# PROPERTIES OF FOAMED CONCRETE WITH OIL PALM ASH INCLUSION AND ITS APPLICATION AS AN INTERLOCKING MORTARLESS BLOCK

**by**

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**Thesis submitted in fulfilment of the requirements**

**for the degree of**

**Doctor of Philosophy**

**December 2015**

# ACKNOWLEDGEMENTS

First and foremost, I offer my sincerest gratitude to my supervisor, Associate Professor Dr. Hanizam bt Awang, who has supported me throughout my thesis with her patience and knowledge whilst allowing me the room to work in my own way. I attribute this work to her encouragement, effort and without her this thesis would not have been completed or written. One simply could not wish for a better or friendlier supervisor. I would also like to show my gratitude to my co-supervisor Professor Dr. Abdul Khalil Shawkataly for his support and kind guidance. I would also like to show my appreciation to Universiti Sains Malaysia for giving me the opportunity of obtaining my Ph.D. My greatest appreciation and respect to all technicians whom have helped me to make this work a tangible dream.

Dear Mum and Dad, if it was not for your unconditional love and daily prayers, this would not have happened. I know that I am indebted to you with my life and I am hoping and praying that this small effort would repay a minute amount of what you have sacrificed for me in order to reach this point in my life. I bow to you with respect, love and appreciation.

To my beloved wife who was patient, loving and caring throughout this bumpy journey. If it was not for your encouragement and love, this endeavour would not have reached its end.

I would like to thank my brothers Usama and Rayth; sister Noor and my best friends Zaid and Mohammed for their support and guidance. I would also like to show my great gratitude to my friend Ng Phei Li who has been a great help and showed me how selfless she was when lending a hand throughout the period of this research.

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**CIRI-CIRI KONKRIT BERBUSA DENGAN PENAMBAHAN ABU KELAPA SAWIT DAN APPLIKASINYA SEBAGAI BLOK TANPA MORTAR SALING MENGUNCI**

## ABSTRAK

Abu minyak kelapa sawit (OPA) merupakan salah satu bahan buangan yang dihasilkan daripada industri minyak kelapa sawit. Ianya menjadi kebiasaan dibiarkan mereput di kilang kelapa sawit atau dibuang di kawasan tanah tambak yang menimbulkan pelbagai isu alam sekitar. OPA telah digunakan sebagai bahan pozzolana dalam pelbagai kajian bagi menghasilkan konkrit dan produk berkaitan simen yang lain. Walaubagaimanapun, OPA yang digunakan hendaklah melalui proses lanjut bagi menguatkan ciri-ciri fizikal dan mekanikal, yang mengakibatkan peningkatan kos dan mengurangkan peluang untuk digunakan dalam pengeluaran konkrit berskala besar. Kajian ini cuba menggunakan OPA yang diayak melepasi saiz ayak 300µm (UOPA) bagi menggantikan simen dalam penghasilan konkrit berbusa. Campuran konkrit berbusa dengan kandungan UOPA yang optimum telah dipilih bagi menghasilkan blok tanpa mortar saling mengunci (blok BTechLiTe) baru. Sehingga 65% berat simen akan digantikan oleh UOPA dalam campuran konkrit berbusa dengan densiti 1150kg/m$^3$ dan 1450kg/m$^3$ dan nisbah pengisi kepada pengikat (FB), masing-masing iaitu 1, 1.15 dan 2. Sebanyak 36 campuran telah disediakan dan akan dikaji dari segi ciri-ciri fizikal, mekanikal dan ketahanan pada tempoh masa yang berbeza. Hasil kajian menunjukkan UOPA berpotensi digunakan dalam penghasilan konkrit berbusa dengan penambahan bahan pemplastik dan mencapai tahap gantian yang hampir sama seperti yang dicadangkan dalam kajian menggunakan OPA yang diproses. Campuran mengandungi tahap gantian 35% UOPA (II-35), telah digunakan bagi menghasilkan blok BTechLiTe. Sistem blok

BTechLiTe menunjukkan  kekuatan sebanyak 3.75 MPa dimana lebih tinggi daripada had minimum yang ditetapkan dalam BS 5628.

**PROPERTIES OF FOAMED CONCRETE WITH OIL PALM ASH INCLUSION AND ITS APPLICATION AS AN INTERLOCKING MORTARLESS BLOCK**

## ABSTRACT

Oil palm ash (OPA) is one of the waste materials produced by the palm oil industry. It is normally left to rot on the premises of the palm oil mills or dumped into low cost landfills causing a number of environmental issues. OPA has been used as a pozzolanic material in numerous studies for producing concrete and other cement related products. However, OPA had to be processed further to enhance its physical and mechanical properties, as a result, increasing its cost and reducing its opportunity to be used in concrete production on a larger scale. This study endeavoured on using OPA passing through a 300μm sieve (UOPA) to partially replace cement in the production of foamed concrete. The foamed concrete mix containing an optimum amount of UOPA was chosen to fabricate a novel mortar-less interlocking block (BTechLiTe block). Up to 65% by weight of cement was replaced by UOPA in foamed concrete mixes with design densities of 1150 and 1450kg/m$^3$ and having filler to binder ratios (FB) of 1, 1.5 and 2. In total 36 mixes were prepared and were tested for their physical, mechanical and durability properties at different ages. The results showed that it was potential to use UOPA in producing foamed concrete with the aid of a superplasticiser and achieving similar replacement levels recommended by studies using processed OPA. The mix containing 35% UOPA replacement level (II-35) was chosen for the fabrication of the BTechLiTe block. The BTechlite block system showed strength of 3.75MPa which is higher than the minimal requirement for block strength according to BS 5628.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Global warming is a phenomenon that is pushing the world towards making drastic changes in order to mitigate its effects. Experimenting and producing alternative fuels and the recycling of waste materials into producing new materials are measures used to reduce greenhouse emissions. The construction industry is one of the contributors to global warming. The cement industry alone contributes to 5% of the total carbon dioxide ($CO_2$) emissions (Worrell et al., 2001). One tonne of produced ordinary Portland cement produces a tonne of $CO_2$ and other greenhouse gasses (Naik, 2005). Reducing the dependency on cement has been a major focus for researchers. This has been translated to using a number of waste materials such as fly ash, silica fume, rice husk ash and ground granulated blast furnace slag as cement replacements. Designing and constructing energy efficient buildings is another approach for reducing greenhouse emissions. This is done through using lightweight materials and incorporating waste into the building construction materials (Al-Jabri et al., 2005).

Lightweight materials are beneficial when used in the construction of any structure. Utilising lightweight materials can reduce the weight of the super structure; hence, enabling the designers to use smaller foundations and smaller support structures and as a result reducing the amount of cement used and eventually cost (Sales et al., 2010). In addition, lightweight materials have low thermal conductivity characteristics; therefore, they reduce the energy needed to cool and heat the building (Zhang and Poon, 2015).

Foamed concrete is a type of lightweight concrete. It is known to be highly flow-able, possesses low self-weight, has a minimal aggregate consumption, controlled low strength and superior thermal insulation properties (Ramamurthy et al., 2009). Controlling the quantity of foam can produce foamed concrete with densities ranging from 500kg/$m^3$ to 1600kg/$m^3$ (Jitchaiyaphum et al., 2011). Foamed concrete is considered to be an environmental friendly material due to its limited use of aggregate because of the absence of coarse aggregate and its high capacity in incorporating waste materials (Noordin and Awang, 2005). A number of waste materials have been used as cement and sand replacements in its production (Ramamurthy et al., 2009). They have been used to enhance the properties of foamed concrete and to reduce its cost.

Oil palm ash (OPA) is one of these wastes that have been discovered to be a good pozzolanic material. Although it is a new waste to be introduced to the construction industry, numerous studies have endeavoured on utilising it in concrete production. OPA is a waste produced by countries that have a booming palm oil industry. It originates from the incineration of palm oil biomass (empty fruit bunch, kernel shell and palm oil fibre) as alternative fuel to produce electricity for the mill's energy needs.

## 1.2 Background

The surge in fossil fuel prices, fear of future supply shortages alongside the increasing awareness of greenhouse gas emissions increased the shift towards the search for alternative fuels. These alternative fuels are conditioned to be technically feasible, environmentally friendly, competitive from an economic perspective and readily available (Sumathi et al., 2008). Vegetable oils, which are from plant origin, are considered to be an alternative to fossil fuels. The alternative fuel is named as bio-diesel. Bio-diesel is biodegradable, non-toxic and has low $CO_2$ emission profiles in comparison to conventional fossil diesel. Using bio-diesel will allow a balance to occur between agricultural economic development and the environment (Meher et al., 2006). Various plants have been identified as raw stock for the production of bio-diesel such as rapeseed and soybeans in the United Sates and palm oil and jatropha in the Asian region (Mekhilef et al., 2011). However, among these resources of bio-diesel, palm oil is considered to be the cheapest and has the highest oil yield per hectare of plantation (Sumathi et al., 2008).

Today, Malaysia is the world's largest producer and exporter of palm oil and its palm oil industry is an important contributor to the country's Gross domestic product (GDP) (Yusoff, 2006). Before the bio-diesel boom, 90% of the oil was used in food related commodities with the remaining 10% is used as raw material in soap production (Mahlia et al., 2001). However, after realising the potential of palm oil in producing bio-diesel, the Malaysian palm oil industry grew from a shy 400 hectares in 1920 (Abdullah et al., 2009) to 4.17 million hectares in 2006 and producing nearly 4.5 million tonnes of palm oil in 2008 (Sulaiman et al., 2011). In 2008, about 17.7 million tonnes of crude palm oil have been produced from the 410 palm oil mills in Malaysia reaching a 41% of the world's palm oil production (Chiew et al., 2011).

As a result to the thriving Malaysian palm oil industry, the amount of biomass produced will increase. A single hectare of palm oil plantation can generate up to 70 tonnes of biomass residues (Shuit et al., 2009). As a rough estimate, 1kg of palm oil results in 4kg of biomass produced alongside it (Sulaiman et al., 2011). About 90 million metric tonnes of biomass is produced in Malaysia annually (Safiuddin et al., 2011). This biomass residue consists of empty fruit bunch, fibre, shell, wet shell, palm kernel, fronds and trunks. Each oil palm tree fruit bunch produces about 21% palm oil, 6-7% palm kernel oil, 14-15% fibre, 6-7% shell and 23% empty fruit bunch (Dalimin, 1995).

It has been a common practice for palm oil mills to burn their biomass instead of using conventional fossil fuels for heating up their boilers and generate steam (Mahlia et al., 2001; Sumathi et al., 2008). According to Shuit et al. (2009), more than 300 palm oil mills are operated by self-generated electricity using palm oil biomass in Malaysia. In addition, the generated electricity is not only used for their internal use in crude palm oil extraction but also providing the surrounding remote areas with electricity. Due to the abundant amounts of biomass produced, Malaysia has the potential to utilise these quantities in power generating. Using such alternative fuels to partially or fully replace fossil fuels used in all Malaysian industries to generate energy, will result in a significant drop in $CO_2$ emissions, achieving the vision to be a developed country without degrading the environment and promoting the utilisation of renewable energy in power generating (Shuit et al., 2009).

However, the process of burning palm oil biomass will result in a new type of waste. This waste is called oil palm ash (OPA) which is causing numerous problems to the environment. OPA quantities are expected to increase due to the increasing demand for energy and the thriving palm oil industry.

### 1.3 Problem statement

As mentioned earlier, the construction industry is a huge contributor to global warming. The cement industry alone emits one tonne of $CO_2$ to the atmosphere when producing 1 tonne of cement. Furthermore, the exhaustion of natural resources is also a damaging factor to the environment. Therefore, researchers around the world are striving towards the production of a better concrete both greener and stronger with the use of mineral admixtures and supplementary cementing materials (Siddique and Khan, 2011). The materials used as a substitution to cement not only improve the properties of concrete, but also they conserve energy and have a positive impact on the environment. This positive impact is due to reducing cement consumption and as a result reducing the $CO_2$ emissions.

For the goal of encouraging power generation using renewable energy and reducing greenhouse emissions, the Malaysian government launched two programmes. These programmes are the Small Renewable Energy Programme (SREP) and Renewable Energy Power Purchase Agreement (REPPA) (Chiew et al., 2011). Electricity generated from small power producers, including power plants that are using palm oil biomass, are able to sell their produced electricity to the national power grid. These programmes will promote the creation of biomass plants and as a result will reduce the waste disposal problems facing various mills in the region.

However, the incineration of palm oil biomass creates a new by-product to deal with. OPA is created through the incineration of palm oil biomass. OPA is produced at a percentage of 5% by weight of palm oil biomass (Sata et al., 2004). In Malaysia alone, nearly four million tonnes of oil palm ash is produced annually (Mohamed et al., 2005). To this date, due to the huge amounts produced, it is commonly practiced that oil palm waste is disposed of by uncontrolled dumping and tipping methods. This operation is conducted by spreading the waste over the vicinity of the mill or dumped to fill up low economic value dumps on pieces of land that are selected previously (inundated swampland, abandoned sand mines and quarries) (Foo and Hameed, 2009a). These methods are done without putting into consideration the surrounding environment, nor taking any precautions to compact, cover and barring the contaminants to spread into the underlying waterways. Remaining a complex challenge for the 21st century, oil palm ash's infiltration into the aquifer systems and ground water tables is possessing possible risks and extreme hazards towards the ecosystems and public health (Foo and Hameed, 2009a). The uncontrolled disposal of such waste, especially ash, will lead to the deterioration of the environment due to the fact that they are rich in organic substance (Singh et al., 2011). Another issue with improper disposal of oil palm ash is that the ash particles, due to their light weight, will be carried by winds creating smog in a humid day (Tay, 1990; Tay and Show, 1995). On the other hand, due to the increasing cost of ash disposal in landfills or ash ponds ($5/tonne in developing countries and $50/tonne in developed countries) is another factor that urges researchers for using this residue into a more valuable end product (Foo and Hameed, 2009b).

Recycling of oil palm ash is receiving increasing attention because of its huge potential in improving economic benefits and environmental awareness (Kaosol et al., 2010). As an alternative to oil palm ash disposal, recycling of this residue is a good method to decrease its environmental impact. Although OPA is considered to be a newly introduced pozzolanic material, numerous studies have incorporated it in the production of concrete (Tangchirapat and Jaturapitakkul, 2010), mortar (Rukzon and Chindaprasirt, 2009a), cement pastes (Chandara et al., 2012), high-strength concrete (Megat Johari et al., 2012) and aerated concrete (Abdullah et al., 2010). However, the incorporation of OPA into foamed concrete as a partial cement replacement has not yet been investigated. Using OPA as a partial cement replacement in producing foamed concrete will increase the possibility of creating a more environmentally friendly foamed concrete and decreasing the amount of cement used in its production. These studies have used this waste after further processing it by either enhancing its physical and/or chemical properties. Despite the positive results that these enhancements showed on the performance of OPA, they do apply considerable cost (Chao-Lung et al., 2011; Zerbino et al., 2011). In addition to the applied cost, the further processing procedures hinder the utilisation of OPA and confine it to laboratory conditions.

Against all the mentioned issues, this study utilised coarse OPA sieved through a 300µm sieve (UOPA) to partially replace cement in producing foamed concrete. The uniqueness of such incorporation lies in the type of OPA used in this study. The OPA is produced by incinerating palm oil biomass at temperatures exceeding 1000ºC. As a result of such high temperatures, the OPA produced has a reduced carbon footprint and has a finer particle size distribution. Hence, eliminating the need for further processing methods to be conducted on the OPA. In addition, UOPA is used to partially replace cement in producing foamed concrete where the effect of such incorporation on the properties of foamed concrete is studied. As a result of this utilisation, the prospect of broadening the recycling methods of such waste is increased.

The resulting UOPA foamed concrete is introduced to manufacture a newly designed interlocking mortar-less block. Interlocking mortar-less block systems are known to be made from conventional concrete. As a result, these blocks are heavy and have poor thermal insulation properties. In addition, they are designed to have increased number of components to enable them for wall construction. Furthermore, the existing mortar-less interlocking block systems are unable to construct a double-leaf wall. The newly designed interlocking block system will be made out of UOPA foamed concrete. The block system is environmentally friendly due to the utilisation of a waste material in its fabrication. In addition, the newly designed mortar-less interlocking block system is made out of foamed concrete; hence, it is lightweight and possesses all the good properties of thermal and fire resistance.

### 1.4 Aims and objectives

This study is aiming on investigating the feasibility of using unground OPA (UOPA) as a partial cement replacement in the production of foamed concrete. The UOPA is obtained by sieving OPA produced from incinerating palm oil biomass at temperatures exceeding 1000ºC through a 300μm sieve. UOPA was used to replace cement by different replacement levels using different filler/binder ratios (FB) and different densities of foamed concrete.

A thorough study of the physical and chemical properties of the used UOPA was conducted. Furthermore, the effect of replacing large quantities of cement by UOPA on the mechanical, physical and durability properties of foamed concrete were studied. The mechanical properties include compressive, flexural and tensile splitting strengths of the foamed concrete specimens. Durability properties were studied via investigating the water absorption, intrinsic permeability and porosity of the foamed concrete specimens. Physical properties of the foamed concrete specimens were studied through determining the density and drying shrinkage characteristics of the specimens. Through these tests, the study came up with recommendations on the best UOPA replacement level that can be used without affecting the properties of foamed concrete.

The study utilised the recommended mix in producing a novel interlocking block. The research aimed on producing a mortar-less interlocking block that could be used in semi and none structural applications. The novel block was tested for its strength and its loading characteristics.

The objectives of this research are:

1. To investigate the effect of UOPA utilisation in large amounts on the physical, mechanical and durability properties of foamed concrete mixtures.

2. To utilise the recommended replacement level in producing a novel interlocking mortar-less block which complies with the modular system and possess an interlocking system that enables adequate interlocking and alignment.

3. To investigate the structural behaviour of the newly designed interlocking mortar-less block and to determine its strength correlations between individual, prism and panel.

### 1.5 Significance of the research

Environmentally, utilising unground oil palm ash (UOPA) into foamed concrete as a partial cement replacement has a number of benefits. Using this waste will reduce the dependency on cement; hence, reducing the amount of cement used and as a result reducing the greenhouse emissions due to the production of cement. In addition, the utilisation of UOPA into producing foamed concrete will be an attempt for its recycling and its introduction to a broader variety of concrete types. UOPA's utilisation into foamed concrete as a cement replacement has not seen serious research attempts. Therefore, this type of utilisation will be beneficial in increasing the knowledge of such incorporation on the properties of foamed concrete. In addition, this research will give an insight on to what level that such incorporation is possible without negatively affecting the properties of foamed concrete. Furthermore, using UOPA will increase the feasibility of this waste's introduction to the construction industry and release it from Laboratory condition confinement.

In addition, the resulting UOPA foamed concrete is used in the fabrication of an interlocking mortar-less block. The BTechLiTe block system is designed to have an interlocking mechanism which enables a 360º interlocking. In addition, the

BTechLite block system is designed to have no corner block and is able to construct a double leaf wall.

### 1.6 Scope of the research

This study investigated the potential of using UOPA as a cement replacement in foamed concrete. The used OPA was studied for its physical properties by assessing its particle size distribution, particle shape, median particle size and specific gravity. The chemical properties were assessed by studying the chemical composition, loss on ignition (LOI) and the mineral morphology of the UOPA particles.

The investigated UOPA is used as a partial cement replacement in producing foamed concrete using different replacement levels (25% to 65% by weight of binder) with different FB ratios (1.0, 1.5 and 2.0) and different design densities (1150 and 1450kg/$m^3$). The mechanical properties of the foamed concrete mixtures were evaluated by testing their compressive strength, tensile splitting strength, flexural strength and ultrasound pulse velocity. Physical properties were determined via density and drying shrinkage. Durability properties of the mixtures were measured through testing the specimens for their water absorption, intrinsic permeability, porosity and carbonation ingress depth. A total of 36 foamed concrete mixtures were cast and the properties were determined at different ages.

The final phase of this research was utilising the knowledge gained from the previous tests in the fabrication of a novel lightweight loadbearing interlocking block. The newly designed block will be tested for its loading characteristics and building patterns.

## 1.7 Layout of the research

A total of six chapters were written to cover the whole research. The first chapter dealt with an introduction to this research, background of the research and shed light on the problem that this research intends to solve. In addition, this chapter gave an insight to the aims and objectives of the research, the significance and the scope.

Chapter 2 critically reviewed the work done by other researchers on foamed concrete, OPA's effects when incorporated into producing concrete/mortar and then highlighted the development of the interlocking mortar-less blocks. In the case of foamed concrete, it gave an insight to its constituents and physical, mechanical and durability properties. This chapter also shed light on the effects of OPA incorporation on the physical, mechanical and durability properties of concrete/mortar using this waste as partial cement replacement. In addition, chapter 2 reviewed the attempts of creating interlocking blocks and their properties.

Chapter 3 dealt with the properties of the constituents, mixing procedure and tests to be conducted on the foamed concrete mixtures. In addition, Chapter 3 laid out the method for testing the newly designed block system. Chapter 4 listed the results for all the conducted tests on the foamed concrete mixtures alongside a thorough analysis and discussion of the results. This chapter came up with the optimum mix containing an optimum UOPA replacement level to be used in fabricating the newly designed interlocking block. Chapter 5 listed the results for the tests conducted on the newly designed block and presented a thorough discussion for the novel block's performance. Chapter 6 listed the conclusions drawn from the research and gave recommendations for future research to be conducted to further understand the effect of UOPA incorporation on the properties of foamed concrete.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

In this chapter, the definition of foamed concrete, constituents, properties and its utilisation will be presented. This chapter will also give a thorough background to the oil palm ash, its origin, physical and chemical properties, its effect when incorporated as a partial cement replacement on the fresh and hardened properties of concrete and mortar as well as other types of cement based materials. In addition, this chapter will give a detailed background on the latest trends in masonry and masonry design with a thorough discussion on the advantages and disadvantages of interlocking concrete blocks.

## 2.2 Foamed concrete

The term foamed concrete in itself is misleading (Aldridge, 2005). Foamed concrete is a cement, sand, water mixture and foam either mixed or injected to the base mix. So, it is simply a mortar and foam (Liew, 2005), hence, it is closer to mortar than it is to concrete (Al-Noury et al., 1990). Foamed concrete is a relatively lightweight, low strength concrete produced by entraining air to a sand-cement mortar (Wimpenny, 1996). The air is introduced to the base mixture by the addition of either preformed foam or a chemical admixture. Foamed concrete distinguishes itself from other air entrained materials by having an air content more than 25% of its volume (Aldridge, 2005). In some cases, the air cells created by the preformed foam might account for 80% of its volume (Fouad, 2006). Foamed concrete is beneficial in reducing the dead weight of a structure in return reducing the design of supporting structures including foundations and walls of lower floors (Hamidah et al., 2005).

Lightweight foamed concrete is produced to have a wide range of densities making it appropriate to be used in a wide range of applications. Such applications are nonstructural, namely floor fills, sloping roof screeds, void filling in slabs and roadways for the reduction of lateral loads on wall structure; and structural applications such as load bearing building components. Foamed concrete is believed to be an environmental friendly construction material because it uses fewer natural resources, due to the absence of coarse aggregates, and uses waste materials such as fly ash and rice husk ash whenever possible (Noordin and Awang, 2005).

Foamed concrete has a number of types. It is classified according to its binder type, curing method or the method used in creating its microstructure (pores). Fouad (2006) classified foamed concrete or "cellular concrete" according to its wide range of densities and its application. Foamed concrete ranges from 320kg/m$^3$ to 1920kg/$^3$ in density (Fouad, 2006); where in other studies stated that cellular concrete has a range of 400kg/m$^3$ to 1600kg/m$^3$ (Ramamurthy et al., 2009) and a density range between (300kg/m$^3$ to 1800kg/m$^3$) (Narayanan and Ramamurthy, 2000). Fouad (2006) stated that foamed concrete having a density of less than 800kg/m$^3$ is used for non-structural applications such as thermal and sound insulation, roof decks, slab-on-grade sub-base fill, firewalls and underground thermal conduit linings. For densities ranging from 800kg/m$^3$ to 1900kg/m$^3$, the application of lower densities will be for non-structural fill for thermal and sound insulation of floors and roofs to cast in place walls, floors and roofs at higher densities. However, Liew (2005) presented a detailed classification for the densities and their applications which will be presented later on in a different section.

## 2.3 Constituent materials

A basic foamed concrete mixture contains cement, sand, water and foam. However, a number of changes to the contents of foamed concrete have been attempted by other researchers. Using cement paste for a base mix and replacing 75% of the cement by fly ash is studied (Kearsley and Wainwright, 2001b). Using fly ash as a cement replacement in a conventional foamed concrete mix is also studied for its properties (Jones and McCarthy, 2005b; Jones and McCarthy, 2005c). Silica fume has also been added as a constituent into a foamed concrete of 1150 $kg/m^3$ density mix at an addition rate of 10-20% by weight of cement (Zulkarnain and Ramli, 2011). Ground granulated blast furnace slag has been reported to be used as a cement replacement at a replacement level of 30-50% by weight of cement (Brady et al., 2001).

Fly ash is also used in replacing cement and sand at the same time and studied for its compressive strength, drying shrinkage and heat evolution (Jones et al., 2003). Fly ash is also used to completely replace sand in foamed concrete mixes (Nambiar and Ramamurthy, 2006). OPA sieved through a 600μm sieve is also used to replace sand at 10 and 20% by weight of sand (Lim et al., 2013). Blast furnace slag is used as a main binder material in a 500$kg/m^3$ foamed concrete mix used for thermal insulation (Yang et al., 2014).

Foaming agents that are protein based or synthetic have been used in producing the pre-formed foam. Protein based foaming agents are found to be more suitable in producing high strength and high density foamed concrete due to their smaller bubbles and closed microstructure (Brady et al., 2001; Panesar, 2013).

### 2.4 Properties of foamed concrete

In the following sections, the properties of foamed concrete will be listed and discussed thoroughly. These properties are the fresh and hardened properties of foamed concrete.

#### 2.4.1 Fresh state

Lightweight foamed concrete is, due to the absence of coarse aggregates, is high in its consistency (Liew, 2005). As a result of this higher consistency, foamed concrete is highly flow-able and has admirable workability (Fouad, 2006) making it easy to fill moulds and cavities without the need for any compaction. Therefore, the slump test conducted on conventional concrete is pointless with foamed concrete since it is placed in fluid state. The flow-ability and self-compactability of foamed concrete are assessed by the consistency and stability of the foamed concrete mortar base mixture (Ramamurthy et al., 2009). These properties of foamed concrete are affected by the water content in the base mix, the other constituents of the mix and the amount of foam added to the mix to obtain the needed density (Nambiar and Ramamurthy, 2008).

The consistency of a foamed concrete mix is determined using the density ratio. The density ratio is defined as the ratio between the measured fresh density of a foamed concrete mix to the chosen design density. The density ratio should be equal to unity (Nambiar and Ramamurthy, 2006; Nambiar and Ramamurthy, 2008).

The stability of the foamed concrete mix is defined as the ratio between the fresh density to its hardened density when removed from the moulds (Valore, 1954). This ratio should be unity to show that there was no clear deformation in the pore microstructure of the mix.

### 2.4.2. Drying shrinkage

Drying shrinkage is defined as the withdrawal of moisture from concrete when stored in unsaturated air (Neville, 1995). Foamed concrete exhibits higher shrinkage readings in comparison to conventional concrete. Moist-cured foamed concrete samples having a base mix made out of neat cement exhibited drying shrinkage readings higher than that of conventional concrete by 10 times (Valore, 1954). The lack of coarse aggregates and the high grout/fine aggregate content attributes to the higher drying shrinkage readings of foamed concrete (Jones and McCarthy, 2005a). Furthermore, higher shrinkage readings exhibited by foamed concrete are attributed to both of its higher cement and water content (Brady et al., 2001).

Typical values of drying shrinkage for foamed concrete range from 0.06 to 0.6% (Valore, 1954), 700 and $3000 \times 10^{-6}$ micro strains (Neville, 1995), 0.1 to 0.35% (Jones and McCarthy, 2005a) and 0.1 to 0.6% (Fouad, 2006). The drying shrinkage can be reduced for a foamed concrete sample having a specific foam content by using ash as a partial cement replacement and by the reduction of water content by using a dosage of super-plasticiser (Kearsley, 1996).

A 30% replacement of cement by fine fly ash in a foamed concrete mixture with a density of 1400kg/m$^3$ showed lower shrinkage strain readings than that made out of 100% cement by 2.6 times (Jones and McCarthy, 2005b). This was attributed to the provided restraint by the unreacted fly ash particles in the mixture. The same study also showed that replacing fine sand in a foamed concrete mixture with coarse fly ash at replacement levels of 50% and 100% exhibited higher drying shrinkage strains than the 100% sand foamed concrete mixture. The authors reasoned this increase in shrinkage strains to the increased amount of actual water content in the coarse fly ash mixtures and as a consequence to the largest volume of paste than the equivalent sand specimens.

Nambiar and Ramamurthy (2009) studied the effects of density, moisture content, filler to cement ratio, replacing sand with fly ash using different replacement levels and foam volume on the shrinkage of preformed foam concrete. Results showed that a decrease in shrinkage readings was observed with higher filler to cement ratios. They attributed this to the reduced cement content and the higher restraining effect that increased amounts of fine aggregate contents have. In addition, the results agreed with what Jones and McCarthy (2005b) concluded that replacing sand with fly ash will lead to increased drying shrinkage readings. The results showed that a foamed concrete mixture having a 30% foam content and a 40% replacement of sand by fly ash would exhibit a 20% higher drying shrinkage than that of its corresponding cement-sand mixture (Nambiar and Ramamurthy, 2009). The authors attributed this increase to the inferior restraining capacity of the fly ash in comparison to sand as well as to the increased water-solids ratio needed for the mixes with fly ash as a filler replacement to obtain a homogeneous, stable and workable mix.

Results also showed that an increase in foam volume would decrease the drying shrinkage in foamed concrete. The authors reasoned this decrease to the fact that the micro-pores affecting the shrinkage can be proportionate to the paste volume in a foamed concrete mixture. Hence, the lower drying shrinkage reading is a result of lower paste volume in the foamed concrete mix. Furthermore, the authors came to realise that lower density foamed concrete mixes are more stable than heavier mixes in terms of their shrinkage readings. They reasoned this to artificial air pores which might have an effect on volume stability by allowing some shrinkage and this effect increases with the increase in foam volume. This contradicts the results of (Brady et al., 2001; Jones and McCarthy, 2005b; Kearsley, 1996) stating that lighter foamed concrete mixtures (with higher foam volumes) exhibit higher drying shrinkage readings in comparison to heavier foamed concrete mixtures with lower foam volumes.

The drying shrinkage of foamed concrete is not usually considered to be critical when it is used as in fill and roof deck insulation applications. However, drying shrinkage of foamed concrete should be put into consideration when utilised in structural applications (Fouad, 2006).

**2.4.3 Density**

It has been noted that physical properties of foamed concrete are dependent on the density (Valore, 1954). Density of foamed concrete is expressed as fresh and hardened densities. Fresh density (as-cast, plastic or wet density) is used for designing the foamed concrete mix and also for control purposes (Ramamurthy et al., 2009). On the other hand, confusion may arise when expressing the hardened density. Therefore, the moisture condition of the foamed concrete sample should be stated (Fouad, 2006). Hardened density of foamed concrete is expressed as air-dry density (at a stated age and curing) or oven dry density. The plastic density is obtained within ±50kg/m$^3$ of the design density (Jones and McCarthy, 2005b; Jones and McCarthy, 2005c). Oven dry density is obtained by drying the specimens in an oven at a temperature of 105ºC (220ºF) for 24 hours or until achieving constant density (Valore, 1954). Fouad (2006) stated that the air-dry density of the foamed concrete mix is less than its wet density (as cast density). As a rough estimate, the air dry density of foamed concrete is 80kg/m$^3$ lower than that of its wet density (as cast density) (Neville, 1995).

Foamed concrete can be produced having a wide range of densities. Neville (1995) based foamed concrete classification depending on the existence of aggregate in its mixture. Foamed concrete can be produced at an oven dry density of 300 or as low as 200kg/$m^3$ for thermal insulation purposes when no aggregate is used. On the other hand, when aggregate is used while producing foamed concrete, a wide range of wet densities can be produced ranging from 800 to 2080kg/$m^3$.

Fouad (2006) classified the application of foamed concrete according to its density. Fouad stated that foamed concrete mixtures having a density lower than 800kg/$m^3$ are mainly used in non-structural applications for sound and thermal insulation, fire walls, roof decks, underground conduit lining and fill for slab-on-grade sub-bases. Foamed concrete having densities ranging from 800 to 1920kg/$m^3$ are mainly used in semi-structural applications. The lower densities are used in sound and thermal insulation for floors and roofs. Higher densities are used in cast in place roofs, walls and floors. A further detailed classification was presented by Liew (2005). The researcher classified the applications of foamed concrete with densities ranging from 300 to 1800kg/$m^3$ into four groups according to their density and they are listed in Table 2.1 below.

Table 2.1: Applications for foamed concrete according to density (Liew, 2005)

| Density (kg/$m^3$) | Application |
|---|---|
| 300-600 | Thermal insulation for flat roofing with required gradient. Cavity wall fillings. Floor sub surfaces. Thermal and sound insulation for general purposes. |
| 600-900 | Roofing slabs. Surface for stables and poultry farms. Walls, roofs and floor sub-surface of large cool rooms. Blocks and panels used for internal partitions. |
| 900-1200 | Structural and non-structural Blocks and panels for external walls. General sound proofing for industrial areas. |
| 1200-1800 | Medium weight blocks and slabs. Large reinforced slabs and panels. Walls either pre-cast or cast in place. |

Density has been studied to affect the mechanical and durability properties of foamed concrete. A research has been conducted in studying the relationship between compressive strength and density in order to determine the possibility of using foamed concrete in non-structural elements (Kiattikomol et al., 1988). The results showed that compressive strength of foamed concrete is proportional to its density. The authors also found that density of foamed concrete is proportional to the filler to binder ratio and inversely proportional to the amount of foam added. Results show that a mix with filler to binder ratio of one achieved a higher compressive strength, however, at the same time obtaining a lower density.

Porosity of foamed concrete was shown to be strongly related to dry density of foamed concrete and not on type or ash content (Kearsley and Wainwright, 2001b). Higher density foamed concrete specimens were less porous than the low density foamed concrete specimens. In addition, the water absorption was inversely proportional to density where higher absorption readings were exhibited by lower density foamed concrete specimens.

### 2.4.4 Compressive strength

Compressive strength of foamed concrete is affected by a number of factors. These factors can be of an influence on the compressive strength at the time of testing. Such factors are shape and size of the specimen, direction of loading, specimen's content of free moisture and the influence of age (Valore, 1954). Overall, compressive strength of foamed concrete is affected by the density, water/cement ratio, cement content, type and quantity of aggregate used, special admixtures and curing conditions (Fouad, 2006).

Similar to conventional concrete, strength of concrete is inversely proportional to the amount of air within the mix. Therefore, with foamed concrete densities, it is not a surprise that lower densities show lower strengths and even the upper limits do not produce strengths exceeding 15MPa (Aldridge, 2005). At any given density, the compressive strength of foamed concrete decreases with increasing the aggregate/cement ratio due to the decrease in cement content (Wimpenny, 1996). It can be stated that the density of foamed concrete is a function of foam quantity while the strength of foamed concrete is a function of sand quantity. Liew (2005) stated that at a given density, it is possible to produce foamed concrete having different strength just by changing the cement sand ratio of the mix. As an example, a 1400kg/m$^3$ when filler to binder ratio of 1/0.5 is used a 25MPa strength can be achieved, the same density will exhibit a lower strength when using filler to binder ratio of 2. Furthermore, a lighter density of foamed concrete can achieve a compressive strength similar to that exhibited by a heavier density mix by only increasing the cement content (Hamidah et al., 2005).

The type of foaming agent used in producing the pre-formed foam affects the compressive strength. Foamed concrete mixes using protein based foaming agents achieved higher compressive strengths and a more closed-cell bubble structure than those using synthetic foaming agents (Jones and McCarthy, 2005a)

Altering the type of filler used in the foamed concrete mixture will give different compressive strengths. Foamed concrete mixtures with fine sand as filler exhibited higher strengths than those with coarse sand (McCormick, 1967). Nambiar and Ramamurthy (2006) reasoned this to the uniform distribution of the pores within the matrix of the mix when using fine sand in contrast to larger irregular shaped pores in the case of coarse sand.

Fly ash was used to partially or totally replace sand in producing foamed concrete. When using coarse fly ash (retaining on a 45µm sieve is 26.0%) to totally replace sand, 2.5 times the strength of sand foamed concrete mixes was achieved at the age of 56 days (Jones and McCarthy, 2005b). In addition, for a specific foamed concrete density, mixtures with sand as filler contain higher air content than mixes with coarse fly ash as filler, hence, explaining the lower strengths (Jones and McCarthy, 2005c; Nambiar and Ramamurthy, 2006). Coarse oil palm ash (OPA) (sieved through a 600μm sieve) has been used in replacing sand at 10 and 20% replacement levels in foamed concrete (Lim et al., 2013). The authors of this research found that the higher the replacement level the greater compressive strength achieved.

Replacing the cement by other pozzolanic materials would affect the compressive strength of foamed concrete. Using an ash/cement ratio of 1 in a cement slurry based foamed concrete mix, Kearsley (1996) found that the compressive strength was higher than that of the control mix (when using unclassified fly ash). Compressive strength at 28 days suggested that foamed concrete mixes with unclassified and classified fly ash were lower than that of mixes without such replacements. However, at later ages (365 days), a foamed concrete mix having a 1.5 ash/cement ratio exhibited higher compressive strengths than those with ash/cement ratio of 0 despite of ash type (Kearsley and Wainwright, 2002). It has to be stated that compressive strengths of foamed concrete with unclassified fly ash were lower than that of foamed concrete mixtures with classified fly ash as cement replacement. Table 2.2 below summarises a number of studies that investigated the compressive strength of foamed concrete.

Table2.2: A summary of studies investigating the compressive strength of foamed concrete

| Author(s) | Mix Ratio | | | Weight of cement (kg/m$^3$) | Type of aggregate used | Densities tested (kg/m$^3$) | Compressive strength achieved (MPa) |
|---|---|---|---|---|---|---|---|
| | W/C* | S/C** | F/C*** | | | | |
| Bessey and Dilnot (1949) | 1.07 | 2 | - | - | Ground sand | 870-890 | 3.8-5.4 |
| | 0.90 | 1.5 | - | - | Ground sand | 850-860 | 8.1-12.2 |
| | 0.87 | 3 | - | - | Natural sand | 1230-1260 | 3.2-5.4 |
| | 0.87 | 3 | - | - | Natural sand | 1230-1240 | 8.9-13.7 |
| McCormick (1967) | 0.35-0.57 | 1-3 | - | | Sand | 929-1922 | 0.21-27.2 |
| | 0.35-0.50 | 0.65-1.43 | - | | shale | 737-1362 | 0.1-10.5 |
| Kiattikomol et al. (1988) | 0.4-0.7 | 1-2.5 | - | - | sand | 520-1890 | 0.03-22.3 |
| Kearsley and Wainwright (2001a) | 0.6-1.17 | - | 1-3 | 226-346 | - | 1000-1500 | 6-40 |
| Jones and McCarthy (2005b) | 0.26-0.5 | 1.45 | 30-50 | 500 | Sand-fly ash | 1400-1800 | 10-60 |
| Jones and McCarthy (2005c) | 0.5-1.6 | 1.5-3.0 | - | 300 | Sand-fly ash | 1000-1400 | 0.5-10 |
| Nambiar and Ramamurthy (2006) | 0.2-0.55 | 1 | - | - | Sand-fly ash | 1000-1500 | 0.5-11 |
| Bing et al. (2012) | 0.35-0.60 | - | 1 | 380-580 | Fly ash | 800-1500 | 10-55 |
| Panesar (2013) | 0.29 | 1.6 | - | 361-611 | - | 1581-2362 | 5-10 |
| Lim et al. (2013) | 0.54-0.56 | 1 | - | - | Sand-OPA | 1300 | 7.17 |
| Pan et al. (2014) | 0.52 | - | - | 300 | - | 15-300 | 0.33-1.1 |

*W/C: the water to cement ratio , **S/C: the sand to cement ratio, ***F/C: the fly ash to cement ratio

### 2.4.5 Tensile splitting strength

Although foamed concrete is lower in strength than conventional concrete, the tensile to compressive strength ratio is similar to that of conventional concrete. Tensile strengths are in the range of 10-15% of the compressive strength (Fouad, 2006). The minimum requirement for the tensile strength of foamed concrete is 0.17MPa as stated by ASTM C869-91(ASTM, 2001d).

Foamed concrete specimens with plastic densities of 1400, 1600 and 1800kg/m$^3$ were tested for their tensile strength when replacing sand with fly ash (Jones and McCarthy, 2005b). Results show that foamed concrete specimens with fly ash as filler had lower tensile strengths than those with sand as filler. The authors reasoned this to the improved shear capacity between the sand particles and the paste of the mix.

OPA passing through a 600µm sieve was used to replace filler in a 1300kg/m$^3$ foamed concrete mix at 10 and 20% replacement levels (Lim et al., 2013). OPA foamed concrete mixes showed higher tensile strengths with increasing OPA. The 10 and 20% foamed concrete samples exhibited tensile strength readings greater than that of the control mix by 19 and 9% at the age of 90 days. Lim et al. (2013) reasoned these higher tensile strengths to the increased amount of formed C-S-H, hence, increasing the bonding property and as a result demanding extra load. Tensile strengths of foamed concrete can be increased substantially by using polypropylene fibres in the mix (Brady et al., 2001; Fouad, 2006).

Using 15mm polypropylene fibres greatly increased the tensile strength of foamed concrete (Bing et al., 2012). Test results show that with increasing foam volume, the advantage of fibre addition increased. They stated when foam volume is