STRENGTH AND DURABILITY PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE FOR HOUSING CONSTRUCTION

by

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In Memory of my Father

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ABSTRAK

Konkrit berbusa adalah sama ada pasta simen yang diklasifikasikan sebagai simen ringan, di mana rongga-rongga udara terperangkap dalam mortar oleh agen pembusaan yang sesuai. Ia mempunyai keboleh aliran yang tinggi, berat yang rendah, penggunaan aggregat yang rendah, kekuatan rendah yang terkawal, dan sifat penebatan haba yang sangat baik. Ketumpatan-ketumpatan konkrit berbusa dalam julat yang luas di antara (1600-400 kg/m^3), melalui kawalan dos yang sesuai, boleh diperolehi untuk applikasi kepada struktur, dinding sekat, atau gred pengisian. Dalam penyelidikan ini, konkrit berbusa menggunakan aggregat halus yang melepasi tapisan 5 mm atau 3/16 inci, dan 10% Norizal Hardener Powder Code: 4 (NHP4) berdasarkan berat simen, untuk meningkatkan kekuatan dan ketahanan konkrit ringan berbusa. Nisbah bagi rekabentuk campuran ini adalah 1:1.5:0.45 dengan ketumpatan sasaran dari 1050 kg/m^3, 1150 kg/m^3, 1250 kg/m^3, 1350 kg/m^3 dan 1450 kg/m^3. Rekabentuk campuran dalam penyelidikan ini mempunyai isipadu 0.05 m^3 dan ujian penurunan sekitar 18 cm hingga 20 cm. Ketumpatan mortar sekitar 2150 kg/m^3 bagi kesemua ketumpatan sasaran dan berat busa dalam rekabentuk campuran sekitar 75-80 g/liter. Konkrit ringan berbusa dijalankan dengan pengawetan selama 3, 7, 28, 60, 90, 180, dan 365 hari. Ujian bagi semua spesimen dalam penyelidikan meliputi kekuatan mampat, kekuatan lentur, kekuatan tegangan pecah dan blok konkrit selular ringan dalam jangkamasa pengawetan didapati berbeza. Kekuatan mampatan bagi konkrit berbusa telah ditentukan daripada kiub berukuran 100 mm x 100 mm,

kekuatan lentur diuji dengan ukuran 100 mm x 100 mm x 500 mm, kekuatan tegangan pecah diuji dengan ukuran diameter 150 mm x 300 mm panjang bagi silinder dan blok konkrit selular ringan diuji dengan ukuran 200 mm x 100 mm x 500 mm. Kiub-kiub tersebut telah dituang dalam acuan-acuan keluli, dikeluarkan daripada acuan setelah 24 jam, dibalut dalam pembalut politena, dan disimpan dalam sebuah bilik dengan suhu malar ± 28°C sehinggalah ke hari ia diuji. Setiap satu kiub telah dibuka pembalutnya dan ditimbang sebelum ujian. Kajian ini telah menghasilkan ketumpatan sasaran berbeza dan juga jenis ujian yang berbeza. Kekuatan mampatan minimum untuk kekuatan mampatan dalam ACI 532.2R-96 adalah 300 psi (2.07 MPa), bagi unit-unit lantai konkrit seluar bertetulang pratuang, bumbung dan dinding. Berdasarkan piawaian British (BS) 5628: Part 1: 1978, kekuatan mampatan adalah 2.8 N/mm^2. Bagi sampel 28 hari, kesemua data mempunyai nilai melebihi nilai minimum daripada ACI atau BS, dan kesimpulan daripada kajian ini juga, secara umumnya boleh digunakan untuk pembinaan bangunan.

STRENGTH AND DURABILITY PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE FOR HOUSING CONSTRUCTION

ABSTRACT

Foamed concrete is either cement paste classified as lightweight concrete, where air-voids are entrapped in mortar by a suitable foaming agent. It possesses high-flow ability, low self-weight, minimal consumption of aggregate, controlled low strength, and excellent thermal insulation properties. A wide range of densities of the foam concrete between (1600-400 kg/m^3), with proper control in the dosage of the foam, can be obtained for the structural, partition, insulation application and the filling grades. In this research, foam concrete uses fine aggregate passing a 5 mm or 3/16 inch sieve, and 10% of Norizal Hardener Powder Code: 4 (NHP4) based on the weight of cement, for increasing the strength and durability of lightweight foamed concrete. The ratio for this mix design is 1:1.5:0.45 with target density from 1050 kg/m^3, 1150 kg/m^3, 1250 kg/m^3, 1350 kg/m^3 to 1450 kg/m^3. The mix design adopted for this research has the volume of 0.05 m^3 and slump test around 18 cm to 20 cm. Mortar density around 2150 kg/m^3 for all target densities and foam weights in mix design is around 75-80 g/litre. Lightweight foamed concrete with curing time took place for 3, 7, 28, 60, 90, 180, and 365 days. Tests for all specimens in this research such as the compressive strength, flexural strength, splitting tensile strength and lightweight cellular concrete block had been performed in different durations of the curing time. The compressive strength of the foamed concrete was determined from 100 mm x 100 mm cubes, flexural strength with 100 mm x 100 mm x 500 mm, tensile splitting strength with 150 mm diameter x 300 mm long for cylinders and

lightweight cellular concrete block with 200 mm x 100 mm x 500 mm. The cubes were cast in steel moulds, demoulded after 24 hours, wrapped in polythene wrapping, and stored in a room with a constant room temperature of ± 28°C up to the day of testing. Each cube was unwrapped and weighed before testing. This research has resulted in different target densities and also different types of testing. The minimum compressive strength for that in American Concrete Institute (ACI) 532.2R-96 is 300 psi (2.07 MPa), where this is used for precast reinforced cellular concrete floor, roof, and wall units. From the British Standard (BS) 5628: Part 1: 1978, the compressive strength is 2.8 N/mm^2. This research also ensures that the material and foam for this research are suitable in the non-loadbearing lightweight block foam. The strength and durability of these specimens also include the tests for the compressive strength, flexural strength and tensile splitting strength. All specimens with the mixed design of the lightweight foamed concrete are tested in different target densities, which were 1050 kg/m^3, 1150 kg/m^3, 1250 kg/m^3, 1350 kg/m^3 and 1450 kg/m^3. The target density of 1050 kg/m^3 has the maximum compressive strength of 15.27 N/mm^2 in 365 days of curing time. The maximum compressive strength for the target density 1150 kg/m^3 would be 21.15 N/mm^2 in 365 days of curing time. The maximum compressive strength for the target density 1250 kg/m^3 is 24.06 N/mm^2 in 365 days of curing time. The maximum compressive strength for the target density of 1350 kg/m^3 is 25.43 N/mm^2 in 365 days of curing time. Next, the maximum compressive strength for the target density 1450 kg/m^3 is 29.52 N/mm^2 in 365 days of curing time. For 28 days, the results concerning compressive strength from either the ACI or BS have been minimal, and the conclusion deduced from this research can also be used for the housing construction in general.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the last four decades, lightweight concrete has been employed in both residential housing and tall building construction. Precast lightweight concrete panels have become widely used materials in construction. Considerable attention is being paid to reducing the dead load and thermal conductivity of concrete panels and improving their fire resistance. In addition the earthquake resistance and seismic of concrete structure are becoming more important issues (Kim, 2004).

According to Kearsley (1999), foam concrete is perceived to be weak, non-durable with high shrinkage characteristics and untreated aerated concrete should not be exposed to an aggressive atmosphere and that unprotected reinforcement in aerated concrete would be vulnerable to corrosion even when the external attack is not very severe. Low density concrete is normally defined as concrete having an air-dry density of below 2000 kg/m^3 as opposed to normal concrete with a density in the region of 2350 kg/m^3. Low density concrete has practical and economical advantages as the reduced weight of the superstructure can lead to savings in the cost of super and substructures and components can be handled and erected relatively easily. Fire resistance and thermal insulation of low density concrete are superior to those of normal density concrete.

Low density concrete can be manufactured with a density of between 300 and 1850 kg/m^3. The strength of low density concrete is a function of density and therefore density can be used to classify low density concrete according to the purpose for which it is to be used. Low density concrete can be used to classify as one of the following:

- Structural low density concrete has a density between 1350 kg/m^3 and 1850 kg/m^3 and minimum compressive cylinder strength of 17 MPa.
- Low density concrete has a density between 300 kg/m^3 and 800 kg/m^3 and is used for non-structural applications, mainly for thermal insulation purposes.
- A third category between the previous two used for masonry units.

Since the introduction of cellular concrete systems to the construction industry more than 50 years ago, the use of foamed concrete has been almost exclusively limited to the following applications: non structural void filling, thermal insulation, acoustic damping, trench filling reinstatement of roads and building blocks. In the Netherlands foamed concrete has been used not only for level correction in housing developments, but also for fill-material where ground subsidence has taken place and ask founding layer for road works on very weak soils (Kearsley, 1999).

Structural lightweight concrete is a structural concrete made with lightweight aggregate, the air-dried unit weighed at 28 days is usually in the range of 1440 kg/m^3 to 1850 kg/m^3 and the compressive strength is more than or 17.2 MPa. (213R-87, 1999).

Lightweight concrete maintains its large voids and not forming laitance layers or cement films when placed on the wall. In this research, is based on the performance of aerated lightweight concrete. However, sufficient water cement ratio is vital to produce adequate cohesion between cement and water. Likewise, too much water can cause cement run off aggregates to form laitance layers, subsequently weakening in strength.

Foamed concrete or type of lightweight concrete is either cement paste or mortar classified as lightweight concrete, where air-voids are entrapped in the mortar by a suitable foaming agent. It possesses high flow ability, low self-weight, minimal consumption of aggregate, controlled low strength, and excellent thermal insulation properties. A wide range of densities (1600-400 kg/m^3) of foamed concrete, with proper control in the dosage of the foam, can be obtained to be applied to the structural, partition, insulation, and filling grades (Ramamurthy et al., 2009).

Foamed concrete is a lightweight material consisting of the Portland cement paste or cement filler matrix (mortar), with a homogeneous void or pore structure created by introducing air in the form of small bubbles (Nambiar and Ramamurthy, 2007a).

Pre-formed foam concrete is manufactured by adding foam, prepared by aerating a foaming agent solution, to cement paste or cement mortar. The composition, physical properties and uses of foam concrete have been discussed in detail by (Nambiar and Ramamurthy, 2006).

The properties of its components-the cement paste and the voids-have a measurable effect on the properties of the combined materials (Nambiar and Ramamurthy, 2007b).

The method of production in aerated concrete (either through gas release or foaming) can influence the microstructure and, consequently, its properties. The material structure of aerated concrete is characterized by its solid microporous matrix and macropores (Narayanan and Ramamurthy, 2000). The macropores are formed due to the expansion of the mass caused by aeration. Micropores also appear in the walls between the macropores (Alexanderson, 1979). Macropores have usually been defined as pores with a diameter of more than 60 μm (Petrov and Schlegel, 1994).

Aerated lightweight aggregate concrete is formulated by the minimum matrix methods, which seeks to achieve volume ratio of comentitious matrix to hard aggregate. The optimal value yields the closest possible contact of each particle of aggregate. When the matrix is completely without voids, it is in the minimum matrix condition. For concrete density between 75 and 90 pcf, this conditions produces the best possible values of compressive and tensile strengths, elasticity, and other properties. It requires, only the minimum amount of cement necessary to produce adequate strength, so that the shrinkage is less than in ordinary lightweight concrete. In this manner, cost may also be reducing since cement is most expensive ingredient of concrete (Kim, 2004).

In 1963, Short and Kinniburgh presented the first comprehensive review on cellular concrete, summarizing the composition, properties, and uses of cellular concrete, irrespective of the method of formation of the cell structure. Subsequently, Jones and McCarthy recently reviewed the history of the uses of foamed concrete and its constituent material, properties, and construction application, including for some projects carried out worldwide. These reviews included an evaluation of its functional properties such as fire resistance, thermal conductivity, and acoustics. However, data on fresh state properties, durability, and air-void systems of foamed concrete are found to be limited (Short and Kinniburgh, 1978).

The production of stable foamed concrete mix depends on many factors, such as the selection of foaming agent, method of foam preparation and addition of uniform air-voids distribution, material section and mixture design strategies, and production of foamed concrete (Ramamurthy et al., 2009).

The applications of lightweight concrete for composite structures are ostensible in the building industry. Glass reinforced plastic (GRP) components have been used in this sector for over three decades. As building materials, composites are suitable for numerous applications, such as in pipes, sills, slabs, formwork, linings, pillars, foundations, tanks, housings, containers, doors, covers, bricks, walls, frames, steps, and gutters. The possibilities are virtually unlimited. Composites innovations continue to find usefulness in building sites (Reichl, 2007).

This growing popularity has led to the development of scaffolding boards made of GRP. The idea is to replace the heavy timber boards, relieving the stress on high scaffolding as well as enabling higher transport and erection performance by scaffolders. This objective is achieved. Savings of over 20% (in weight) has been achieved over the conventional timber scaffolding boards after successful load and weathering tests (Reichl, 2007).

Most of the residential houses offered in the market today from a “low cost house”, and the developers cannot lower the cost because the current available construction technology entails too much manpower and material wastage (Lejano, 1997). Kearsley (1999) reported, unstable foams have in the past resulted in foamed concrete having properties unsuitable for reinforced, structural applications. The development of protein-hydrolisation based foaming agents and specialized foam generating equipment have improved the stability of the foam, making it possible to manufacture foamed concrete for structural applications. In recent years foamed concrete has been used as a structural material in schools, apartment and housing developments in countries such as Brazil, Singapore, Kuwait, Nigeria, Botswana, Mexico, Indonesia, Libya, Saudi Arabia, Algeria, Iraq and Egypt.

1.2 Problem Statement

The production of stable foam concrete’s mix design depends on many factors such as the selection of foaming agent, method of foam preparation and addition for uniform air-voids distribution, material section and mixture design strategies, production of foam concrete, and performance with respect to fresh and hardened state are of greater significance (Ramamurthy et al., 2009). Many researchers have paid attention to this area and produced foam with durability and high-performance. All aspects should be considered and produced for sustainable, durable and environmental-friendly housing construction.

The prominent advantage of aerated concrete is its lightweight, which economises the design of the supporting structures including the foundation and walls of lower floors. It provides a high degree of thermal insulation and considerable savings in material due to the porous structure. By adopting an appropriate method of production, aerated concrete with a wide range of densities (300 ± 1800 kg/m^3) can be obtained thereby offering flexibility in manufacturing products for specific applications of structural, partition and insulation grades (Narayanan and Ramamurthy, 2000).

The first element to obtain the durability and strength lightweight foamed concrete is a selection of ratio foam agent with water, and the design of mixture of the current foam concrete, also producing the foam for sustainably low cost in the housing construction.

1.3 Research Aim and Objectives

In general, the main purpose of this research is to examine the lightweight foamed concrete in detail, based on its strength and durability in housing constructions. In the literature review, it is established that lightweight foamed concrete can generally be used in the constructions, especially where the housing industry is concerned. Otherwise, in this particular context, lightweight foamed concrete necessitates further research and practical tests in laboratories to obtain a result with decreased density, increased compressibility and is suitable for use in a housing construction. Also, the quality of the materials would be ensured from the selection stage until the mix design stage.

We now come to the objective of this research:

1. To design and determine a mixed design of lightweight foamed concrete and percentage of foam in lightweight foamed concrete for housing construction.
2. To define and test the structure of the lightweight block foam concrete based on the strength and durability.
3. To evaluate the strength and durability of lightweight foamed concrete for housing construction.

Our pursuit is to design and determine a mixed design of strong and durable lightweight foamed concrete and establish the suitable percentage of foam concrete for the housing construction. Furthermore, a mixed design of lightweight foamed concrete is to be defined and tested in target densities from 1050 kg/m^3 until 1450 kg/m^3, and also in different curing times from 3 days until 365 days.

This study is an attempt to find any method that can work towards improving of building materials. It focuses on the properties and the performance of the stabilized lightweight foamed concrete. One of these studies is to propose and summarize the information, pertaining to the basic characteristics attributable to lightweight foamed concrete and on the stabilization and compaction.

1.4 Scope of this Research

This research will be focusing on lightweight foamed concrete, which offers better quality structure and faster building construction solution other than being economical in the housing construction. Many aspects have been clarified through the literature regarding building material properties and lightweight foamed concrete for building construction. Quite differently, this research focuses on the design and selection of material properties in building construction, and has put forth a technique of processing lightweight foamed concrete.

The scope of this research lingers around the lightweight foamed concrete, where some theoretical principles on the lightweight foamed concrete in correlation to strength and durability for housing construction have been provided. The target densities used in the range of 1050 kg/m^3 to 1450 kg/m^3 in different curing times from 3 days until 365 days were decided. In general term, the lightweight foamed concrete maximum target density is 1850 kg/m^3 approximately, and it comes with different admixtures in the concrete itself. In this research, the maximum target density is chosen to be 1450 kg/m^3 because for 3 days, the compressive strength would be 7.04 N/mm^2, to compare with the Malaysian Standard (MS) 27: 1996 which establishes 2.8 N/mm^2 as the minimum compressive strength for the block. Based on these criteria, target density results are suitable for the lightweight foamed concrete block. On the other hand, basic constituents such as cement, sand, water, with Norizal Hardener Powder Code: 4 (NHP4), and silica fume serve as the contributors for the increase of strength and durability of lightweight foamed concrete.

This research also evaluates strength, durability and performance structure of this lightweight foamed concrete based on the selected materials such as foam, fine aggregate, and cement. Also, we went on to examine the relationship between the control mixture with foam, Ordinary Portland Cement (OPC), fine aggregate, and water, respectively. This relationship scrutinises the fine aggregate and silica fume such as their increased strength and performance, and stabilized lightweight foamed concrete such as fresh density and slump for new mix design of the foam concrete.

1.5 Research Methodology

In this study, elaborated studies equipped with laboratories experiments, their results and the inevitable conclusions. For literature review, the entire source is based on the historical background of lightweight foamed concrete and its contributions to the building construction and the housing construction. The focus of this research therefore is to estimate the strength and durability of a lightweight foamed concrete for constructions, applicable to both building and housing constructions.

In the laboratories, the experimental procedure is divided into six chapters, with research activities already determined. This research such as the test of all materials, test of fresh air void (bubble) foam, test of density a lightweight foamed concrete, test of compressive strength and test of flexural and tensile strengths. In the first research a material is selected for the mix design of the lightweight foamed concrete. There is a test for air void, test for hardened cement paste, test of particle size distribution, test of water absorption, and test of fresh density of concrete.

In this research, a trial and error mix design of lightweight foamed concrete to get a quality and the quantity of mix design is required. The first of this mix design is a fresh density of the lightweight foamed concrete, meaning lightweight foamed concrete must obtain a standard fresh density around 1000 kg/m^3 to 1850 kg/m^3. Before this, a test is performed, with the degradation of cement (slump test) known as the combination of cement and water with a circle diameter of 18.0 cm to 20.0 cm. After the test has produced good results, we then move on to the compressive and flexural strength test. Compressive strength of the foamed concrete is determined from 100 mm cubes. The cubes were cast in steel moulds, demoulded after 24 hours, wrapped in polythene wrapping, and stored in a room with a constant room temperature of ± 28°C up to the day of testing. Each cube was unwrapped and weighed before testing. All of the specimens were kept in storage for the maximum 365 days. Estimation in this research for all specimens, such as the cube and prism is a test of methods of testing cement, determination of relative density and water absorption, methods for determination of particle size distribution, fresh density, slump test, test of quality foam, compressive strength, flexural strength, Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT), carbonation, tensile splitting strength, modulus of elasticity, and the drying shrinkage.

At the end of this research, the lightweight foam's concrete panel with a high ratio compressive strength are selected and ready to be used. This current research also recommends credible performance and high achievement of the lightweight foamed concrete, such as in air condition. All of this research has been carried out, based on the Malaysian Standard (MS), British Standard (BS) and American Standard (ASTM).

1.6 Layout of Thesis

This chapter is divided into six chapters including detailed discussions regarding the research done in the laboratories. This thesis is designed in such a way as for the objectives in this research to be able to be fulfilled, by thorough discussions that are present chapter by chapter. Generally, the substance of every chapter is given below:

For chapter 1, this chapter includes the general introduction between studies that have been done previously, research objectives, scope of this research, problem statement, and research methodology, and the layout of the thesis.

In chapter 2, researcher will be presented with ample literature review, which highlights the discussions that surround the subject matter, which is based on the classification of lightweight concrete, technology of lightweight foamed concrete and historical background of the lightweight concrete, lightweight foamed concrete for housing construction, honeycomb cores, adhesive and other components, chemical aspect of lightweight concrete, and manufacture of foam agent. This chapter also focuses on a process of preparing the material and lightweight foamed concrete in general. In specific, a material and mixed design of lightweight foamed concrete are prepared, such as a material concrete for structural lightweight foamed concrete for housing construction.

Chapter 3, highlights the research methodology performed in laboratories, with respect to the lightweight foamed concrete, where this research starts from selecting and testing natural materials or basic materials for use until preparing the lightweight foamed concrete. Another discussion concerns a design and preparation of the mix design of the lightweight foamed concrete and testing of a specimen. Discussion of the final research of this specimen includes a mix design of the lightweight foamed concrete, type of conservation and duration of conservation. Details of these include also the engineering research with basic standard materials being studied, such as the testing of materials, testing of strength of lightweight foamed concrete, testing of durability of lightweight foamed concrete, process and installing mould concrete, processing mixed design concrete, processing preservation lightweight foamed concrete, mixed design concrete, and mixed design in this research.

Chapter 4, sheds light on the strength of lightweight foamed concrete. The discussion brings into the picture the strength of lightweight foamed concrete based on results and the processing of all specimens in the laboratories. Some tests have also been covered such as the slump test, density of lightweight foamed concrete test, effect of different foam density with target density, test of compressive strength, test of flexural strength, test of PUNDIT, modulus of elasticity test, tensile splitting strength test. This research also covers an analysis of results and comparison analysis, where the tests are being compared to another testing in the laboratories.

Chapter 5, sees the durability behaviour of lightweight foamed concrete being discussed. These tests also include the carbonation test, water absorption test, oxygen permeability test, lost of weight test, shrinkage limit test, and structural test. Another evaluation and the impending conclusion are also presented, regarding the durability of lightweight foamed concrete in the housing construction. The test results pertaining to all specimens being tested have also taken place in some paragraphs in this chapter, and what follow are the analysis results of each testing and the comparison with another testing done previously.

Chapter 6 presents the conclusion and suggestion for future research. This chapter also deals with all testing done in laboratories. In overall, the mixed design of the lightweight foamed concrete is in the density of 1450 kg/m^3 with high compressive strength lasting in 365 days. This ratio can be used for the non-load bearing structures. Flexural strength in all tests also increases in different days, where the density of 1450 kg/m^3 produces good results compared with other target densities. The result in 365 days is not very significant but we can notice an increase from the beginning, such as in 3 days. In the structural test there is also noticeably an increase from 3 days to 365 days. Suggestions for similar future research would include the fact that the mixed design lightweight foamed concrete can use different density levels, ratio and curing time. Researcher is also suggested to be more open and flexible to use other materials for the mixed design of the lightweight foamed concrete.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is a construction material that consists of cement, aggregate (fine and coarse), water, and admixtures such as fly ash, silica fume, and other chemical agents. After the mixing process, concrete is hardened by a chemical process called hydration. Concrete can be used for several applications such as pavements, buildings, foundations, pipes, dams, and other civil infrastructural structures. Concrete is one of the most popular construction materials. According to the ASCE (2005), every year approximately six billion cubic meters of concrete is produced. In addition, more than 55,000 miles of roads and highways in America are built by using concrete. Usually, concrete has an outstanding compressive strength but very low tensile strength. Therefore, steel reinforcement is applied in concrete structures to handle the tensile strength of structures (Piyamaikongdech, 2007).

The idea of using lightweight materials in concrete construction has become popular due to economical reasons. If the production of lightweight concrete with adequate strength and ductility is achieved, the construction cost will be significantly reduced. The most important advantages of using concrete are to reduce dead load of a structure. Besides reduction of dead load, faster construction, lower transportation and handling costs and reduction of labour become dominant factors to use lightweight concrete. Besides being lightweight, low thermal conductivity is another characteristic of lightweight concrete. As reducing energy of fuel consumption during operation of buildings become necessary, demands for lightweight concrete increase (Arisoy, 2002).

Lightweight concretes can be produced with a density range of approximately 300-2000 kg/m^3, corresponding cube strength from approximately 1 to over 60 N/mm^2 and thermal conductivities of 0.2 to 1.0 W/m K. These values can be compared with those for formal weight concrete of approximately 2100-2500 kg/m^3, 15 to greater than 100 N/mm^2 and 1.6-1.9 W/m K (Clarke, 1993).

According to Neville and Brooks (1987), the density (unit weight) of such concrete (determined in the dry state) should not exceed 1840 kg/m^3, and usually between 1400 and 1800 kg/m^3. The Draft International Standard Model Code for Concrete Construction classifies lightweight concrete as having densities between 1200 and 2000 kg/m^3.

2.2 History of lightweight foam concrete

Whereas the use of air entrained and foamed concrete has grown rapidly in recent years it is by no means a new product. Two thousand years ago the Romans were making a primitive concrete mix consisting of small gravel and coarse sands mixed together with hot lime and water. They soon discovered that by adding animal blood into the mix and agitating it, small air bubbles were created making the mix more workable and durable; they were even adding horse hair into mixes to reduce shrinkage, much like we use fibres today. There is also evidence of this type of technology being used by the Egyptians over 5000 years ago, with similar results (Aldridge, 2005).

Foamed concrete was used nearly a century ago in the special precast application of autoclaved aerated concrete, with the first reported applications being two apparently independent initiative in 1923, one in Denmark the other in Sweden (Beningfield et al., 2005).

According to Short and Kinniburgh (1978) and Ismail (2010), lightweight concrete has been used since the eighteen centuries by the Romans. The application on the ‘The Pantheon’ where it uses *pumice* aggregate in the construction of cast in-situ concrete is the proof of its usage. In United State of America (USA) and England in the late nineteenth century, *clinker* was used in their construction for example the ‘British Museum’ and other low cost housing. The lightweight concrete was also used in construction during the First World War. The United States used mainly for shipbuilding and concrete blocks. The *foamed blast furnace-slag* and *pumice aggregate* for block making were introduced in England and Sweden around 1930s.

According to Beningfield et al., (2005) foamed concretes based on this concept began to be adopted in the early 1980’s and at that time take up began to accelerate in much of Europe with Germany in particular leading the way. Portable foam generators were developed by Ready Mixed Concrete (RMC) that could be used to add foam directly into the back of a ready-mix truck, via a so-called ‘elephants trunk’. Within the United Kingdom (UK), specifications began to appear in the early 1990’s and the market has continued to grow rapidly, with current estimates of perhaps 300,000 to 350,000 m^3 per annual used in the United Kingdom. Typical applications are for general backfilling, filling of redundant sewers, ducts, tunnels, underground tanks and similar with probably the largest being the backfilling of utility trenches. Other United Kingdom applications include use below bituminous finishes for roofs, multi storey car parks and similar where the light weight is beneficial and the material may be conveniently placed by pump.

One of the earliest, significant research and development of foamed concrete was carried out in the Netherland by the CUR (Dutch Concrete Society) in the late 1980s and 1990s. This helped establish foamed concrete as an accepted building material. In addition to considering a range of constituent materials and different production methods, the extensive test programme aimed at obtaining a database of foamed concrete properties as a function of its density. Some of the properties considered were compressive and bending tensile strength, modulus of elasticity, heat conductivity, freeze/thaw resistance and water absorption (Jones & McCarthy 2005, Van Dijk 1991, & British Cement Association 1991).

Obviously these very early air entrained concretes were extremely basic with no control over air content, etc. It was not until the early 1900's that the manufacture of highly air entrained materials began to be commercially explored, with perhaps surprisingly Sweden being the pioneers behind it, based on the working of Axel Eriksson. Doubtless the extreme weather experienced by this country gave impetus to the development of an extremely thermally efficient building material but this foresight remains today with Sweden still being one of the biggest users of lightweight foamed concrete's (Aldridge, 2005).

The promotion of foamed concrete in the United Kingdom, in term of research into and development of the material, was initiated by the British Cement Association

(BCA). The findings of the work were included in six publications between 1990 and 1994 (Jones & McCarthy 2005, British Cement Association 1990, 1991, 1993, & 1994). This provided an overview of the material (properties, advantages, application and was particularly aimed at the trench reinstatement market (British Cement Association 1990 & 1991).

2.2.1 Lightweight foam concrete in construction

According to Lee and Hung (2005), the first major application of Lightweight Concrete Method (LCM) foamed concrete in Malaysia is at the SMART tunnel project in Kuala Lumpur. The foamed concrete specified was of density 1800 kg/m^3 which achieved compressive strength of 3 N/mm^2 at the age of 28 days. Foam concrete block of size 17 m x 17 m x 6 m was cast in three stages in order to allow a maximum height of 2 m per cast. The completed foamed concrete block serves to protect the diaphragm wall when the tunnelling machine is coming out into the junction box.

Other lightweight, inert, finely divided materials such as powdered waste plastics, rice husk and other locally available biomass are also being experimented. The composition is proposed to be injected at prescribed locations with innovative precast lightweight hollow-core concrete pile to effect replacement of portions of the soil. The system is expected to provide cost-effective geotechnical solution as the surrounding soft ground becomes compacted while foamed concrete solidifies in situ. Foundation system with the utilisation of used tyres is being experimented in some housing project in Malaysia. Successful development of the system is expected to provide a fast-track method for affordable quality-assured housing. The system is applicable for the homeless people who urgently need a decent shelter (Lee and Hung, 2005).

According to Boughrarou and Cale (2005), foamed concrete has been selected as a novel solution for the large scale infilling of old mine working as part of an ongoing project for stabilisation of the historical stone mines in Combe Down. The historical Combe Down mines are located in the centre of the Combe Down area, situated some three kilometres south of the city of Bath. The mines comprise a significant complex of shallow underground workings, mined predominantly during the 18th century to provide dimension stone for buildings and structures in Bath and other cities both in the United Kingdom and around the world. It is planned for over 400,000 m^3 of foamed concrete to be placed in the shallow underground mines, which potentially cover more than 25 hectares.

Problems with surface stability of the area were first formally identified in 1986 when the underground mine workings were exposed by a contractor during excavation of a shallow trench. Initial underground investigation revealed to condition of the mines, including ongoing collapse and progressive deterioration of rock pillars and the mine roof (Hawkins, 1994). Subsequent detailed investigation involved mapping and classification of the majority of the accessible areas, which indicated that the mine workings posed a hazard to life and property. Weight restrictions and other safety measures were imposed on the highways overlying a number of areas identified as posing a high hazard. Given the significant impact that any mine collapse could have on the safety of the life and property in the Combe Down area, an Emergency Works programme was initiated in 2001 by the local authority, Bath and North East Somerset Council. The works have focussed on the reduction of immediate health and safety risks within selected high hazard areas beneath public highways, including a section of major route (A3602) known locally as North Road. The works have also involved the construction of over 4,000 metres of enabling and investigation roadways within accessible parts of the mines (Boughrarou and Cale, 2005).

Boughrarou and Cale, (2005), reported a number of methods are available for the stabilisation of old mines workings. In general, stabilisation entails infilling the mine voids, with selected bulk materials, to provide effective support to the overlying ground. These materials include pulverised fuel ash (pfa), lean mix concretes/grouts, aggregates materials, tailing paste, etc.

Foam concrete has been selected as the principal technique for stabilisation of the Combe Down mine for following reasons:

- It is environmentally acceptable, lightweight and requires less consumption of primary materials that are available locally.
- It can be delivered underground more easily than other materials.
- It can be manufactured to variable mechanical characteristics (strength and density) which can be modified to suit the ground conditions encountered within the mines.
- It is free flowing and therefore has the ability to penetrate and consolidate loose discards and collapsed zones. Variation of its flow characteristics allows control, as required, of the degree of penetration into discards and in situ fractured rock.

- It is self levelling, self compacting and is characteristic by volume stability.
- It satisfies the project design criteria.

Other void filling project worldwide include an undermined road in Poland, which was threatened by collapse when the ground below was washed away by heavy rain, and a geotechnical rehabilitation following an earthquake in San Francisco (Anon, 1997). Old sewer pipes and inspections chambers in Poland were also filled with foamed concrete, before a new system was built above. In addition, 19,500 m^3 density foamed concrete were used in 1986 in the Netherlands, on a large-scale harbour fill, where the maximum permissible settlement in the first year was restricted to 0.08 m (Basiurski, 2000).

The first project in United Kingdom to take a lightweight foam concrete or CLC was Canary Wharf in the London Docklands in the East End of London. The project consisted of 930,000 square meter of total net office space, recreational facilities covering a net surface area of some 46500 square metres. The project houses the largest business centre in London total cast was some £4 billion pounds. Several office buildings and railways station have been constructed; among the buildings was the Tower which is the eye catcher of the project with its 50 floors reaching some 240 metres into the air (Cox, 2005).

According to Cox (2005), foam concrete also use for sub-base for roads in Boston, USA (2001-2002). This project I-90/Route 1A Interchange – Boston, USA, is a part of the Central Artery Project and concerns the interchange of two roads, the I-90 and route 1A. Fly-overs are being constructed, but the ramps leading up to these fly-overs lie on soft soil layers. For that reason, a low settlement solution was obtained by excavating some of the top soils and replacing these soils with low density foam concrete. A Mechanically Stabilised Earth (MSE) panel system was used, serving as formwork and erosion protection at the same time. Panels are anchored in foam concrete with rebar. Foam concrete used has a 450 kg/m^3 density and 0.5 MPa compressive strength.

Cox (2005), reported as part of the Central Artery/Tunnel Project, the I-90 and Route 1A connector roads at Logan Airport were being reconstructed over the existing compressible fill soils. To reduce construction cost and vertical loading, designers chose MSE wall panels with a foam concrete backfill to build 5 bridge abutment ramps and one raised grade structures over soft soils without the need of extensive piling, cantilever walls or surcharging. A levelling pad is place for the MSE panels to sit on; the foam concrete is placed in lifts as the wall panels are erected, anchoring the horizontal strapping in place. The wall panels serve as forms and erosion protection, providing a settlement free construction.

2.2.2 Application of lightweight foam concrete in construction

According to Jones and McCarthy (2005), foamed concrete is widely used in void filling, as an alternative to granular fill, as foamed concrete has the ability to flow easily under its own weight. Some such applications include filling of old sewerage pipes, wells, cellars and basements of old buildings, storage tanks, tunnels and subways (British Cement Association, 1994). Two of the largest foamed concrete void filling projects in United Kingdom is the Heathrow railway tunnel and Combe Down mines. For the former, 14,500 m^3 of foamed concrete of 1400 kg/m^3 density were pumped into the ground over a period of 14 days to stabilise it, following the collapse of the railway express tunnel at Heathrow airport in 1994 (Heathrow tunnel collapse, 2005). Similarly, 500 to 600 kg/m^3 density foamed concrete is currently being used to stabilise a redundant, 200 year old stone mine site of 400,000 m^3 void volume in Combe Down, near Bath (Dolecki, 2003). This project is expected to take around 5 years to complete.

Foamed concrete has also often been used in bridge construction. Bridge abutments have, on several occasions, been built with foamed concrete, as both low density (usually between 1200 to 1400 kg/m^3) and relatively high strength (around 5 N/mm^2) are typically required. In addition, the lateral load imposed on the structure is significantly lower with foamed concrete than with other materials. Furthermore, its light weight minimises the risk of ground settlement and allows a reductions in the size of the bridge foundations, with concomitant savings in steel reinforcement (Pickford 1996, Kessler 1998, & Aldridge 2000). Foamed concrete is also often used to fill the bridge arches until the final road surface. In most cases, a higher density and strength mix (examples 1400 kg/m^3 and 7 N/mm^2 respectively) is used in the layers near the road surface, whilst lower density mixes (example 600 kg/m^3) are usually employed at greater depths (Aldridge, 2005).

The lightweight and excellent thermal properties of foamed concrete have been advantageous in housing applications. Indeed, in the Middle East and South Africa, foamed concrete has been used as roofing insulations material while its low density and resulting high thixotropicity enables the creation of roof slopes (Eabassoc 1996, Wimpey Laboratories Ltd 2004, De Rose and Morris 1999, Dransfield 2000, & Cox