	0.36	565	0.47
N5M5	0.5	5	741	1.84	741	2.11	740	3.31
N5M5b	0.45	4	606	0.27	615	0.35	616	0.43
N5M5c	0.475	3	686	0.73	669	0.99	671	1.40

Table 9: Main mix density and compressive strength results

Table 9 shows the results of the compressive strength tests for the main mixes, and TOPC1, along with the average dry densities of the cubes tested. The maximum difference between the dry densities at each testing time was approximately 3%. This is within the allowable ± 50 kg/m^3 within a batch. Figure 32 shows the relationship between the compressive strength and dry density at 28-days. A number of the mixes were affected by flash setting that prevented homogeneous mixing of the foam into the activated GGBS slurry, giving low compressive strengths. In a couple of these mixes, the proportions of foam to slurry in the cubes are higher than designed due to foam rising above the denser slurry in the mixer. This gave rise to low-density cubes.

There is a large variability in the demoulding day for the FGC mixes. This was due to the different setting times of the mixes caused by a variation in rate of hydration. Therefore, comparison of the early strengths is difficult.

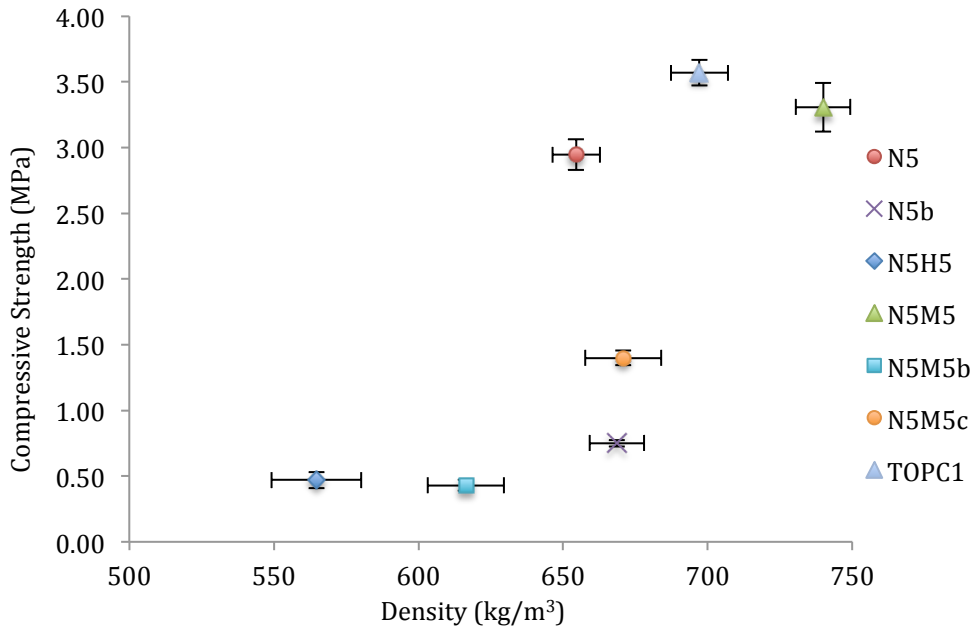


Figure 32: Main mix compressive strength vs. dry density at 28-days

4.5.1.1 Effect of Activator State

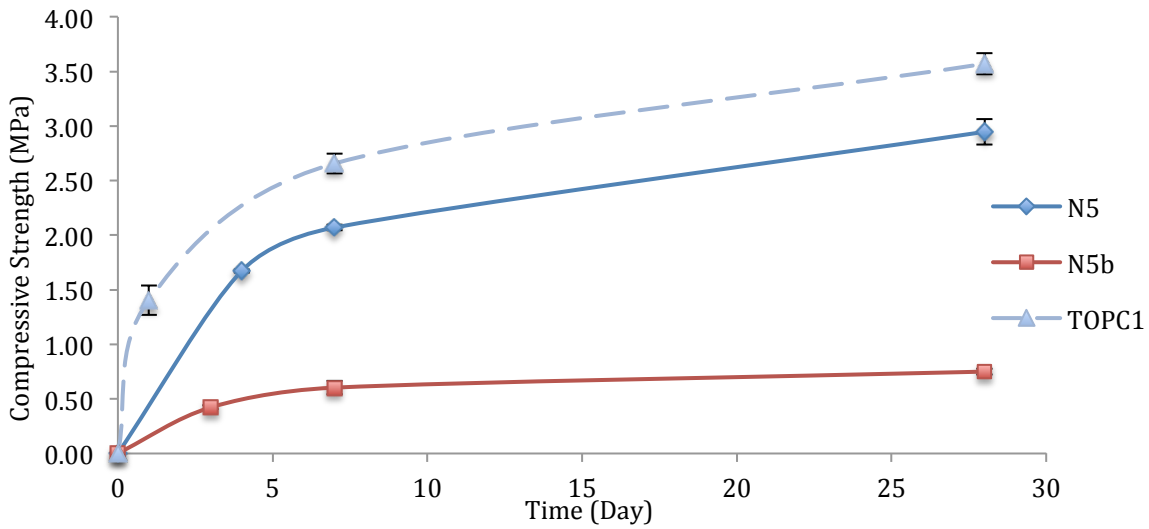
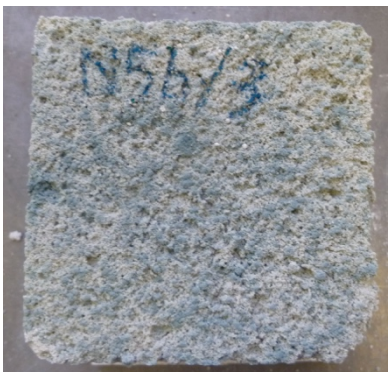


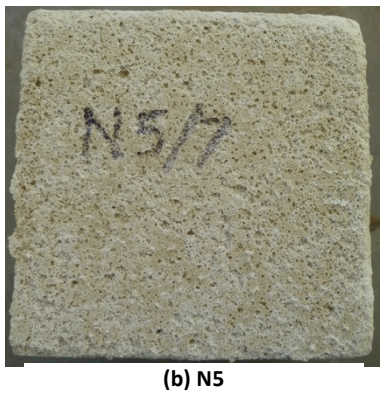
Figure 33: Strength development of the main mixes showing the effect of activator state

The N5 mix, using a powder activator, gave a 28-day compressive strength comparative to the FPC mix at 17% less than the TOPC1 value (Figure 33). Additionally, the dry density for the mix is also within 50 kg/m^3 of the desired dry density (Table 9). The slope of strength development indicates that at a greater age the N5 mix may not exceed the TOPC1 compressive strength. The N5b mix had the same composition as the N5 mix except that the activator was dissolved in the mix water prior to mixing to allow any heat of dissolution to dissipate. The high heat of dissolution was thought to be the instigation of flash setting in

the N5 mix, however this was disproved as the N5b mix exhibited even quicker flash setting. This was because the activator ions were already free to directly react with the GGBS rather than having to first dissolve. The flash setting prevented homogeneity of the activated GGBS slurry with the foam. The activated GGBS was held in balls by the foam matrix, Figure 34 and Figure 35, such that the compressive strength tests gave the strength for the foam matrix rather that the activated GGBS.



(a) N5b



(b) N5

Figure 34: Top of cube specimens

(a) N5b

(b) N5

Figure 35: Close up of internal structure

4.5.1.2 Effect of MgO

MgO was added into the FGC mixes as an expansive agent, with the N5M5 mix the first to be performed with the addition of magnesia. This addition also impacted the compressive strength of the specimens. The activated GGBS slurry, before the addition of the foam, was very thick due to the combination of the high magnesia water consumption and flash setting. This led to the foam rising on top of the dense slurry upon the addition of the foam to the mix. Continual scraping and mixing would not have been effective in thinning the mix due to the possibility of this breaking down the foam. The cast specimens, therefore, contained proportionally more foam than desired, lowing the cube density as seen in Figure 32. The strength value achieved is lower than that of the N5b mix, where the flash setting

caused the activated GGBS to be held by the foam matrix rather than being combined with it. This phenomenon also occurring for the N5H5 mx, and in conjunction with the magnesia water consumption gave very low compressive strengths. These values were more indicative of the strength of the hardened foam matrix than the activated GGBS.

A medium reactivity MgO was used for the rest of the magnesia containing mixes, along with an increased w/b ratio to try to reduce the impact of the magnesia water consumption. The N5M5 mix was the most successful of the magnesia containing mixes in that flash setting did not affect the casting. It did however produce a slump flow test that was not indicative of the nature of the material immediately at casting (See Section 4.2).

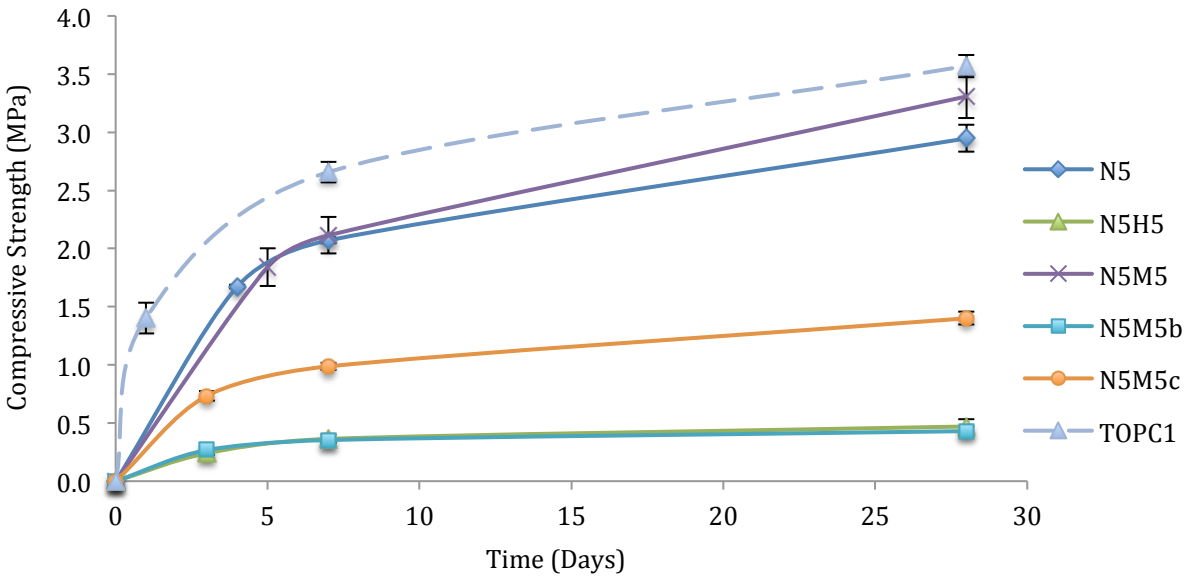


Figure 36: Strength development of the main mixes showing the effect of MgO

In combination with sodium carbonate, the addition of 5% magnesia has been shown to increase the compressive strength of normal-weight alkali-activated GGBS concrete [28]. This benefit was also found in this work as the N5M5 mix at 7-days and 28-days had a greater compressive strength than the N5 mix (Figure 36), even though the MgO slowed the strength development such that demoulding took place a day later than for the N5 mix. This resulted in the N5M5 28-day strength being only 7% less than that of the FPC mix. In addition, the slope of the strength development curve for N5M5 shows that at a greater age, the strength is likely to exceed that of TOPC1, showing that FGC mixes have the potential to produce greater compressive strengths than FPC mixes. Jones suggests that 56 days would

be a more appropriate 'long-term' compressive strength value than the standard 24 days for NAC [35]. This could be extended further given the slow strength development using GGBS.

4.5.1.3 Effect of water/binder content with MgO

For NAC, a reduction in water content generally increases strength provided that there is sufficient water for full hydration [3]. The success of the N5M5 mix at a w/b ratio of 0.5 prompted the investigation of the effect of reducing the w/b content on the compressive strength (N5M5b and N5M5c mixes). The results in Figure 36 show that reducing the w/b content did reduce the strength. This trend is, in part, as a result of the reduced workability of the activated GGBS slurry before the addition of the foam. With a reduced amount of water, the effects of flash setting and the MgO water consumption become more prominent. The N5M5b mix, with the lowest w/b content, showed similar difficulties with combining the foam into the activated GGBS slurry as the N5H5 mix (See section 4.5.1.2), giving low compressive strength and low density (Figure 32). This is evident in the appearance of the cubes in Figure 37.

(a) N5M5 (b) N5M5b (c) N5M5c

Figure 37: Cubes of mixes with medium reactivity magnesia

4.5.1.4 Strength-Porosity Relationship

Hoff's relationship, as mentioned in section 2.1.2, for predicting the strength of foamed concrete relies on the use of a purely PC binder [17]. Suitable adjustments for partial replacement of PC with FA have been found [16] but not for GGBS. Further work is required to assess FGC in terms of Hoff's strength-porosity relationship due to the low volume of data collected in this investigation.

René Féret established a rule that used a different approach to Hoff. It uses a void/cement parameter, $\frac{w+a}{c}$, where w, a and c represent the volume of water, air and cement respectively [46]. This parameter is then related to strength via:

$$S = K\left(\frac{c}{c+w+a}\right)^n = K\left(1+\frac{w+a}{c}\right)^{-n} \quad (8)$$

where K and n are empirical constants (n~2 for NAC).

Tam et al. used this equation to show the impact of water and air content on strength for various foamed concrete compositions with PC and sand [46]. Figure 38 shows their data points and fitted curve along with the data from this investigation. For the mixes in this work, the value of c, cement volume, is replaced with the GGBS volume.

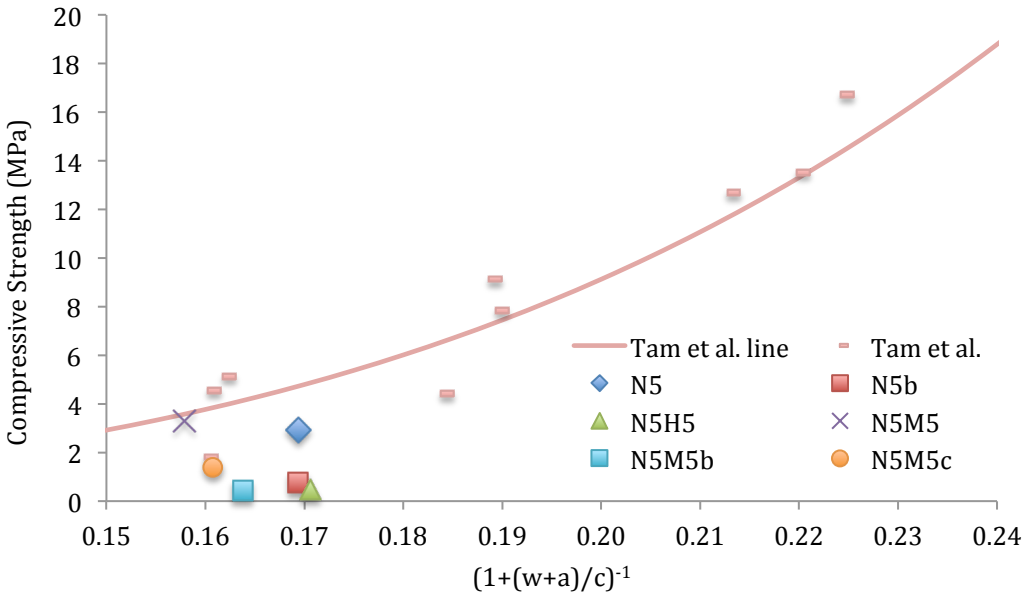


Figure 38: Comparison of the strength-porosity relationship for mixes in this work and from Tam et al. [46], with the power-law relationship from their work

The N5 and N5M5 points both lie within Tam et al.'s data spread [46], implying that their strength is largely governed by Féret's parameter. These are the two mixes that had a successful mixing process and were not detrimentally affected by flash setting, therefore producing good quality cubes with good compressive strengths. Féret's rule shows that FGC compositions' strengths are governed by his parameter, which implies that strength is reduced by increasing the air/GGBS or water/GGBS ratio.

4.5.2 Sealed Shrinkage Behaviour

The autogenous and drying shrinkages of alkali-activated materials are known to be significantly higher than that of PC-based materials [26]. Figure 39 shows that all of the alkali-activated mixes in this work exhibited higher sealed shrinkages than that of FPC, with the majority being between six and eight times greater.

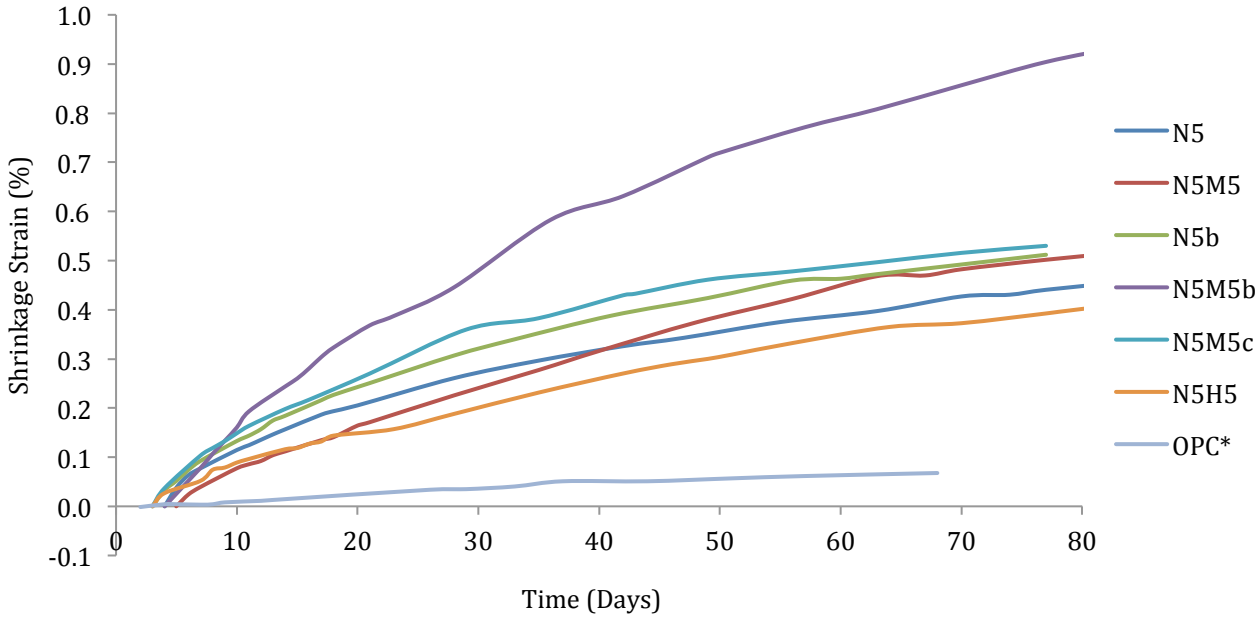


Figure 39: Sealed shrinkage strain for main mixes

*OPC results taken from Wright [15] as mix F6a
Note: The OPC results are for a higher design density than used in this work but are indicative of the order of magnitude of FPC shrinkage.

The term 'autogenous' is associated with the shrinkage that occurs in initial curing when the water inside the binding system is consumed with no moisture exchange to the environment. Results by Holt [47] [48] show that for a variety of PC pastes, mortars and concretes, after about one day of curing, the gradient of the autogenous shrinkage line is approximately the same for all mixes. In addition, the shrinkage that occurs in the first day can be significantly higher than that observed from the demoulding time. Therefore, this early shrinkage can be critical in terms of the overall shrinkage of concrete. There is little information about the early shrinkage of alkali-activated materials but it could be assumed that a similar trend would be seen. Since the sodium carbonate-activated foamed GGBS concretes produced in this work have longer setting times than the equivalent FPC, the shrinkage observed from starting measurements at a later demoulding day, will result in an

even slower autogenous shrinkage rate being observed. Therefore, the shrinkage lines are likely to be more similar in terms of gradient.

This work focused on long-term shrinkage, measuring shrinkage from demoulding. The results in Figure 39 show that the majority of the mixes have similar stable long-term shrinkage performance regardless of composition, except N5M5b. As these mixes took up to 5 days to be hard enough to be demoulded, it could be proposed that the majority of the autogenous shrinkage occurred during curing in the moulds. This is verified by the vertical shrinkages observed of the cube specimens and shrinkage prisms upon demoulding (Figure 40). The sealed shrinkage measured in this work is only indicative of the later stages of autogenous shrinkage where the rate of shrinkage is much slower.

(a) Cube **(b) Shrinkage Prisms**

Figure 40: Vertical shrinkage of specimens

4.5.2.1 Effect of Activator State

Higher sealed shrinkage was observed, as shown in Figure 41, when the activator was added as a liquid than as a powder. The addition of the activator as a liquid allows for quicker hydration of the GGBS because the sodium and carbonate ions are free in the mix water to immediately react with the GGBS. The quicker the hydration occurs, the higher the internal chemical shrinkage and therefore higher measured sealed shrinkage for the same duration.

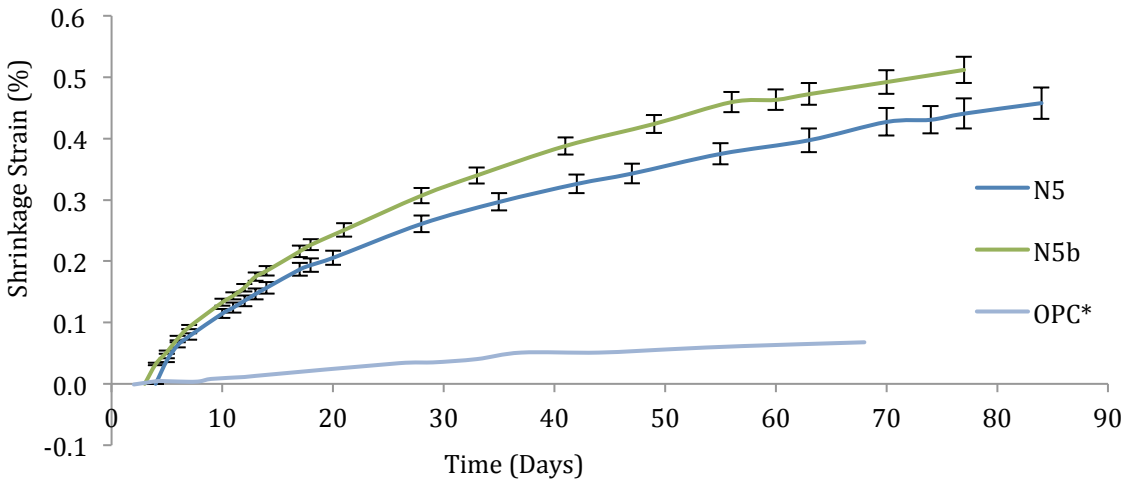


Figure 41: Sealed shrinkage strain showing the effect of activator state

*OPC results taken from Wright [15] as mix F6a

4.5.2.2 Effect of MgO

Wright [15] showed the addition of MgO to FPC reduces the autogenous shrinkage and can lead to expansion. The same effect was not seen in this work with the addition of MgO to FGC. As can be seen in Figure 42, the addition of highly reactive MgO did slightly reduce the shrinkage of FGC but not to the same extent that it does for FPC. This is due to the difference in hydration products that form when MgO and water are in the presence of PC or GGBS.

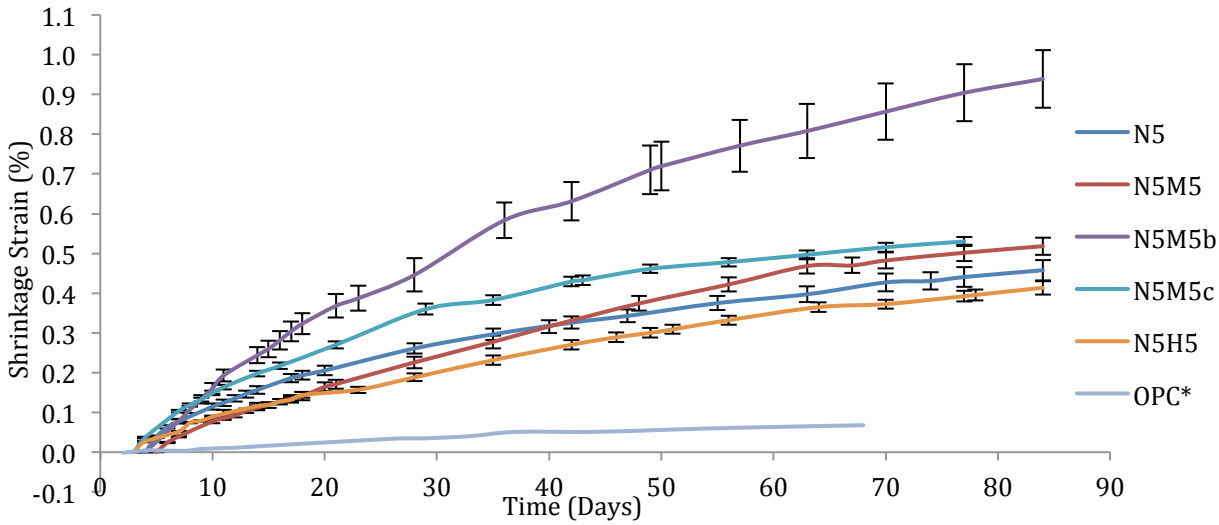


Figure 42: Sealed shrinkage strain showing the effect of MgO

*OPC results taken from Wright [15] as mix F6a

The addition of medium reactive MgO for the N5M5 mix increased the sealed shrinkage compared to N5. It is uncertain why this occurred as the addition of 5% MgO to non-foamed sodium carbonate-activated GGBS results in reduced drying shrinkage as shown by Jin [28].

4.5.2.3 Effect of water/binder content with MgO

From the N5M5 series results in Figure 42, it can be seen that reducing the w/b content increased the sealed shrinkage, with N5M5b giving the highest shrinkage for the lowest w/b. This agrees with the trend of the same nature seen for PC concrete by Holt [48]. Significantly high shrinkage was observed for the N5M5b mix. These results are likely to have been seriously affected by the discrepancy in foam to activated GGBS slurry ratio caused by flash setting and the mixing process.

4.5.3 Foamed vs. Non-foamed PC and AA concretes

Mix	28-day strength (MPa)	Foamed/non-foamed (%)
AA GGBS	54.45[1]	5.41
FGC	2.95	
PC	88.29[2]	5.69
FPC	5.02[3]	

Table 10: Comparison of foamed and non-foamed PC and GGBS pastes

[1]Results from [49], [2]Results from [50], [3]Results from [15]

Comparing the results from Abdalquader [49] of the 28-day strengths of sodium carbonate-activated GGBS paste and from Hekel et al. [50] on the 28-day strengths of PC paste, the effect of foaming a sodium carbonate-activated GGBS paste conserves approximately the same amount of compressive strength as foaming a PC paste. The N5 mix from this work and the F6a mix from work by Wright [15] exhibit approximately 5.5% of the strength of the constituent pastes. This shows that the synthetic foaming agent in the FGC can be equally effective as the protein foaming agent in the FPC.

4.6 Observance of Specimen Quality

The specimen quality for FGC was found to be variable depending on the interaction of the activator, binder and foam. Upon demoulding, a number of cubes had missing corners or flaking sides where the mix had stuck to the moulds but the main bulk of the specimen had shrunk away (Figure 43). Where possible, extreme care was taken that the action of removing the polystyrene did not cause fracture to the specimens. The shrinkage prisms adhered to the steel moulds, even with the use of mould release oil, therefore some

specimens had chunks missing from the sides (Figure 44). There was no discernible effect of these on the measured shrinkage values.

Figure 43: Poor cube corner quality

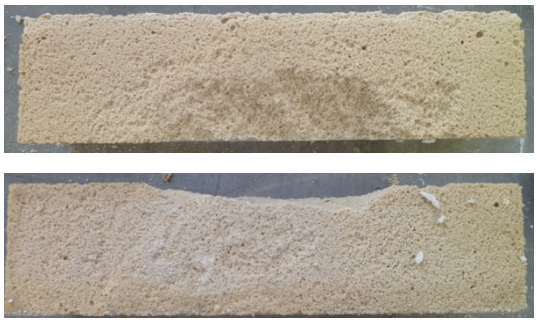


Figure 44: Poor quality shrinkage prism

4.7 Experiment Improvements

The addition of fly ash (FA) to GGBS activated by sodium carbonate has been shown to give increased long-term (>90 days) strengths [21]. The possible addition of FA to the FGC mixes in this work could help to reduce the flash setting by reducing the GGBS content per weight of FGC. This would allow higher strengths and overcome the mixing issues. Furthermore, additions of MgO along with the sodium carbonate activator could further increase the compressive strengths of alkali-activated fly ash/GGBS concretes [21].

Another improvement could be the use of a different type of mixer. The cement mixer, as used in this work, did not effectively break up lumps that formed, requiring manual scraping. The use of a mixer with greater "relative motion" in terms of its mixing action (e.g. a balloon whisk attachment on a kitchen countertop mixer) would help to overcome the thixotropic effects of fast setting and allow quicker combining of the materials. Care would need to be taken when combining the foam to ensure that its structure is not destroyed by the action of the mixer.

4.8 Laing O'Rourke Specification Compliance

Although the findings of the above investigations are valid in their own right, the performance of the FGC mixes has been evaluated against the specification provided by Laing O'Rourke in Section 1.2. Below are brief observations regarding each of the criteria:

1) Density < 800 kg/m^3

   This was successfully met by all of the mixes, with individual cubes being within the allowable ± 50 kg/m^3 batch variation. With the design dry density being 700 kg/m^3, a large variation in the final dry density was seen. This was caused by the effect of flash setting on the homogeneity of some of the mixes and the different contributions of each constituent material in terms of the hardened concrete.

2) Strength > 4 MPa

   This was not met by any of the FGC mixes. Increasing the design dry density closer to 800 kg/m^3 or increasing the content of MgO above 5% may yield higher compressive strengths at 28-days. Additionally, if the strength at a greater age, such as 56 days as suggested by Jones [35], was considered the 'long-term' strength then the FGC mixes in this work have the potential to reach a compressive strength of 4 MPa.

3) Void size < 0.5 mm

   The majority of the void sizes within the FGC were less than 0.5 mm, as shown in Figure 23. However, four of the mixes exhibited maximum void sizes larger than 0.5mm and so this criterion is not met. Altering the settings of the foam generator to produce denser foam, or perhaps using a different foaming agent could reduce the size of the voids.

4) Lightly expansive ~0.5%

   This was not met by any of the mixes. High shrinkage was observed, with minimal expansive effect from the MgO additions. The expansive compounds that MgO forms when included with GGBS in FGC are not the same as those that form when included with PC and not as voluminous.

5) Early strength > 25% of long term strength after 20 hrs at 20^{o}C

   This was not met by any of the mixes. Demoulding was only possible at a minimum of 3 days after casting due to the slow strength development of sodium carbonate-activated GGBS. The addition of superplasticisers may allow the early strength to be increased or demoulding to occur at an early stage.

6) Closed voids for low water absorption

   This was not examined beyond the microscopy work in Figure 24. These images indicate that there are gaps in the walls of the hardened GGBS paste between the voids. These significantly increase the transport of moisture and deleterious species though the FGC. In absences of these holes, diffusion must occur through the hardened GGBS wall itself.

5 Conclusions and Recommendations for Future Work

5.1 Conclusions

Following on from the success of partial cement replacement in PC foamed concrete, this investigation sought to increase the energy-efficiency of foamed concrete through complete substitution of PC by an alkali-activated binder. There is minimal literature currently available about alkali-activated foamed concretes. Most concern fly ash-based material requiring heat treatment for strength development. Therefore, the aim of this work was to explore the development of an alkali-activated foamed GGBS concrete at ambient temperature.

Initial tests trialled a number of activator combinations and two different foaming agents. As a result of these, the requirement for compatibility between the activators and foam was identified and sodium carbonate was chosen as the activator for the main testing.
The main experiments undertaken revealed the principles outlined below:

1) Sodium carbonate-activated GGBS can successfully act as a binder for foamed concrete, exhibiting compressive strengths comparable to FPC.
2) High sealed shrinkage was shown for all the FGC mixes compared to FPC. Stable long-term shrinkage behaviour was reached by all but one mix.
3) Sodium carbonate as an activator causes flash setting and negatively affects the fluidity and homogeneity of fresh FGC. The addition of MgO, with high water consumption, can intensify these effects.
4) The use of a powder activator rather than a liquid activator slows the effects of flash setting resulting in higher compressive strength and lower sealed shrinkage.
5) The substitution of MgO for GGBS can increase the strength of FGC with a 12% increase observed at 28-days.
6) The use of MgO as an expansive agent in FGC had a minimal effect on the sealed shrinkage of ±10%, as measured from the demoulding day, depending on the type of magnesia used. This effect is not as great as is shown for MgO addition to FPC.
7) The void sizes of FGC are not affected by mix composition. However, the synthetic foam caused holes in the hardened paste of the void walls.

With further research and testing to reduce flash setting and autogenous shrinkage, sodium carbonate-activated GGBS could become a viable and sustainable alternative binder in place of Portland cement for the production of foamed concrete.

5.2 Recommendations for Future Work

There are a number of avenues down which future work could be routed. Firstly, understanding the reasons for the flash setting issue by investigating the chemical interactions between the GGBA, activators and foam. An option for reducing flash setting could be the partial replacement of GGBS with another SCM, such as FA, to limit the amount of the flash setting compounds that could form. A greater understanding of the hydration reactions of reactive magnesia and GGBS, and knowledge of the expansive products that form, could be sought to allow the high shrinkage of FGC to be reduced.

Secondly, further development of the mixes established in this work could be explored using more sophisticated mix design procedures, taking into account the water requirement of each constituent material.

Thirdly, improving the properties of FGC towards the ideal specification given by Laing O'Rourke. Through investigating the hydration reaction that occur during setting, earlier demoulding and possibly increased early-age compressive strengths may be possible. For NAC, the use of admixtures is common however they are generally designed for use with PC only and can have a negative impact on foam stability [3]. There would be great value in finding a superplasticiser compatible with fresh foam in order to maintain flowability with a reduced water content or to increase the flowability at constant water content. Strength increases would be an additional benefit.

For commercial use of FGC, the development of standards and design codes would be essential to ensure usage is appropriate and safe. Further research into additional properties of the FGC, such as durability (permeability and resistance to chemical attack), fire resistance and long-term stability, would be required before commercial implementation.

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Appendix A – Risk Assessment Retrospective

The start-of-project risk assessment (RA) quite accurately reflected the risks encountered in this work. Care was taken when writing this RA to include aspects from the previous project's RA.

The project risks can be divided into three groups. In the first category are risks that were anticipated but did not occur. The risk of using electrical equipment, e.g. the mixer, was identified. The equipment was used as intended and no mishaps occurred. Similarly, the lab technicians take a great deal of care to ensure the laboratory environment is clear of clutter, therefore there was little possibility of tripping, as identified in the original RA.

The second category is for risks that did occur but required more specific identification. A rubber mat was implemented as a cover for the mixer while in motion to prevent the escape of hazardous substances. This was identified through the previous project however could not be held in place during the addition of liquids or the foam to the mixer. Prior knowledge of this might have led to the sourcing of a cover that would allow protection during these additions.

No risks for the third category, risks that were not anticipated in the original RA, arose. Alterations were made to the chemical tests performed during the project but the COSHH assessment was updated before any experimental work took place.

Risk assessments attempt to anticipate every risk associated with an activity, aiming to prevent or mitigate the occurrence of injury or damage before it can occur. It is recommended that future risk assessments should build upon the original RA and notes above. Additionally, conducting risk interviews with at least one student and one technician who use the relevant laboratory spaces would be beneficial in identifying risks that are hard to imagine prior to starting work.