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WATER PERMEABILITY AND CARBONATION ON FOAMED CONCRETE

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ABSTRACT

Foamed concrete is a controlled density low strength material with density ranging from 300 kg/m^3 to 1800 kg/m^3 suitable for construction of walls. The acceptance of foamed concrete blocks and panels by the Construction Industry Development Board of Malaysia as components of industrialized building system has promoted its commercial applications. It is made of cement, fine sand, water and preformed foam. Its self-compacting properties have enhanced productivity for mass production. Previous studies revealed findings on the use of large volume partial cement replacement materials without adverse effect on its physical and mechanical properties. This study focused mainly on the effect of the density of foamed concrete on carbonation and water permeability. The ability to vary the density of foamed concrete is considered a unique characteristic compared with normal concrete. Carbonation is usually considered as a negative impact on reinforced concrete. It is the process of pH reduction of concrete from 12.6 to 9.0 in the presence of carbon dioxide and moisture. The reduction of alkalinity means the loss of protection against corrosion to steel bars embedded within concrete. However, for non-structural applications of foamed concrete in wall construction without steel bars or with the use of corrosion inhibitor, carbonation is turned into an advantage for sustainable construction. The ability of foamed concrete to speed up the absorption of carbon dioxide is an important aspect to be explored for its potential use in reducing carbon footprint from the construction industry. The objective of this study is to explore a relationship between carbonation depth, water permeability and the density of foamed concrete. The laboratory tests were conducted on concrete cubes and prisms for up to one and a half years. The water permeability method was developed based on ISO/DIS 7031. The test results indicate that increasing density of foamed concrete tends to reduce its water permeability and carbonation depth.

The plot of carbonation depth against permeability coefficient produces a linear relationship. The rate of carbonation was found to be inversely proportional to the square root of density. An empirical formula incorporating density as a variable based Currie’s formula is produced. This finding is expected to excite researchers who are concerned with the use of concrete for sustainable construction. Its tendency to absorb carbon dioxide faster than normal concrete from the atmosphere in the carbonation process is expected to lead to widespread use of foamed concrete for environmental and economical advantages.

ABSTRAK

Konkrit berbusa adalah material berketumpatan terkawal dan berkekuatan rendah dengan ketumpatan daripada 300 kg/m^3 hingga 1800 kg/m^3 sesuai untuk pembinaan dinding. Penerimaan blok dan panel konkrit berbusa oleh Lembaga Pembangunan Industri Pembinaan Malaysia sebagai komponen sistem bangunan berindustri telah mempromosikan nilai-nilai komersialnya. Ia diperbuat daripada simen, pasir halus, air and busa. Keupayaannya yang tidak memerlukan pemadatan telah menggalakkan pengeluarannya secara besar-besaran. Kajian-kajian terdahulu telah menunjukkan penemuan-penemuan ke atas penggunaan sebahagian besar bahan pengganti material simen tanpa kesan berlawanan terhadap ciri-ciri fizikal dan mekanikalnya. Fokus utama kajian ini adalah terhadap kesan ketumpatan konkrit berbusa ke atas kadar pengkarbonatan dan kebolehtelapan air. Kebolehan untuk mengubah ketumpatan konkrit berbusa dianggap satu sifat yang unik berbanding konkrit biasa. Pengkarbonatan biasanya dianggap satu kesan negatif ke atas konkrit bertetulang. Pengkarbonatan adalah proses pengurangan pH konkrit daripada 12.6 ke 9.0 dengan kehadiran karbon dioksida dan wap air. Pengurangan sifat alkali bermakna kehilangan perlindungan terhadap pengaratan tetulang besi di dalam konkrit. Walaubagaimanapun, untuk penggunaan bukan struktur konkrit berbusa dalam pembinaan dinding tanpa tetulang besi atau dengan penggunaan penghalang karat, pengkarbonatan menjadi satu kelebihan untuk pembinaan lestari. Keupayaan konkrit berbusa untuk mempercepatkan kadar penyerapan karbon dioksida adalah satu aspek penting yang perlu dikaji potensinya di dalam usaha untuk mengurangkan kadar pelepasan karbon daripada industri pembinaan. Objektif utama kajian ini adalah untuk meneroka hubungan di antara kadar pengkarbonatan, kebolehtelapan air dan ketumpatan konkrit berbusa. Ujian makmal dilakukan ke atas kiub-kiub dan prisma-prisma konkrit berusia sehingga satu setengah tahun. Kaedah ujian kebolehtelapan air adalah dibangunkan berdasarkan ISO/DIS 7031. Keputusan ujian yang diperolehi menunjukkan peningkatan ketumpatan konkrit berbusa akan mengurangkan kebolehtelapan air dan kadar pengkarbonatan. Plotan kadar pengkarbonatan terhadap pekali kebolehtelapan menghasilkan satu garisan lurus. Kadar pengkarbonatan didapati berkadar sonsang dengan punca kuasa dua ketumpatan. Satu formula empirik yang menggabungkan ketumpatan sebagai pengubah berdasarkan formula Currie telah dihasilkan. Penemuan ini dijangkakan akan menyemarakkan semangat penyelidik-penyelidik yang berminat dengan penggunaan konkrit untuk pembinaan lestari. Keupayaannya untuk menyerap gas karbón dioksida lebih pantas berbanding konkrit biasa daripada atmosfera di dalam proses pengkarbonatan dijangka akan membuka ruang terhadap penggunaan konkrit berbusa untuk faedah alam sekitar dan ekonomi.

TABLE OF CONTENTS

CONTENT **PAGE**

1. INTRODUCTION

2. LITERATURE REVIEW

3. METHODOLOGY

4. DATA ANALYSIS AND DISCUSSION

5. CONCLUSION

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

ACI	-	American Concrete Institute
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
DOE	-	Department of Environmental
MS	-	Malaysia Standard
OPC	-	Ordinary Portland Cement
C_2S	-	Dicalcium Silicate
C_3S	-	Tricalcium Silicate
CH	-	Calcium Hydroxide
C-S-H	-	Calcium Silicate Hydrate
TIA	-	Timber Industrial Ash
Mpa	-	Mega Pascal
^0C	-	Degree Celcius
CO_2	-	Carbon Dioxide
$CaCO_3$	-	Calcium Carbonate
RH	-	Relative Humidity
SAA	-	Surface Active Agents
AAC	-	Autoclaved Aerated Concrete

LIST OF APPENDICES

CHAPTER I

INTRODUCTION

1.1 GENERAL

Concrete is a composite material which consists essentially of cement, aggregates, water and admixtures in certain proportion. It is an important and widely used construction material. The self-weight of normal weight concrete represents a very large proportion of the total load on the structure.

Based on density of concrete, it can be classified into three major categories. The density of heavy weight concrete is more than 3600 kg/m^3 and normal weight concrete is about 2400 kg/m^3. Neville, A.M, (1995) classifies lightweight concrete is one with density of 2000 kg/m^3 or less. The practical range of densities of lightweight concrete is between 300 kg/m^3 and 1800 kg/m^3.

Lightweight concrete has unique benefits in construction to increase productivity. The use of lightweight concrete will reduce the self-weight of the concrete structures (Short, A. et al., 1978). Besides that, lightweight concrete also gives better thermal insulation compared with the normal weight concrete.

Lightweight concrete can be divided into three types namely lightweight aggregate concrete, no fines concrete and aerated concrete (Neville, A.M. and Brooks., J.J., 1987). Lightweight concrete has traditionally been made using manufactured aggregates such as expanded shale, clay, vermiculite, pumice and scoria. However, the study conducted by August, J. (1997) noted that the very lightest mixes (densities from 300 to 900 kg/m^3) contain air voids in the absence of aggregates and in Europe it is referred to as cellular or aerated concrete. Cellular concrete is also known as Autoclaved Aerated Concrete (AAC) in some countries because of the way the aerated concrete is cured.

Foamed concrete which is also known as aerated concrete and cellular concrete was first developed in Scandinavia some thirty years ago (Neville, A.M, 1995). It is one of the lightweight product produced by adding a foaming agent (usually some form of hydrolyzed protein or resin soap) to the mortar during mixing. The agent introduces and stabilizes air bubble during mixing at high speed. In some process, stable pre-formed foam is added to the mortar during mixing to produce foamed concrete.

Nowadays, foamed concrete has been widely used in construction industry especially for building walls. Foamed concrete technology is relatively new in Malaysia even though it has been used long time ago in Europe and USA. By using this type of technology in concrete construction, many benefits can be obtained like reduction in member sizes, provide better thermal insulation, savings in cost, enables much faster pace of building construction and reduce the carbon footprint from the industries by absorbing CO_2. The production of foamed concrete on a small scale is a fairly easy process which does not involve any expensive or heavy machinery and in most cases uses equipment that is already available for normal concrete production. A construction research with precast block and cast in situ foamed concrete wall system is branded as KUiK Wall. The concrete density varies between 1000 kg/m^3 and 1500 kg/m^3. Precast block is designed to be of lower density around 1000 kg/m^3. Higher density cast in situ wall is designed to achieve higher compressive strength.

Permeability is the ability to transport different fluids or gases, such as water, chlorides, sulfates, oxygen and carbon dioxide. They can move through the concrete in different ways, but all transport depends primarily on the structure of the hydrated cement paste. Actually, permeability refers to flow through a pore medium. But the fluids can also penetrate through concrete by diffusion and sorption (Neville, A.M, 1995). The two parameters involved in this study are water permeability and carbonation depth penetration.

1.2 AIM AND OBJECTIVES OF STUDY

The aim of this study is to find the relationship between water permeability, carbonation depth and density of foamed concrete. The purpose is to predict carbonation depth and water permeability based on foamed concrete density. The information will provide useful reference for the contractors to use foamed concrete in the construction industry towards carbon neutral development in Malaysia.

The objectives of this research are:

i. To determine the water permeability and carbonation depth of foamed concrete.

ii. To develop a relationship between water permeability, carbonation depth and density of foamed concrete.

1.3 PROBLEM STATEMENT

Foamed concrete is a well-established material in building, void filling and highway reinstatement uses in European countries. In Malaysia, it has a potential in environmental sustainability by reducing the carbon footprint from industries. The foamed concrete can reduce the carbon footprint from the concrete industry by absorbing CO_2 from the environment. Concrete's carbon footprint is fairly large due to the energy used to heat limestone ($CaCO_3$) in kilns to form CaO, one of major components in concrete and the large quantities of CO_2 released as the conversion of limestone to CaO proceeds. By using foamed concrete, the carbon footprint can be reduced for environmental sustainability.

Foamed concrete can be used as non structural components in building and precast product especially for Industrialized Building System (IBS). Since water permeability and carbonation depth are closely related to density, therefore this study has been focusing on these two parameters. The lack of information and study on the effect of water permeability and carbonation on foamed concrete makes the findings relevant for specifying the foamed concrete with respect to density.

1.4 SCOPE OF WORK

The scope of this research was to study the effects of water permeability and carbonation on foamed concrete. This research was also to develop a relationship between water permeability, carbonation depth and density of foamed concrete. The scopes can be summarized as:

i. Experimental study on water permeability and carbonation of foamed concrete with densities from 1300 kg/m^3 to 1800 kg/m^3.

ii. Analytical study on the relationship between water permeability, carbonation depth and density of foamed concrete.

1.5 HYPOTHESIS

The hypothesis of this study is the foamed concrete has high water permeability and a high carbonation depth. Carbonation is related to CO_2 uptake from the atmosphere which adds value to foamed concrete applications towards sustainable development.

1.6 THE RESEARCH LIMITATIONS

This research is limited to the study of foamed concrete densities ranging from 1300 to 1800 kg/m^3. The maximum time period for carbonation test was 1.5 years. The curing methods used were air curing and moist curing based on British Standard Institution 1881: Part 111:1983. The foamed concrete was exposed in laboratory condition and also in natural environment condition which was exposed to rain and sun outside the laboratory. The water permeability value was determined using Germann Water Permeability Test GWT ISO/DIS 7031 based on Danish Standard. The carbonation depth was determined using phenolphthalein indicator and based on British Standard Institution 1881: Part 201:1986. The compressive strength was using Compressive Strength Test Machine and based on British Standard Institution 1881: Part 116:1983. Water absorption was determined as a percentage of the dry weight and was based on British Standard Institution 1881:Part 122:1983.

1.7 SIGNIFICANCE OF RESEARCH

The main purpose of this study is to find the relationship between water permeability, carbonation depth and density of foamed concrete. If the relationship can be established, then the carbonation depth and water permeability can be specified based on foamed concrete density. This information is very useful for the designing of non structural applications with a good absorbing parameter to neutralize carbon emissions. This will contributed for the realization of Green Building Concept in our country and reduce the carbon footprint. The information will be a very useful reference to the industry's players towards building greener properties.

The relationship between water permeability, carbonation depth and density of foamed concrete can also be a part in creating sustainability indicators. The sustainability indicators are the instruments for measuring the changes in the quality and state of sustainability of any system. It is a tool to measure and calibrate progress towards sustainable construction. The indicator can provide an early warning to prevent environmental damage from the development. It will set a milestone for projects towards environmental sustainability. The indicator can provide crucial guidance for decision making in variety of ways. Without indicators, the status, trends and long term changes can not be measure. The foamed concrete is a part of sustainable construction because it can reduce carbon emissions. Therefore, the water permeability, carbonation depth and density of foamed concrete can become sustainability indicators.

1.8 LAYOUT OF THESIS

The layout of the thesis are :

- Chapter I provides the introduction, aim and objectives of study, problem statement, scope of work, hypothesis, limitation of research, significance of research and layout of thesis.

- Chapter II examines initially the existing body of knowledge on the subject. This chapter comprises fourteen sub-chapters which are introduction of foamed concrete, materials in foamed concrete, composition of foamed concrete, properties of foamed concrete, density of foamed concrete, advantages of using foamed concrete, foamed concrete applications, the effect of curing on the water permeability of foamed concrete and normal weight concrete, carbonation, effect of carbonation, rate of carbonation, water absorption, sustainable construction and lastly conclusion. Each sub-chapter written with critical discussion regarding the subject.

- The methodology of research is described in Chapter III. There are nine sub-chapters in it. The sub-chapters are introduction, methodology of study, foamed concrete mix design, equipment, preparation of materials, mixing of concrete, curing methods, testing and summary. Chapter III describes the methodology adopted in this research in order to produce best results comparable to other research findings and to follow the existing established standards.

- The analysis of data is presented in Chapter IV. This section compromise of eight sub-chapters which are introduction, water permeability, carbonation, compressive strength, water absorption, relationship between permeability coefficient, k and carbonation depth and also relationship between water permeability and carbonation depth. All the results were analyze and discussed briefly with the support from other research findings.

- The conclusions and recommendations are given in Chapter V. This chapter includes brief conclusions and detailed conclusions. The brief conclusions will help other researchers to quick understanding of the thesis. Meanwhile, the detailed conclusions will provided the fully information involved in this research.

CHAPTER II

LITERATURE REVIEW

2.0 INTRODUCTION

The density of normal weight concrete is about 2400 kg/m^3. Concrete with density lower than 2000 kg/m^3 is defined as lightweight concrete. According to Neville, A.M. (1995), the practical range of densities of lightweight concrete is between about 300 and 1850 kg/m^3. Clarke, J.L. (1993) defined that structural lightweight concrete as having an oven-dry density of less than 2000 kg/m^3. Foamed concrete is another type of lightweight concrete and is clearly described in the following section.

2.1 FOAMED CONCRETE

The history of foamed concrete began much later than lightweight aggregate concrete. According to Dubral, W. (1992), the development of the Autoclaved Aerated Concrete (AAC) began approximately 100 years ago. In 1914, the Swedes first discovered a mixture of cement, lime, water and sand that expanded by the adding aluminium powder to generate hydrogen gas in the cement slurry. Prior to that, inventive minds had tried beaten egg whites, yeast and other unusual methods of adding air to concrete. It was reported that foamed concrete was developed in Europe over 60 years ago and has since then been on the international market for more than 20 years.

The foamed concrete is similar to wood in its characteristics but without the disadvantages of combustibility, decay and termite damage. Foamed concrete exhibits a wealth of desirable characteristics such as low weight, compressive strength, good heat insulation, fire resistant and good impact and airborne sound insulation. The Autoclaved Aerated Concrete was first used mainly in Scandinavia as roof and floor units and wall panels and was patented in 1931. It involves producing cellular concrete prepared by foaming methods followed by curing in high-pressure steam. Patents were issued in 1929 on foaming agent formulations, mixing procedures and mixing machines (Kumpulan IKRAM Sdn. Bhd., 2004).

Preformed foam was developed in the early 1950’s following the development of simple, reliable and easily controlled, foam-generating equipment and highly refined foam stabilizers. The method was cost effective and provided an accurate means of controlling density. This method has been widely used for the production of low density cast-in-place roof decks, filling voids, tunnel gap filling and insulating underground heat distribution lines until today (Portland Cement Association, 1980).

Foamed concrete is a new alternative construction material that was introduced recently. Foamed concrete is a lightweight product consisting of Portland cement, cement-silica, cement-pozzolan, lime-pozzolan, lime-silica pastes, or pastes containing blends of these ingredients and having a homogeneous void or cell structure, attained with gas-forming chemicals or foaming agents. Foamed concrete is produced by entraining relatively large volumes of air into the cement paste by the use of a chemical foaming agent which once hardened results in a strong lightweight concrete containing millions of evenly distributed, consistently sized air bubbles or cells. High air contents resulting lower densities, higher porosities and lower strengths (Mohd Haziman, 2004).

Kearsley, E.P. (2000) stated that porosity of foamed concrete after replacing large volume of cement with both classified and unclassified fly ash (up to 75 % by weight) was found to be dependent mainly on the dry density of the concrete and not on ash type and ash content. The volume of water absorbed by foamed concrete was approximately twice that of an equivalent cement paste but was independent of volume of air entrained, ash type and ash content.

2.2 MATERIALS IN FOAMED CONCRETE

Foamed concrete is a composite material which is made up of filler and a binder. Typical foamed concrete is a mixture of cement, water, fine aggregate (sand) and foam.

2.2.1 Foam

Preformed foam is commonly used to make lightweight foamed concrete to improve the properties of conventional concrete. It can be divided into two main groups which are Natural Foaming Agents and Synthetical Foaming Agents. Foamers which are Surface Active Agents (SAA) can be divided into anion-active foaming agents (sodium salts of carbon and naphthene acids), cation-active foaming agents (amines and their derivatives), non-ionic foaming agents (derivatives of polyethyleneglycol esters of grades OP-7 and OP-10). The most commonly used foam concentrates to manufacture foamed concrete are based on protein hydrolyzates or synthetic surfactants. The bubbles vary in size from 0.1 mm to 1.5 mm in diameter (Brady, K. C. et al. 2001).

2.3 COMPOSITION OF FOAMED CONCRETE

Foamed concrete is produced by incorporating a metered volume of preformed foam (air bubbles) into a cement paste or mortar mix. The foam is produced by a foam generator in which a foam concentrate usually diluted in the ratio of one part of concentrate to between 5 and 40 parts of water is mixed with compressed air in pre-determined quantities. The mix is then forced through a restriction to produce the foam. The generator can be hand-held, or fixed to discharge directly into a mixer. The density of the foam is typically between 25 and 80 g/liter.

The most commonly used foam concentrates are based on protein hydrolyzates or synthetic surfactants. They are formulated to produce air bubbles that are stable and able to resist the physical and chemical forces imposed during mixing, placing and hardening of the concrete.

Foamed concrete with dry densities below 600 kg/m^3 usually consists of cement, foam and water, or cement, fly ash, foam and water. Adding sand produces higher densities. Fine sand of 5 mm maximum size may be used, but research has indicated that, for given cement content, a higher strength is achieved using fine sand of 2 mm maximum size with 60 to 95% passing the 600 micron sieve. Waste sands, such as single-sized falling and granite dust, have been used successfully, but the same restrictions on grading and maximum size apply (Mohd Haziman, 2004).

Coarse natural aggregates cannot be used because they would segregate in the lightweight foamed concrete, but it is possible to use lightweight aggregates with a similar density to the foamed concrete.

2.4 PROPERTIES OF FOAMED CONCRETE

The compressive strength of foamed concrete will depend on the density, initial water/cement ratio and cement content. The density of the foam can have an influence on the ultimate strength, particularly for the lower density foamed concretes. Uniformly sized small bubbles appear to produce higher ultimate strength at all densities (Mohd. Haziman, 2004).

This avoids segregation, improves the strength for a given density and reduces the higher drying shrinkage associated with the lower density mixes. Ordinary Portland Cement (OPC) is used as the binder in most foamed concretes. Cement contents for the most commonly used mixes are between 300 kg/m^3 and 375 kg/m^3.

Table 2.1 show the details of typical mixes used for foamed concretes of various densities (British Cement Association, 1994). An indication only of batch weights is given because the type and grading of the sand and the characteristics of the foam will all influence the weight required. For optimum results, the water / cement ratio of the base mix should be kept fairly high to provide a base mix with a high workability. A base mix that is too dry and stiff is liable to extract water from the foam and cause it to collapse. In general, the optimum water / cement ratio for the base mix lies between 0.5 and 0.6. The water used in the mixes, as with dense concretes, should be potable. This is particularly important when using protein-based foaming agents. As any organic contamination could have an adverse effect on the quality of the foam produced.

Table 2.1 : Typical Mix Details For Foamed Concrete

Wet Density (kg/m^3)	500	900	1300	1700
Dry Density (kg/m^3)	360	760	1180	1550
Cement (kg/m^3)	300	320	360	400
Base Mix W/C Ratio	Between 0.5 and 0.6			
Sand (kg/m^3)	-	420	780	1130
Air Content (%)	78	62	45	28

*Source: British Cement Association (1994).

Table 2.2 shows of the typical properties of foamed concrete at various densities. The dry shrinkage for foamed concrete is higher than that of dense concrete; the highest shrinkage being associated with the lowest densities, where the material is essentially a foamed cement paste.

An advantage of lower density foamed concrete it its lower thermal conductivity, which gives better insulation properties. As shown in Table 2.5, the thermal conductivity is between 5 to 30% of that for dense concrete. The modulus of elasticity is also of a similar order when compared with dense concrete (British Cement Association, 1994).

Table 2.2 : Typical Properties Of Foamed Concrete

Dry Density (kg/m3)	Compressive Strength (N/mm^2)	Thermal Conductivity (W/mK)	Modulus of Elasticity (kN/mm^2)	Drying Shrinkage (%)
400	0.5-1.0	0.10	0.8-1.0	0.30-0.35
600	1.0-1.5	0.11	1.0-1.5	0.22-0.25
800	1.5-2.0	0.17-0.23	2.0-2.5	0.20-0.22
1000	2.5-3.0	0.23-0.30	2.5-3.0	0.18-0.15
1200	4.5-5.0	0.38-0.42	3.5-4.0	0.11-0.09
1400	6.0-8.0	0.50-0.55	5.0-6.0	0.09-0.07
1600	7.5-10.0	0.62-0.66	10.0-12.0	0.07-0.06

*Source: British Cement Association (1994).

2.4.1 Physical Properties

Foamed concrete differs from the other class of aerated concrete in a way air is being introduced into a cement-based media. Therefore, it follows the properties of aerated concrete which would have much similarity to foamed concrete. The physical properties discussed are microstructure, density, permeability and compressive strength.

2.4.1.1 Microstructure

In aerated concrete, the method of pore-formation through gas release or foaming influences the microstructure, thus its properties. The material structure of aerated concrete is characterized by its solid microporous matrix and macropores. The macropores are formed due to the expansion of the mass caused by aeration which the micropores appear in the walls between the macropores. Macropores have been envisaged as pores with a diameter of more than 60µm. The orientation of the hydrated products of hydration of cement is significantly altered due to the presence of the voids (Kumpulan IKRAM Sdn. Bhd., 2004).

The porous system of aerated concrete is also classified in terms of pore size distribution functioning as artificial air pores, inter-cluster pores and interparticle pores and the distribution of these pores in the matrix has bearings on its properties. Pores introduced by aerating or surface active agents in aerated concrete are of radii ranging from 50 to 500 µm, while pores of 5 µm in size are considered large in ordinary mortar. Pores can be classified into 2 types according to their sizes. Micropores are the microcapillaries of 50 nm or smaller formed in the walls between the air pores, whereas capillaries macros are pores of 50 µm to 50 µm. The void structure of aerated concrete is discreet and nearly spherical bubbles (Mindess, S. and Young, 1981).

Although the air-void system in aerated concrete remains largely identical, there are differences between the structures of autoclaved and non-autoclaved. These are caused by the variation in the hydration products, which explains the foamed concrete variations in their properties. On autoclaving, part of the fine siliceous material reacts chemically with calcareous materials like lime and those liberated by cement hydration, forming a microcrystalline structure of much lower specific surface. It is reported that non-autoclaved matrix has a larger volume of fine pores due to the presence of excessive pore water. It has been observed that macropores size distribution does not have much influence on compressive strength (Kumpulan IKRAM Sdn. Bhd., 2004).

Properties of aerated concrete such as strength, permeability, diffusivity, shrinkage and creep are intimately related to its porosity and pore size distribution.

Thus, the characterization of the pore structure is important and more so in the case of aerated concrete where the porosity may be as high as 80%. Porosity and pore size distribution of aerated concrete vary considerably with the composition of the mix and the method of curing (Kumpulan IKRAM Sdn. Bhd., 2004).

Higher porosity of aerated concrete has been established to be the consequence of the increase in the volume of the macropores which in turn results in thinner pore walls, thereby reducing the micropore volume share (Mindess, S. and Young, 1981). It has also been highlighted that the porosity must be qualified with the pre-treatment method adopted, as oven drying of the sample to determine the porosity is reported to have led to collapse of the cell structure. Although the porosity varies considerably between autoclaved foamed concrete made with foaming agent and gas forming methods, the permeability is found not to vary much. The artificial air pores were found to have little influence on permeability.

The type, size and distributions of pores are mainly responsible for permeability. Thus, the measurement of gas permeability indirectly characterizes the pore structure of autoclaved aerated concrete. Only those pores, which are continuous and permit the gases to flow through the entire thickness of the material, are significant for gas permeability. The difference in the evolution of the porous structure caused by various manufacturing methods can be identified using this method (Kumpulan IKRAM Sdn. Bhd., 2004).

2.4.1.2 Density

The water-cementitious material ratio is related to the amount of aeration obtained and thus the density. For a given density, the water-cement ratio increased with the proportion of sand. For Autoclaved Aerated Concrete (AAC) with pozzolans, water-solid ratio appears to be more important than water-cementitious ratio, irrespective of the method of pore-formation. For gas concrete, low water-solid ratio leads to insufficient aeration while a high ratio results in rupture of the voids with an increase in the density being the consequence in both cases. Thus, the water requirement is to be gauged by the consistency of the fresh mix rather than by a pre-determined water-cement or water-solid ratio (Kumpulan IKRAM Sdn. Bhd., 2004).

As many physical properties of aerated concrete depend on the density (300 – 1800 kg/m^3), it is essential that its properties be qualified with density. While, specifying the density, the moisture condition for example oven-dry condition or at equilibrium with atmosphere needs to be indicated. The material freshly delivered from an autoclave may be 15 – 25% heavier than an oven dried material. This value can be as high as 45% for a very low density aerated concrete. A significant increase in the density of Autoclaved Aerated Concrete with changing relative humidity and temperature has been reported and is attributed to the carbonation process, with the increase being proportional to its initial dry density.

As stated earlier, aerated concrete with a wide range of densities for specific applications can be manufactured by varying the composition, which in turn affects the structure, size and distribution of pores. A stable and preferably spherical cell structure is vital for optimum and desirable structural and functional properties. Uniformly distributed pores in a mass results in foamed concrete products of uniform density. Larger macropores in the matrix has been reported to reduce the density significantly. In conventional terms, the density of aerated concrete is related to its compactness and porosity (Kumpulan IKRAM Sdn. Bhd., 2004).

2.4.1.3 Permeability

Concrete is a porous material. Therefore, moisture movement can occur by flow, diffusion, or sorption. Generally the overall potential for moisture and ion ingress in concrete by these three modes is referred to as its permeability. Permeability is defined as the property that governs the rate of flow of a fluid into a porous solid (Neville, A.M., 1995). Permeability is the ease with which liquids or gases can travel through concrete.

Permeability of aerated concrete is greatly influenced by the type, size and distribution of the pores, and not the pore volume. Pores are classified into two types; open pores, which connect to the outside boundary of the material, and closed pores, which are isolated from the outside and may contain fluid (Ishizaki, Kozo et al., 1998). Permeability of aerated concrete is contributed by the open pores and not the closed pores. Closed pore materials are used mainly for sonic and thermal insulators or low-specific gravity structural components.

Figure 2.1 illustrates a schematic diagram of both types of pores. Introducing open pores will change the properties of the material such as reducing its density, reducing strength and increasing its specific surface area but on the other hand increasing its thermal and acoustic insulation capabilities. However, a porous material is suitable to be used as filters in gas distribution, catalyst and bioreactors, sensors and bearing oil applications. According to Wagner, F et al. (1995), only those pores that are continuous and permit gases to flow through the entire block are of significance for gas permeability and evaluating the porosity of aerated concrete. Ishizaki, Kozo et al. (1998) also agreed that the fluid permeability of porous materials depends on the degree of open porosity, pore size, pore shape and the tortuosity of pore network. With a total porosity of 75% to 90%, the density of the aerated concrete might reach 300 kg/m^3 and the volume percentages of macropores and micropores will be about 75% and 15% - 25%, respectively (Wagner, F et al., 1995).

The wettability of pore surface is significant for the successful evaluation of permeability by the liquid suction test. Wettability is greatly influenced by surface roughness, surface state such as oxidation and absorption, ambient humidity and temperature during experiment.

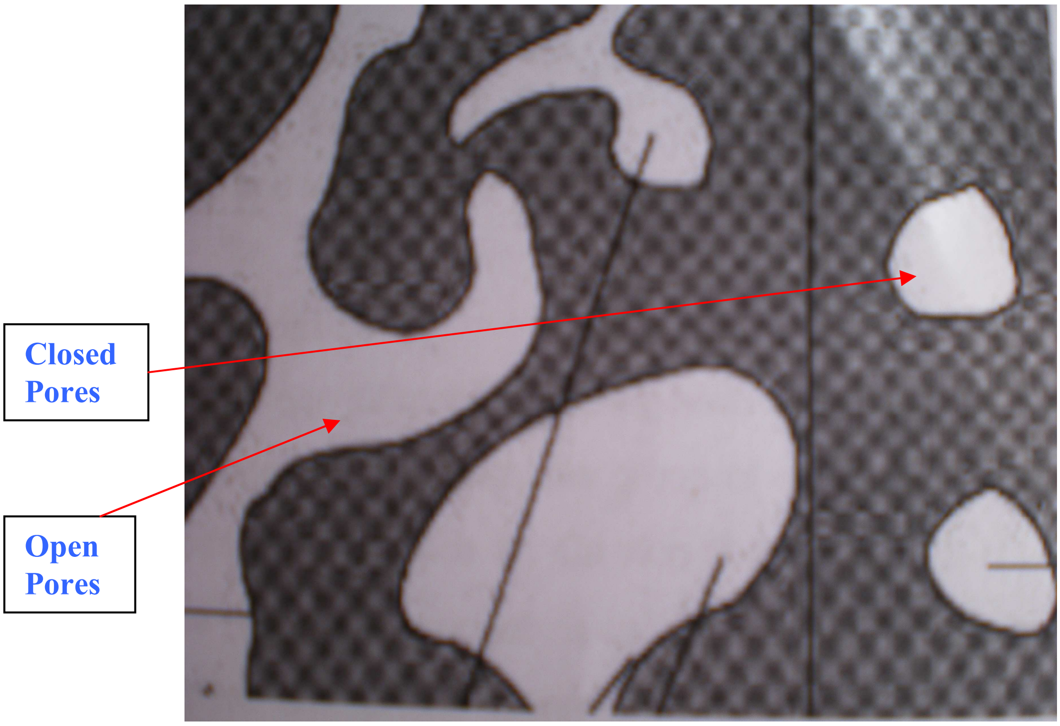

Figure 2.1 : Schematic Diagram Of The Pores (Ishizaki, Kozo, 1998)

The water permeability of concrete can be determined by measuring the quantity of water flowing through a given thickness of concrete in a given time when steady state conditions have been reached. The water permeability is expressed as a coefficient of permeability, k, given by Darcy's equation.

Darcy equation:

$$\frac{dq}{dt} = \frac{k\Delta hA}{L}$$

where,

$\frac{dq}{dt}$ = the rate of fluid flow in m^3/s

L = thickness of the sample in m

A = cross-sectional area of the sample in m^2

Δh = drop in hydraulic head through the sample, measured in m

k = coefficient of permeability in m/s

Concrete is a slightly permeable material, in which water impermeability is often as important as strength. Permeability of concrete must be distinguished from absorption and diffusion. Absorption is the ability of concrete to transmit water by capillary attraction when the water is not under pressure. Diffusion is the movement of fluids due to difference in concentration.

Studies by Powers, T.C. et. al (1954) revealed that the permeability of mature cement pastes is governed by the water / cement ratio and the degree of hydration. It was found that coefficient of permeability reduced by a factor of a thousand when there was a reduction of water / cement ratio from 0.7 to 0.3. When the surface of concrete is exposed to air and water, the concrete cover will become a shield to protect the steel reinforcement from corrosion. Therefore, proper designed concrete cover is very important.

The typical water permeability values associated with concrete quality are stated in the Concrete Society Technical Report No. 31 (1998) as showed in Table 2.3.

Table 2.3 : Water Permeability And Concrete Quality

Water permeability (m/s)	Quality
$< 10^{-12}$	Good
10^{-12} - 10^{-10}	Average
$>10^{-10}$	Poor

Source: Concrete Society Technical Report No. 31. (1988).

Figure 2.2 show the relation between water permeability and hardened density of foamed concrete (Brady, K.C., 2000). The densities of type 1, type 2 and type 3 in the graph were 1330 kg/m^3, 1570 kg/m^3 and 1750 kg/m^3. The cement contents were 270 kg/m^3 (type 1), 255 kg/m^3 (type 2) and 355 kg/m^3 (type 3) with all specimens sealed cured. From Figure 2.2, the water permeability for type 1, type 2 and type 3 were in the magnitude of 10^{-6} m/s, 10^{-8} m/s and 10^{-9} m/s. The results indicate that foamed concrete are more permeable to water than normal weight concrete.

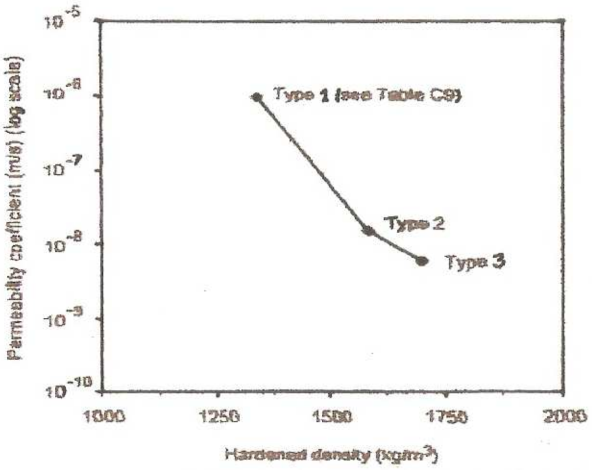

Figure 2.2 : Relation Between Water Permeability And Hardened Density (Brady, K.C., 2000).

Until now, there are too little published data on short and long term of water permeability on foamed concrete especially for Malaysia's environment. The lacks of knowledge on this topic will mislead people to a bad impression of the usage of foamed concrete in the constructions. Therefore, the study on this topic can reduce the huge knowledge gap between the researchers and the industries' players.

2.4.1.4 Compressive Strength

The compressive strength of foamed concrete is relatively low. The specimen size and shape, method of pore-formation, duration of loading, age, water content, characteristics of ingredients used and method of curing are reported to influence the strength of foamed concrete. The lower density, the higher the content of foaming agent introduced and hence the greater is the reduction of the compressive strength. The combination of using foaming agent and lightweight aggregate is a future potential area to be developed in foamed concrete to compensate for the reduction in the compressive strength of foamed concrete.

The structure and the mechanical condition of the pores have a marked influence on the compressive strength of the hardened foamed concrete. Density reduction by the formation of large macropores is found to cause a significant strength drop. Generally, compressive strength increases linearly with density. Autoclaving increases the compressive strength significantly, as the high temperature and pressure result in a stable form of tobermerite. The final strength is achieved in this case, depending on the pressure and duration of autoclaving over a shorter period of curing time. The strength of Non Autoclaved Aerated Concrete increases 30 – 80% between 28 days and 6 months and marginally beyond this period. A portion of this increase is attributed to the process of carbonation (Kumpulan IKRAM Sdn. Bhd., 2004).

On the other hand, compressive strength varies inversely with moisture content. On drying to equilibrium in normal atmosphere, there is an increase in strength an even larger increase upon complete drying out. Compressive strength of Non Autoclaved Aerated Concrete and Autoclaved Aerated Concrete using fly ash as a partial/complete replacement of the filler has been shown to result in a higher strength-to-density ratio of foamed concrete.

Strength to gel-space ratio relationship for foamed concrete made with proprietary foaming agents was developed by Durack, J.M. and Weiqing, L. (1998). Porosity is considered to have a significant impact on compressive strength of aerated/foamed concrete.

While establishing the strength-porosity relationship for Autoclaved Aerated Concrete with slate waste, a factor called reciprocal porosity (Vs/Vp – solid-to-pore volume ratio) has been coined, the relation of which with compressive strength is

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