GRANULATED BLAST FURNACE SLAG IN STRUCTURAL LIGHTWEIGHT PANEL FOR HOUSING

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by

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GBS	Granulated Blast Furnace Slag
GGBS	Ground Granulated Blast Furnace Slag
SCM's	Supplementary Cementitious Materials
ASTM	American Society for Testing Materials
ACI	American Concrete Institute
UPV	Ultrasonic Pulse Velocity
BOF	Oxygen Furnace Slag
EAF	Electrical Arc Furnace Slag
LDF	Ladle Furnace Slag
SCC	Self Compacting Concrete
ITZ	Interfacial Transition Zone
LVDT	Linear Variation Differential Transformer
n_w	Ultimate design load per meter run

SANGGA RELAU BAGAS BERBUTIR DALAM PANEL STRUKTUR RINGAN UNTUK PERUMAHAN

ABSTRAK

Sangga relau bagas berbutir (GBS) adalah bahan buangan utama yang dihasilkan oleh industri besi. Dalam usaha untuk menjadikan sebagai bahan pozzolanik yang berkesan, GBS perlu dikisar. Dengan proses tersebut, ianya mengakibatkan penambahan kos dan meletakkan tenaga pengeluaran yang lebih, dan hasilnya, pelepasan gas yang tinggi kepada alam sekitar. Kajian ini bertujuan untuk menggunakan GBS sebagai pengganti simen separa untuk pengeluaran konkrit busa. GBS digunakan sebahagiannya bagi menggantikan simen pada tahap penggantian 30-70% mengikut berat simen pada ketumpatan 1300 kg /m^3 campuran konkrit berbusa menggunakan tiga nisbah pengisi kepada pengikat yang berbeza (1.0, 1.5 dan 2.0). Dalam usaha untuk mempunyai pemahaman yang lebih baik tentang perbezaan prestasi antara GBS dan sangga relau bagas hancur (GGBS) yang digunakan secara meluas, GGBS telah digunakan dalam menghasilkan konkrit berbusa menggunakan ketumpatan, tahap penggantian dan nisbah pengisi untuk pengikat yang sama. Sebanyak 36 campuran disediakan dan telah diuji untuk sifat fizikal, mekanik dan ketahanan pada tempoh masa yang berbeza. Hasil kajian menunjukkan campuran optima konkrit berbusa GBS adalah campuran yang mengandungi 30% daripada GBS dan nisbah pengisi untuk pengikat 1.5. Campuran ini dipilih untuk fabrikasi kelompang luar untuk panel dinding pratuang. Panel dinding direka sebagai dinding tanggung beban yang dibuat daripada dua bahagian lapisan disambungkan bersama-sama menggunakan bolt keluli. Kedua-dua kelompang luar direka sebagai panel berusuk dan teras dalaman yang terdiri daripada campuran 500 kg/m^3 konkrit berbusa. Melalui ujian eksperimen, panel dinding

mencapai purata beban pemecah sebanyak 391kN, iaitu 51.6% lebih tinggi berbanding dengan beban teori yang diperolehi menggunakan beban rekabentuk muktamad.

GRANULATED BLAST FURNACE SLAG IN STRUCTURAL LIGHTWEIGHT PANEL FOR HOUSING

ABSTRACT

Granulated blast furnace slag (GBS) is the main waste material produced by the iron industry. In order to activate as an effective pozzolanic material, GBS needs to be ground. Hence, adding to its value in cost and putting in to its production more energy, and as a result, more gas emissions to the environment. This study aimed on using GBS to be used as partial cement replacement for the production of foam concrete. GBS is used to partially replace cement at replacement levels of 30-70% by weight of cement in a 1300kg/m^3 foam concrete mix using three different filler to binder ratios (1.0, 1.5 and 2.0). In order to have a better understanding about the difference in performance between GBS and the widely used enhanced ground granulated blast furnace slag (GGBS), GGBS was used in producing foam concrete using similar density, replacement levels and filler to binder ratios. A total of 36 mixes were prepared and were tested for their physical, mechanical and durability properties at different ages. Results showed that the optimum foam concrete GBS mix was the mix that contained 30% of GBS and with filler to binder ratio of 1.5. This mix was chosen for the fabrication of the outer shell for the precast wall panel. The load bearing wall panel made out of two halves connected together using steel bolts. The outer shells are designed as a ribbed panel and an inner core made out of a 500kg/m^3 foam concrete mix. Through the experimental test, the wall panels achieved an average breaking load of 391kN, which is greater by 51.6% in comparison to the theoretical load determined using the ultimate design load.

CHAPTER 1

1.1 INTRODUCTION

Due to its versatility, economy, raw materials availability, durability and strength; concrete is the most widely used material on the planet after water. It can be designed to endure the harshest of environmental circumstances and can be fabricated to take any shape and form (Ozlutas *et al.*, 2012). Although concrete is used extensively, it is a huge contributor to global warming. In the construction industry, and especially in the production of concrete, the amount of crushed rocks and gravel needed annually is estimated to be up to 11 billion tons (Mehta, 2001). Furthermore, to produce a ton of cement, the needed energy consumption and the emitted emissions of carbon dioxide (CO_2) into the atmosphere are estimated to be approximately 150 kWT and 0.81 tons, respectively (Chandra, 1996; Huntzinger and Eatmon, 2009).

It is a well-known fact that technology is becoming increasingly prominent in the construction industry. This prominence is the result of the construction industries' need to produce innovative building materials. Hence, nowadays, concrete contents are not limited to cement, aggregate, and water, but it also has minerals and admixtures that can enhance the quality of the concrete and reduce its negative impact on the environment (Aïtcin, 2000). In addition, new types of concrete have been developed to ensure the creation of more environmentally friendly concretes. This is done by reducing the concrete's exploitation of natural resources and reducing the concrete's energy consumption by making them lighter (Ul Haq and Liew, 2007).

Scientists and engineers are continuously striving towards the creation of innovative chemical admixtures and supplementary cementing materials (SCMs). The use of such materials conserves energy and has environmental benefits because of reducing the amount of manufactured cement, and as a result, reducing the amount of green house emissions to the atmosphere. Strict regulations and air pollution controls caused the production of numerous industrial by-products that can be used as SCMs. Such examples are fly ash, ground granulated blast furnace slag (GGBS), metakaoline and rice husk ash. These materials have been typically used in concrete manufacturing for the sake of cement content reduction, workability and strength improvement, and durability enhancement (Chandra, 1996; Siddique, 2007; Siddique and Khan, 2011).

New types of concrete have been developed to counter the effects of global warming. Concrete types that are lightweight or use lightweight materials are an attempt to re-establish concrete as an environmental friendly material (Noordin and Awang, 2005). Lightweight concretes when used in construction reduce the cost and sizes of the super and substructures in the building. Lightweight building components also reduce the energy consumption used in their transportation and placement. In addition, using lightweight concrete in the construction of buildings will reduce the building's energy consumption used for cooling and heating (Fouad, 2006).

Foam concrete, as a type of lightweight concrete, has been proven to be more environmentally friendly as it uses fewer natural resources than conventional concrete. Additionally, it is superior to conventional concrete in terms of fire resistance as well as thermal and sound insulation. Foam concrete can offer moderate mechanical properties, reduce the weight of superstructures or substructures, minimise the overall cost of construction, and it can be handled and constructed relatively faster and easier (Kearsley, 1999; Mahmood, 2010; Noordin and Awang, 2005).

Aiming on making foam concrete more environmentally friendly and more cost effective (Huntzinger and Eatmon, 2009), extensive research has been done in using SCMs in its fabrication. SCMs such as fly ash, GGBS and rice husk ash has been used as partial or complete replacements for the binding and/or filler materials (Neville, 1996).

GGBS is a by-product of the iron industry. In a 1500C blast furnace, iron ore, limestone and coke are heated up and melted. As a result of the melting process, two products emerge and they are molten iron and molten slag. Due to its lightness, the molten slag floats on the molten iron. The molten slag comprises of silicates and alumina from the original iron ore with a combination of some oxides that originate from the limestone. As mentioned before, GGBS has been used extensively in concrete as a partial cement replacement at different levels by weight of cement. GGBS is known to have a positive impact on the strength and durability of concrete (Siddique, 2007).

1.2 PROBLEM STATEMENT

According to a report published by the World Steel Association in 2013, Malaysia was placed among the top 25 countries that produce an average 5.9 million tons of steel annually (World Steel Association, 2010). The processing of each ton of steel produces around 300 kilograms of by-product materials (Neville, 1996). Specifically, the steel slag waste in Malaysia is around 1.77 million tons per year. 65% of slag waste is used as GGBS and the remainder, which is around 620,000 tons, is disposed in the environment (Motz and Geiseler, 2001). The storage of slag not only occupies large amounts of land resources but also has a negative impact on the environment by polluting the soil, underground water and the atmosphere (Li *et al.*, 2015).

GGBS has been exploited extensively in the production of concrete. However, after several attempts done by (Bijen, 1996; Chen, 2007; Chi *et al.*, 2012; Memon *et al.*, 2007; N. Arreshvhina *et al.*, 2006; Parniani *et al.*, 2011; Wang *et al.*, 2005; Yüksel *et al.*, 2007; Yüksel *et al.*, 2008), the integration of GGBS was mostly limited to conventional concrete while only a few researchers investigated the possibility of integrating GGBS in foam concrete. In addition, the replacement level of the binder was also limited (Pan *et al.*, 2007; Sanjaya *et al.*, 2007; Wee *et al.*, 2006; Wee *et al.*, 2011).

Granulated blast furnace slag (GBS) is yet to be investigated as a partial cement replacement. The utilisation of GBS in concrete production will cause a reduction in both cost and energy consumption. It is a known fact, that slag particles require longer time to be ground than that of cement clinker; hence, require more energy (Zandi and Vefa Akpinar, 2012). Conventional methods of construction are divided into two major components. The first component is the structural system, which comprises of beams, columns and slab frames that are cast in-situ. The construction of these frames goes through four operations.

These operations are erecting the timber formwork and scaffolding, erecting the steel bars for reinforcement, fresh concrete pouring into the form and finally, the dismantling of formwork and scaffolding. These conventional methods are labor intensive, tiresome and require a lot of onsite coordination. The second component consists of erecting the partitions, which consist of brick work and plastering (Abdul Kadir *et al.*, 2006).

As a response to the problems associated with conventional construction methods, the technology of industrialised construction is becoming a preferable option, especially in making lightweight prefabricated structures, which perform better than conventional concrete due to their lesser weight, thermal insulation properties, and good strength to weight ratio (Sumadi and Memon, 2008). Along with the benefits of utilising the IBS application that was mentioned by in previous studies (Onyeizu *et al.*, 2011; Taherkhani *et al.*, 2012), IBS technology saves approximately 20% of the wastages from the overall construction cost, such wastages typically occur when using conventional construction methods (Lim, 2006).

The pre-fabrication and pre-casting of structural wall panels have many advantages than the other systems. A precast structural wall has the capacity to eliminate the structural frame system (columns and beams), sustain the lateral and gravity loads, reduce the exterior and interior frame (if they are present in construction), and increase the span of the slab. Furthermore, it is able to increase the thermal insulation and become part of the precast wall (Ragan, 2011). Moreover, if the Malaysian construction industry adopts the IBS construction system, a total reduction of 4.72 million tons of CO_2 emissions can be achieved.

In addition, when selecting a precast wall panel system in a given structure, a total reduction in emissions of 26.27% is achievable (Omar *et al.*, 2014). However, wall panels constructed using conventional concrete are heavy and require special attention when transported and erected into their position. Therefore, lighter weight wall panels are a good solution in reducing both the cost and energy consumption of such construction method.

Motivated by the problems mentioned previously in this section, this study incorporated GBS as a partial cement replacement into producing foam concrete. In addition, a GBS foamed concrete mix is used to fabricate a lightweight wall panel, which will be designed and used in the construction of a low medium cost house.

1.3 OBJECTIVES OF THE STUDY

The aim of this study is to investigate the possibility of using GBS in the production of foam concrete. The GBS is used to partially replace cement at different replacement levels. The assessment of such incorporation is made through the determination of the physical, mechanical and durability properties of the GBS foam concrete. For the sake of comparison, foam concrete containing similar cement replacement levels of GGBS has been prepared and its physical, mechanical and durability properties were determined. Finally, the foam concrete mix containing GBS that offers a balance between maximum GBS content and properties is used to fabricate the lightweight wall panel. Therefore, the following objectives are set to be achieved by this study:

1- To investigate the physical, mechanical and durability properties of foam concrete using GBS as cement replacement at different levels and binder/filler ratio.
2- To compare the properties of GBS and GGBS foam concrete using similar replacement levels and binder/filler ratio.
3- To establish the optimum replacement level and mix ratio of GBS in foam concrete based on adequate mechanical, physical and durability properties.
4- To construct a functional precast load-bearing wall for low-rise residential buildings using the optimum GBS foam concrete mix.

1.4 SIGINIFCANCE OF THE STUDY

From an environmental perspective, utilising GBS as partial cement replacement in foam concrete will reduce the dependency on cement and as a result decrease the carbon footprint of foam concrete. In addition, GBS utilisation will reduce the negative impact of leftover slag on the environment. As a result increasing the possibility of using such a slag in the production of other types of concrete. Moreover, using GBS instead of GGBS will eliminate the energy consumed for the production of GGBS. Furthermore, GBS is more cost effective than its ground counter part, hence, manufacturing a cheaper type of foam concrete.

Since GBS is a new material that its incorporation as a partial cement replacement is yet to be investigated, the effect of GBS as a partial cement replacement was compared to the well-known and the extensively researched GGBS. The uniqueness of such an endeavour was to increase the knowledge about the difference in performance of these two materials. These two materials (GBS and GGBS) were used to partially replace up to 70% of the cement in foam concrete mixes that have a semi-structural density of 1300kg/m^3.

The foam concrete mix that incorporates a maximum amount of GBS without affecting the properties negatively was used to fabricate the precast wall panel. The panel has unique features in itself. The optimum GBS foam concrete mix will be used to fabricate the outer shell in which it is using a semi-structural density and not a structural density. In addition, the wall panel will be made out purely from foam concrete, hence, creating a lightweight wall panel used for structural applications. In addition, the uniqueness of this wall panel also arises from its thinner outer shell (thickness = 30mm), which is designed as a ribbed panel.

1.5 SCOPE OF THE STUDY

In this study, GBS will be used as a partial cement replacement in foam concrete having a semi structural density of 1300kg/m^3. GBS will replace the cement using a replacement level of 30-70% by weight of cement at 10% increments. Also three different filler to binder ratios will be utilised namely 1.0, 1.5, and 2.0. Each GBS foam concrete mix is tested for its mechanical (compressive strength, flexural strength, and splitting tensile stress), physical (density, drying shrinkage, ultrasonic pules velocity, and porosity) and durability properties (intrinsic permeability, water absorption, and carbonation) at various ages.

At the same time and for the sake of comparison, foam concrete mixes containing GGBS with similar replacement levels, density and filler to binder ratio are prepared and tested for similar properties at the same age. The lightweight load-bearing wall will be casted using the optimum GBS foam concrete mix. The wall panel design is based on a two story low medium cost house, which its details are listed in chapter five. For the sake of easiness of handling and transportation, the lightweight wall is made out of two halves. Each half panel is designed to have an outer shell and core. The outer shell is designed as a ribbed panel and is fabricated from the optimum GBS foam concrete mix. While, the core is made out of lower foam concrete density (100% cement). The two halves are joined using steel bolts to form the lightweight load-bearing wall.

1.6 THESIS LAYOUT

This thesis comprises of six chapters. Chapter One already discussed the motive of this thesis and its aims, significances and scope. Chapter Two will review the literature related to this study. This chapter contains mainly three parts, the first part discusses the applications of foam concrete, foam concrete properties for fresh and hardening density, foam concrete constituents, and the effect of the type of by-product material or pozzolanic material used as a filler or binder on the properties of the mix. The second part of this chapter will briefly discuss the by-product material and, especially, steel slag and it's processing. It also discusses the effects of GGBS as a by-product material on properties of concreting material (normal, mortar, and lightweight concrete) in the fresh and plastic phases. The third will review types of concrete wall panels; the standards used to design these wall panels and studied foam concrete wall panels.

Chapter Three explains in detail the experimental sequence and the methods that will achieve the objectives of this study. This chapter consists of two parts; the first part describes the preliminary study examining GBS as a supplementary cementitious material. Furthermore, it examined the use of GBS as a foam concrete constituent. The second part is the main study, which describes the foam concrete's constituents, properties, material testing, and mixing procedure. The properties of fresh and hardened foam concrete have been tested according to the standards. Moreover, the machinery and testing procedure for the wall was also included as part of this chapter.

Chapter Four reviews the results of the created foam concrete's mechanical, physical, and durability properties. The results are illustrated in graphs and tables, which discuss the effects of GBS and GGBS on fresh and hardened properties of the foam concrete. Meanwhile, Chapter Five will discuss the design concept of the wall panel. This chapter will explain the wall's design concept and its mathematical calculations. The testing procedures and the results obtained from the actual laboratory test and the engineering software (STAAD Pro) will be discussed.

Chapter Six will list the conclusions drawn from this research and laid down a number of future works based on the current study.

CHAPTER 2

LITERATURE REVIEW AND RELATED WORK

2.1 INTRODUCTION

This chapter describes various topics that are related to the objectives of this research project. It initially describes foam concrete discretion, application, constituents, and its fresh and hardened characteristics. Also, various cementaious materials that have been used as binder or filler as well as their effect on the properties of foam concrete will be illustrated in this chapter. Furthermore, this chapter will review the types of produced by-products as well as their properties and utilisation into the construction industry. Moreover, this chapter will review and discuss the precast wall panels using lightweight concrete as well as their advantages and disadvantages in comparison to other systems.

2.2 FOAM CONCRETE

Hoff (1972) defined foam concrete as a type of lightweight concrete with a homogenous cell or void structure attained by the inclusion of a foaming agent or by the generation of gas within a fresh cementation mixture. It has been calculated that, possibly, between 30-80% of the total volume of foam concrete is made up of air bubbles or foam. In addition, Tam et al. (1987) described it as slurry or mortar with air bubbles, ranging in size from 0.1 mm to 1 mm, that have been introduced chemically or mechanically into the wet mixture. Fouad (2006) described foam concrete as a low-density material with structural cells or homogeneous voids generated by the introduction of preformed foam or gas into the mortar matrix. The common casting densities range from 320 to 1920 kg/m^3.

Therefore, based on the definitions above, foam concrete can be defined as a lightweight concrete that has different densities ranging from 320 to1920 kg/m^3. The constituents of foam concrete can be any mortar mixture with or without an infill material. Any type of binder, like normal concrete, can be used, and instead of coarse aggregate, air bubbles with diameters ranging from 0.1 to 1 mm can be introduced into the matrix mechanically or chemically by introducing gas in the wet mixture. This foam does not perform any chemical action until the cement sets and holds the desired shape. The amount of air or foam that is added to the mortar slurry has been calculated to range from 30% to 80% of the total volume (ASTM, 2004c; Barnes, 2008; Fouad, 2006; Hoff, 1972; Liew, 2005; Tam *et al.*, 1987).

There are two types of foam concrete based on the curing conditions, namely, autoclaved and moist foam concrete. In the first type, the foam concrete is cured under high-pressure steam at temperatures ranging from 180 to 210 ^{o}C, while in the second type; the foam concrete is cured under atmospheric pressure and steam. The first method of curing is generally used for making precast structural cellular elements. Precast moist-cured products are used as secondary structural elements because of their good thermal and sound insulation properties (Al-Noury *et al.*, 1990; Tam *et al.*, 1987).

Liew (2005) classified foam concrete based on the densities utilised in construction, while Fouad (2006) listed the constituents of the foam concrete based on density. Table 2.1 illustrates Liew's classification. It is worth mentioning that the production of aerated concrete was commercialised in Sweden in 1929 and was rapidly distributed to other parts of the world at the end of the Second World War. From that time, various methods have been devised and different types of foam concrete have been produced and used in construction applications in many countries

(Abdullah *et al.*, 2006; Brady *et al.*, 2001).

Table 2.1: Utilization of foam concrete in various application (Liew, 2005)

Based on density		
Author	Density range (kg/m^3)	Application
Liew (2005)	300-600	Thermal insulation for flat roofing with required grading. Floor sub-surfaces. Block infills for sub-floor slabs. Cavity walls filling. General thermal and acoustic insulation. Heat insulation slabs.
	600-800	Internal partition wall blocks and panels. Roofing slabs. Floors. Sub-surface for stables, pig sties and poultry farms. Walls, floor sub-surfaces of large cool rooms. Façade panels. Trench reinstatements.
	600-800	Internal partition wall blocks and panels. Roofing slabs. Floors. Sub-surfaces for stables, pig sties and poultry farms. Walls, floor sub-surfaces of large cool rooms. Façade panels. Trench reinstatements.
	900-1200	External wall blocks and panels, both structural and non-structural. General sound-proofing in industrial areas.
	1200 -1800	Medium weight blocks and slabs. Large reinforcement slabs and panels. Walls, either precast or poured in situ. Garden ornaments

2.3 MATERIALS UTILISED IN FOAM CONCRETE

As mentioned before, foam concrete can be based on slurry or mortar mixture that consists of Portland cement and water or Portland cement, fine aggregate (sand), and water. The binder can be Portland cement or blended cement, consisting of Portland cement slag, Pozzolans, lime with siliceous material, fly ash, metakaolin, or any other hydraulic material (ACI, 1996; Brady *et al.*, 2001). Pozzolanic materials are utilised with varying percentages to replace cement or sand in the foam concrete mixture. These materials are cost efficient and environmentally friendly, as well as they can enhance the properties of the foam concrete in its fresh and plastic phases (ACI, 2006). It is possible to use admixtures (chemical additives) in foam concrete as a percentage of the total weight of the binder.

The tests listed in ASTM C796 (2004d) and the 1996 and 2006 ACI reports are recommended for the trial mixes before the admixtures and supplementary materials are utilised in the production of foam concrete in order to determine their compatibility with the foam concrete. The typical foaming agents are protein hydrozylates or synthetic surfactants with a density varying between 32 to 64 kg/m^3, as recommended by ASTM (ASTM, 2004c). However, ACI (2006) and Fouad (2006), proposed a density of 40 to 65 kg/m^3 and 32 to 56 kg/m^3, respectively.

Kearsley (2006) determined the compatibility of the foaming agent by mixing samples containing only cement, water, and foam. The water required was obtained from various foam percentages and was based on visual observations. Essentially, there are two methods for the use of preformed foam in the production of foam concrete, namely the wet and dry method. The first method, which is suitable for the production of foam concrete with a density of up to 1000 kg/m^3, involves spraying a solution of the foaming agent with water through a fine mesh to generate bubbles with a diameter of 2 to 5 mm.

The second method is the dry preform method, which involves using the power of an air compressor to force the foaming agent and water into a mixing chamber, thus resulting in the generation of stable air bubbles having a diameter of less than 1 mm (Barnes, 2008; Brady *et al.*, 2001; Ramamurthy *et al.*, 2009). The preformed foam technique is the more economical method of producing foam concrete as it uses less foaming agent and the mix can be controlled and possibly adjusted if there is a human error (Ramamurthy *et al.*, 2009; Wee *et al.*, 2006).

Due to the small size of bubbles, the near bubble skeleton, and the stability of the protein foaming agent reflect the bond strength of the final foam concrete product (Mcgovern, 2000; Nambiar and Ramamurthy, 2007a; Othuman Mydin, 2010). Dransfield (2000) stated that although a synthetic foaming agent can be easily formulated and it is more stable, its high expansion can open cells and create large bubble sizes which can reduce the strength of the foam concrete. Therefore, a protein foaming agent is preferable to a synthetic one. A filler or fine aggregate, with a maximum particle size of not more than 5 mm, can be used.

Furthermore, a high strength foam concrete can be obtained by mixing 60 to 95% sand passing through a 600-micron sieve (ACI, 1996; ACI, 2006; ASTM, 2004a; ASTM, 2004c; Barnes, 2008; Brady *et al.*, 2001; Fouad, 2006; Ramamurthy *et al.*, 2009). Table 2.2 reviews several researches that had been carried out utilising different materials and admixtures in powder or liquid form in foam concrete.

Table 2.2: Utilization of various materials as additives and admixtures in constituents of foam concrete

Author	Density Kg/m^3	Mix ratio	Replacements (%)	Additives (%)	W/b	Foam type	Foam density
(Ranjani and Ramamurthy, 2012)	1000-1500	1:1	FA[a] (10-30) (OPC	-	-	Synthetic	25-38
(Jitchaiyaphum *et al.*, 2011)	800	-	FA[a] (10-30) (OPC)	-	0.5	Protein	45
(Wee *et al.*, 2006)	600-1900	-	GGBS (50) (OPC)	-	0.3	Protein	-
(Kearsley and Wainwright, 2001b)	1000-1500	-	FA & PF[b] (50-67.7-75) (OPC)	-	0.3	Protein	70
(Tam *et al.*, 1987)	1300-1600	1:1.58-1:1.75	-	-	0.6-0.8	Protein	59
(Jones *et al.*, 2003)	1000	1:1.83	FA (30) (OPC), FA_{coarse} (30) (sand)	-	0.5-1.11	-	50
(Jones and McCarthy, 2005b)	1400-1800	1:1.5-1:2.3	FA (30-50) (OPC), FA_{coarse} (50-100)	Sp[d]	0.26-0.5	Synthetic	50
(Jones and McCarthy, 2005b)	1000-1400	1:1.83	FA_{coarse} (66-70) (sand)	-	0.5	Synthetic	50
(Nambiar and Ramamurthy, 2006)	1000-1500	1:1	FA (50-100) (sand)	-	-	Protein	50
(Pan *et al.*, 2007)	620-1600	1:2.3	-	-	0.7	Protein	-
(Nambiar and Ramamurthy, 2007b)	840-1753	1:2	FA (0-100) (sand)	-	0.94-1.65	Protein	40
(Wee *et al.*, 2011)	693-1635	1:0	GGBS (50) (OPC)	Sp (8ml/kg)	0.22-0.6	Protein	-
(Zulkarnain and Ramli, 2011)	1150	1:1.5	SF[c] (10-15) (OPC)	Sp	0.45	Protein	80
(Chindaprasirt and Rattanasak, 2011)	1600	1:2.5	FA (15-30) (OPC)	Propylene glycol (1) Triethylene glycol (1) Dipropylene glycol(1)	0.5	-	50
(Shi *et al.*, 2012)	500-1000	1:0, 1:0.6	FA (20-40-60) (OPC)	Sp (0.1)	0.3	Protein	55
(Mydin, 2011)	1000	1:0.5	-	0.5	0.5	Protein	80
(Panesar, 2013)	500-900	-	-	-	0.29	Protein & two Synthetic	65 45-65, 50-60
(Lim *et al.*, 2013)	1300	-	OPA (10-20) (sand)	-	0.52-0.6	Synthetic	45
(Awang *et al.*, 2014)	1300	1:2	OPA (25-65) (OPC)	Sp (1)	0.45	Protein	65
(Rahyan *et al.*, 2008)	1000-1500	1:1.5	-	Sp (1.25)	0.45	Protein	80

[a]FA: Fly ash, [b]PF: Pozz-Fill, SF[c]: Silica fume, Sp[d]: Super-plasticiser

2.4 PROPERTIES OF FOAM CONCRETE

This section will explain various properties of foam concrete in fresh and hardened stages.

2.4.1 CONSISTENCY AND STABILITY OF FOAM CONCRETE

The workability of foam concrete, whether it is mortar-based (cement, sand and water) or neat cement, is described by the ACI (2005b) as the characteristic of a normal fresh mortar mix that is homogeneous and permits easy mixing, placing, compacting, and finishing. A common workability test for a basic foam concrete mixture is the Brewer test or any other test in ASTM C230 (ASTM, 2004b). In a study conducted by Li (2013), the workability of the mortar was determined based on the modified cylinder plate method in accordance with ASTM C230 (ASTM, 2004b), which was adopted from the company that supplied the foaming agent and foam generator.

Valore (1954) noticed that at lower foam concrete densities, the water to cement ratio increased with the increase of sand level in the mix. Moreover, he stated that the amount of water required in the mix was determined by the consistency rather than by a predetermined water/cement ratio. Based on the actual flow table test, Kearsley and Mostert (2005) were able to determine the workability of a base mixture of foam concrete according to ASTM C230 (ASTM, 2004b). The water required for the cement used in their study made up 35% of the total weight of the cement, which meant that the minimum water to cement ratio needed to avoid the cement pulling the water from the foam is 0.35. When fly ash was included in the matrix, the water demand was 0.25 litres for each kg of fly ash. This phenomenon occurred due to the spherical shape of the particles. This is also reported in a study carried out by Pretorius (2006). An additional reason for this phenomenon is that fly ash (pozzolanic material) is not engaged in the hydration process during the early stages (early hours) because it only participates in the processes after the formation of calcium hydroxide.

Fly ash, which contains up to 10% unburnt carbon, has a large particle size (more than 45 micron) and is reported to increase the water required to achieve a specific workability (Kearsley, 1999). However, when fly ash is excluded, Kersealy (2006) indicated that the optimum w/c ratio is in the range of 0.38 based on the foam content. However, this ratio increased with increment of the ash ratio. Furthermore, water demand tends to increase with the increasing percentage of foam. The inclusion of GGBS in the foam concrete base mixture at an equal percentage of the binder can increase workability. However, increasing the level of GGBS content in the mixture in addition to the low w/c ratio can cause the foam to separate from the paste (Brady *et al.*, 2001).

Lim et al. (2013) defined the consistency of foam concrete as the freshly obtained density over the designed density. On the other hand, Ramamurthy et al. (2009) described it as the ratio of water to solid that can attain the design density. If the base mixture of the foam concrete has a low consistency, it will cause the bubbles to brake due to the stiffness of the mixture, and if it is too watery, it will lead to an increase in density due to segregation. Furthermore, the consistency of the foam concrete tends to decline with the addition of foam into the base matrix. In other words, the consistency of the foam concrete depends on the volume of water added for the desired density, the type of filler, and the water to solid ratio (Brady *et al.*, 2001; Ramamurthy *et al.*, 2009). Nevertheless, Jones and McCarthy (2005c) concluded based on their experiment that replacing the unprocessed fly ash with sand enhances the consistency of the matrix compared to using sand as the filler because of the finer state and shape of the fly ash particles. Meanwhile, Lim et al. (2013) concluded that the incorporation of oil palm ash as a filler replacement decreases the flow-ability of the fresh mix.

The stability of foam concrete is related to the consistency of the base mix and can be represented by the ratio of water to solid, which differs according to the filler type. Lim et al. (2013), Valore (1954), and Nambair and Ramamurthy (2007b) described the stability of foam concrete as the ratio of the demoulded (hardened) density over the obtained density (fresh). In general, the consistency and stability of the foam concrete are affected by the amount of foam, the w/s ratio, and the other solid materials that are introduced into the mixture (Brady *et al.*, 2001; Ramamurthy *et al.*, 2009). Jones and McCarthy (2005c) and in other paper that published by the main authors above at (2006) suggested that the stability of foam concrete can be indicated by comparing the theoretical and actual amount of foam that is added to achieve the desired plastic density which is within the range of ±50 kg/m^3 of the design value or 3% of the fresh (wet) density.

Also, it was indicated that in terms of the stability of foam concrete with unprocessed fly ash as a replacement for the sand, the amount of foam required is more than three times that of normal filler. This is due to the high consistency of the base mixture as well as the high content of carbon in the ash. Panesar (2013) mentioned in his study that the inclusion of fine aggregate in the base mixture of the foam concrete increases the stability of the foam concrete compared to a slurry (neat cement) mixture, which, although it has more consistency, it is unable to hold the air bubbles due to segregation.

2.4.2 DENSITY

In order to determine the oven dry density, the ASTM C513 (2004e) and BS EN 12390 part seven at (2009a) recommended that a temperature of 110 ^{o}C ± 5 ^{o}C should be applied to the specimen for 24 hours, and the dimensions of the sample and its weight per cubic meter or cubic foot should be determined. Both dry and fresh densities of foam concrete are important to determine the requirements of the mix design, to ensure quality control, and because most of the characteristics of foam concrete are explained with regard to oven dry density (Fouad, 2006; Jones and McCarthy, 2006; Ramamurthy *et al.*, 2009).

Basically, preformed foamed concrete with a cement to sand based mixture has a higher density and requires more cement (Ramamurthy *et al.*, 2009) than fly ash, which has a relatively lower density and requires less foam, as the filler replacement. Furthermore, A1-Noury et al. (1990) mentioned that the loss in dry density of foam concrete increases with the increasing water to cement ratio. Due to the loss of water in the plastic density of foam concrete, Kearsley and Mostert (2005) determined that the difference added to the dry density (oven-dried) of the foam concrete should range from 600 to 1200 kg/m^3 in order to obtain the target density, as calculated from the liner equation below:

$$\text{Target density} = 1.034\ Pdry + 101.96 \quad \ldots .2.1$$

On the other hand, Jones and McCarthy (2005b) used the equations below to determine the plastic density of foam concrete incorporated with fly ash as a binder and filler substitute,

$$D = C + w + f, \text{ where } c = PC + FA_{\text{finer}}, f = FA_{\text{coarse}} + \text{sand} \ldots\ldots\ldots 2.2$$

Where D is the target plastic density, C is the cement content, f is the content of fine aggregate, and W is the free water content, which determined as:

$W = (w/c) \times (\text{PC} + FA_{\text{finer}} + FA_{\text{coarse}})$

Nevertheless, Fouad (2006) and Neville (1996), in their calculation of the amount of solid material based on the oven dry density and with a water content of 20% of the total binder cement weight, made the following assumption:

$$D = 1.2C \times A \text{ (C and A in kg/m}^3\text{)} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.3$$

Where D is the dry density, C is the weight of the cement, and A is the weight of the aggregate.

McCormick (1967) determined the wet density with a difference of 5% from the design density by using the solid volume calculation method. In his study, he also examined the effect of the fineness of the sand, the type of foam agent, and the sand-cement ratio on the wet density of foam concrete. Jones and McCarthy (2005b) mentioned that the proportion of the foam concrete mix can be designed according to the plastic density. Nonetheless, it is difficult to do this with the dry density as the density of the foam concrete usually drops by about 50 to 200 kg/m^3, according to the total water content in the mixture. Thus, the design of foam concrete mix depends on the foam concrete plastic density and the curing regime.

In a research by Noordin and Awang (2005), it was noted that there was a reduction of 60-120 kg/m^3 in the dry density (oven-dried) compared to the target density. Thus, indicating that the designed density tends to be higher than the dry density. The difference in the dry density and the targeted design density is mostly due to the water-cement ratio and the casting density.

Jeong and Kim (2011) mentioned in his study that the variation between the wet density and the oven-dry density depends on the amount of cement paste in the matrix. The difference, however, increases with an increase in the amount of cement paste. Also, they discovered in their study that the type of the synthetic foaming agent also influences the gap between the wet and the oven-dry density. The air-dry density or air curing method for foam concrete is the most convenient industrial method. The air-dry density technique relies on many factors, such as weather conditions (temperature and humidity), duration of exposure to the weather, the density obtained, and the water to binder ratio. Based on the variables and the casting conditions, air-dry densities are probably lower by about 80 kg/m^3 than the cast density (Fouad, 2006; Neville, 1996).

2.4.3 COMPRESSIVE STRENGTH

Many factors influence the compressive strength of foam concrete, including density, quantity of cement in the matrix, w/c ratio, mix proportions, type of binder and filler, admixture, period and type of curing regime, specimen shape and size, and pore formation method (Fouad, 2006; Narayanan and Ramamurthy, 2000b). In addition, the size, spacing, and regularity of the air voids as well as the void to paste ratio might also affect the mechanical properties of the foam concrete (Wee *et al.*, 2006).

The curing regime is one of the most important factors influencing the mechanical properties of foam concrete. The conventional water curing practice promises a higher strength. It has been proven that relative humidity influences the compressive strength of the foam concrete when it is exposed to the environment and its strength could be reduced by about 35% within a humidity range of 30 to 80% (Lee *et al.*, 2011).

Based on laboratory experiments, Kearsley (2006) concluded that the best curing for foam concrete is moist curing, also known as curing under plastic cover. In addition, this method of curing can reduce the cost of foam concrete production. It has been reported that moist-cured foam concrete is affordable and can be used for many applications (Tam *et al.*, 1987). Moreover, it has been proven that a good curing regime can generate high compressive strength in the long run regardless of whether a high level classified or non-classified fly ash is replaced by cement in the foam concrete (Kearsley and Wainwright, 2001b). On the other hand, the experimental study conducted by Alwi et al. (2010) indicated that curing in salt-water results in a higher compressive strength than curing in fresh water and in air due to the development of a strong matrix bond in the foam concrete samples.

A comparison that was made based on the ash/cement ratio for the mix with and without foam indicated that increasing the ratio decreased the strength of the mix without foam, while the mix with the foam acted oppositely or maintained its strength as the control mix. The optimum replacement level of the ash by cement is 50% for a mix content that has 30 or 40% foam (air voids) (Kearsley, 2006). Better mechanical properties can lead to optimal strength-to-weight ratio, and this is achieved by having a dense microstructure with relatively small air voids and large spacing factor (Wee *et al.*, 2006).

Increasing the w/c ratio in foam concrete positively influences the mechanical properties as long as there is no reduction in the a/c ratio. The compressive strength of foam concrete depends on both the water to cement and the air to cement ratios, unlike mortar, which undergoes a reduction in compressive strength with the increase in the w/c ratio (Fouad, 2006; Tam *et al.*, 1987; Wimpenny, 2006). Moreover, the presence of 5% to 2% voids in normal concrete dramatically reduces the strength by 30% to 10%, respectively (Al-Noury *et al.*, 1990). The study by Wimpenny (2006) indicated a dramatic change in compressive strength for foam concrete that has a density of 1350 kg/m^3. However, he found that the strength remained statically the same when the w/c ratio was above 0.9 and below 0.75.

It was reported that small changes in the w/c ratio due to the amount of water content in the sand, which varied between 6%-14%, did not have an effect on the strength of the foam concrete (Tam *et al.*, 1987). The sand to cement ratio affects the strength and the linear trend reduction when there is an increase in the amount of sand. Furthermore, it is worth mentioning that the reduction in compressive strength is not affected by further increases in the sand content. The optimum sand/cement ratios vary between 0.5-1 for foam concrete containing 20% to 60% foam (Kearsley, 2006). The fineness of the sand has been reported to increase the compressive strength of the foam concrete (Wimpenny, 2006). This phenomenon is attributed to the uniform coating on each bubble that prevents overlapping and merging, unlike coarse sand which forms large and irregular pores and also leads to the clustering of the bubbles (Jitchaiyaphum *et al.*, 2011; Jones and Giannakou, 2004; Nambiar and Ramamurthy, 2006).

Wimpenny (2006) utilised an equal amount of w/c and a/c to examine the effect of integrating GGBS in foam concrete. The researcher found that when cement is replaced by an equal amount of GGBS, the strength of the foam concrete at 7 days is reported to be much lower than the mix that has no GGBS. However, the scenario changes at 28 days as the mix with GGBS develops strength that is higher than the control mix. It has also been reported that the use of coarse fly ash as a filler in the base mix of foam concrete enhances the compressive strength of the foam concrete. This phenomenon can be explained as being part of a pozzolanic reaction, where fly ash, having a lower specific density than fine aggregate, results in reducing the amount of foam required (Nambiar and Ramamurthy, 2006; Valore Jr, 1954).

Kearsley and Wainwright (2001a) demonstrated that no harmful or major effects on the compressive strength of high-density foam concrete for long term