Feasibility of Making Aircrete with Autoclave using Local Materials in Bangladesh

by

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CERTIFICATION

The thesis titled **Feasibility of Making Aircrete with Autoclave using Local Materials in Bangladesh** submitted by **Md. Shamsuddoha** Roll No: **100604313** Session: **October 2006** has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science on January 2011.

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January 2011 Md. Shamsuddoha

DEDICATION

I am indebted to ***my father*** for living, but to ***my teachers*** for living well.

…Alexander the Great (356-323 BC)

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LIST OF ABBREVIATION

A	Aluminium Powder
AAC	Autoclaved Aerated Concrete
ACC	Autoclaved Cellular Concrete
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
C_1	Portland Composite Cement (PCC)
C_2	Ordinary Portland Cement (OPC)
FB	Feasibility Band
L	Lime
LWAC	Lightweight Aggregate Concrete
LWACC	Lightweight Autoclave Cellular Concrete
LWCC	Lightweight Cellular Concrete
LWGAC	Lightweight Glass Aggregate Concrete
LWGC	Lightweight Gel Concrete
LWHPC	Lightweight High Performance Concrete
LWPC	Lightweight Pervious Concrete
LWRPC	Lightweight Aggregate Reactive Powder Concrete
LWWC	Lightweight Wood Concrete
OB	Optimization Band
P	Plasticizer (ml per kg of cement)
RILEM	French acronym for International Union of Testing and Research Laboratories for Materials, Systems and Structures
S_1	Local Sand
S_2	Sylhet Sand
VC	Vapor Curing for 6 hours
VMA	Viscosity Modifying Admixture (ml per kg of cement)
W	Water

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ABSTRACT

This study is aimed at investigating the feasibility of producing lightweight concrete in Bangladesh. Aircrete; a prominent branch of lightweight concrete is produced by reducing unit weight through introduction of void in the concrete matrix. The potential of lightweight concretes have already been identified and are intensively used in developed countries for various infill and structural purposes. This study demonstrates the feasibility and sequential approach for producing lightweight concrete using indigenous ingredients and acquiescent technology of Bangladesh.

First, a thorough search for local materials and appropriate production technique is administered. Bangladesh, being a tertiary-geological-featured country, possesses no natural lightweight concrete that could be incorporated in this research. However, relatively suitable indigenous and easily available foreign material options are identified and utilized in the study. Methods used to produce lightweight concrete in recent times all over the world are found sometimes inappropriate in Bangladesh due to lack of resource options and technical knowhow. Thus, an easily practicable method is identified to carry out the study. It is found that a binder (OPC or PCC), local sand (Local sand and Sylhet sand), a foaming agent preferably aluminium as non-mechanized foam generator and lime to enhance performance of aluminium and admixtures if required are applied in this study.

Feasibility study integrating a series of materials revealed the optimistic notion towards the production of lightweight concrete (density<1000 kg/m^3) in Bangladesh. Range of ingredient contents is identified through this study. Major problem associated with lightweight concrete is low strength due to high water-cement ratio, low cementation index and foamy honey comb structure.

Further detail optimization study with moist curing is carried out involving a series of materials options. From the results, it is seen that density decreased with increased cement and water content, whereas compressive strength increased with increased cement but decreased with water content, thereby indicating a conflicting

relation. Consequently, a number of interpretable charts are constructed to correlate density and compressive strength with material contents. However, although target density range is achieved, strength criteria are insufficient for practical application. Therefore, an improved curing technique is eminent.

Autoclaving is a special curing method subjected to high temperature and pressure. This method is used for early strength gain of concrete. Due to lack of resource and technical knowledge, use of autoclaving with high pressure is not an appropriate option for Bangladesh. As an alternative, autoclaving without pressure is applied in special curing chamber using local resources. Compressive strength range of produced aircrete is improved to a practicable level. Finally, after optimization, lightweight concrete with density, compressive strength and thermal conductivity within range of 700-1000 kg/m^3, 0.5-2.0 MPa and 0.2-0.4 W/m-k, respectively is produced.

Cellular concrete produced from locally available materials through non-mechanized foaming and non-autoclaving treatment, resulted in lighter (<1000 kg/m3) but lower strength (1.0 MPa) concrete product. Finer sands were more appropriate to contribute as filler than coarse aggregate in cellular concrete. The drag force exerted by foam generation was unable to disperse coarser aggregate uniformly in the matrix rather allowed settlement due to gravity. Lime used in this research acted simultaneously as filler and expansive ingredient. Unslaked lime is one of the major causes of low compressive strength and through generation of heat affects hydration moisture and the action of admixtures. However, lime contributed the most in reducing strength of produced aircrete. Author suggests future study to be programmed without including lime as a potential ingredient of aircrete. Plasticizer and viscosity modifying admixture were unsuccessful in their performance to improve strength. Reason behind might be elevated temperature due to hydration of lime. Further study is suggested. Moisture loss at the early stage of setting was observed emerging necessity of humidity restoration. Both density and compressive strength were reported to improve by application of steam curing environment. Thermal conductivity and absorption for selected samples were found within the

range of 0.2-0.4 W/m-k and 25-35 percent respectively with well-established trend with corresponding density. As per RILEM classification, lightweight concrete produced in this research can be grouped under class-III and Insulating type lightweight concrete. Although not covered in this research, cork granules and polystyrene fiber are expected to be suitable as filler to reduce unit weight of concrete. However, cement-cork and cement-fiber compatibility should be studied rigorously. Mechanized mixing should be preferred in preparing aircrete otherwise ingredients may not disperse uniformly. Foaming agent can be used associated with mechanical mixing to achieve aircrete.

This study is a new approach for producing lightweight concrete in Bangladesh. It is believed that the outcome and recommendations may provide ahead start for the next researchers interested in this field.

Chapter 1
INTRODUCTION

1.1 General

The civil engineers through their persistent effort have made substantial progress in utilizing natural resources and indigenous materials for the betterment of humankind. The invention of concrete is a giant step for the development of human civilization. Concrete is by far the most widely used construction material worldwide. In fact, it is more widely used than any other material, except water. Its huge popularity is the result of a number of well-known advantages, such as low cost, general availability, and adaptability to a wide spectrum of performance requirements. High density, (2000-2500 kg/m^3) which is obvious for concrete, is a great advantage in terms of strength and durability. However, to endure with modern rapid growing civilization, lightweight concrete has become imminent for special purposes even for a developing country like Bangladesh.

1.2 Scope of the Study

It has always been a challenge for the engineers to reduce the loads; those are within our capabilities, on a structure and introduce alternative materials or their modified forms to get specified desired performance. In early days, stone blocks were used as wall or infill material to transfer the load of the structure. Obviously long built heavy structures were not possible to build with stones. Bricks possess almost all properties an engineer needs to perform partitioning and sometimes load bearing. Now a day modern engineers seek functional use of materials for a particular purpose such as for partitioning, the material, which only can perform this purpose, is sought and where structural support from that partitioning wall is needed, stronger material is sought to perform it. Engineers best suitable option to reduce dead load of a structure lie within the deduction of self weight of concrete of nonstructural

elements i.e. other than structural floors, beams and columns etc. Decoration elements such as timber, plastics are inadequate and their uses are concerned with adverse impacts on environment. Different from normal concrete, foamed concrete possesses many advantageous properties owing to the introduction of air bubbles, therefore, can be widely used in the area of building construction and other civil engineering application, such as lightweight, thermal and sound insulation of roof-deck systems and void filling. They can also be used for engineering fills for geotechnical applications. Precast autoclaved products are widely used as load bearing blocks, reinforced wall, roof and floor units and as non-load bearing cladding panels over a primary structural frame. In addition, the low elastic modulus also makes it possible for application in road and tunnel construction or the embedding or large diameter pipelines as roadbed or cushion material to homogenously disperse the stress from the external and uneven loading. Thus, lightweight concrete is a need to cope up with modern needs of partitioning and decorating or even structural purposes.

This study is aimed at investigating the feasibility of producing lightweight concrete in Bangladesh. Aircrete; a prominent branch of lightweight concrete is produced by reducing unit weight through introduction of void in the concrete matrix. The potential of lightweight concretes have already been identified and are intensively used in developed countries for various infill and structural purposes. This study demonstrates the feasibility and sequential approach for producing lightweight concrete using indigenous ingredients and acquiescent technology of Bangladesh.

1.3 Objectives

The objective of the study is to find best suitable option to produce lightweight concrete using local ingredients available in our country with local autoclaving technique. The objectives can be pointed as followings:

i. To search for the indigenous materials those can be useful to produce lightweight concrete using local technology.

ii. To reach a conclusion whether indigenous materials are sufficient enough to produce lightweight concrete.

iii. To search for any other material those can be useful to produce lightweight concrete in conjunction with local materials.

iv. To investigate on the possible methods of autoclaving especially locally available raw techniques and to select one to get better performance attainable in local scenario.

v. To prepare and organize mix design charts and graphs to aid users for wide spectrum performance and to abet an ahead start for next researchers interested in lightweight concrete in Bangladesh

vi. To determine various physical properties of produced aircrete like strength, thermal conductivity, absorption capacity.

1.4 Organization of the Thesis

The study of above objectives is presented in the several chapters of this paper. A diminutive description of each chapter is as follows:

i. Chapter 2 describes literature review about concrete, lightweight concrete and properties of materials from which lightweight concrete can be produced.

ii. Chapter 3 presents identification of possible material options and their properties to produce aircrete in Bangladesh.

iii. Chapter 4 describes sequential details of methodology, test plan and conducted experiments, results and discussion on the results obtained form experiments to search for the viability of aircrete production in Bangladesh.

iv. Chapter 5 illustrates optimization of aircrete properties using both moist curing and special indigenous curing conditions.

v. Chapter 6 provides the concluding outcomes and recommendations of the thesis.

Chapter 2
LITERATURE REVIEW

2.1 General

Concrete is a construction material composed of cement (commonly Portland cement) as well as other cementitious materials such as fly ash and slag cement, aggregate (generally a coarse aggregate such as gravel, limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures. The word concrete comes from the Latin word “concretus”, which means “hardened” or “hard”. Concrete solidifies and hardens after mixing and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a stone-like material. It is used to make pavements, architectural structures, foundations, motorways / roads, overpasses, parking structures, brick / block walls and footings for gates, fences and poles, etc. Concrete is used more than any other manmade materials on the planet. According to Oss (2010), about 2,840,000,000 metric tons of concrete was consumed all over the world in the year 2008.

2.2 Lightweight Concrete

By the word “lightweight”, this group of concrete gives a simple indication that lower unit weight is necessary for being a lightweight concrete. However, in reality the definition is not that simple and not easy to categorize due to variety of lightweight concrete branches, origin, uses and production processes. The range of unit weight that can be referred as lightweight is also diverse. Komar (1979) stated range of unit weight for being lightweight concrete to be 500-1800 kg/m^3, whereas Neville (2000) suggested range of 300-1850 kg/m^3. In addition to unit weight, another major commitment of lightweight concrete is applicability i.e. strength and thermal conductivity. Sometimes thermal conductivity is the prime requirement along with strength as seen from Dunaeva (2006).

Lightweight concrete often called no-fines concrete, cellular concrete, aircrete or aerated concrete and lightweight aggregate concrete. Sometimes two of these are combined. For example, a no-fines concrete made of coarse foamed slag or clinker or other lightweight aggregate is not only more insulating and lighter in weight than a no-fines wall of dense stone and the same thickness, but it is nailable, which is very convenient. Aerated concretes are the most insulating and lightest in weight. Recent trend of lightweight concrete is focused on aerated concrete than as well as no-fines concrete. Diverse use of lightweight concrete is well recognized all over the world.

Hunaiti (1997) and NRMCA (2003) suggested that the best suitable option to reduce dead load of a structure lie within the deduction of self-weight of concrete, which eventually reduces size of structural elements. Reducing the self-weight of a structure is undoubtedly considered an advantage if not a necessity in some cases. Using lightweight concrete is one way of achieving such reduction. In addition to reducing stresses through the lifetime of the structure, due to using smaller elements, the total weight of materials to be handled during construction is also reduced, with consequently increase productivity. Furthermore, lightweight concrete offers better thermal insulation and better fire protection than ordinary concrete.

Lightweight concrete is generally produced by two means as suggested by ACI 523 (1993) and ACI 213 (2003). One is cellular concretes referred to lightweight concretes, which contain stable air or gas cells uniformly distributed in the mixture. Cellular concretes commonly include natural or manufactured sand aggregate. In other types, aggregates may be added; for example, manufactured lightweight aggregates such as expanded clay, shale, slate, sintered fly ash, perlite, and vermiculite as well as natural lightweight aggregates such as pumice, scoria, or tuff. Air cells can be intruded from outside through rigorous mixing or by chemically by mean of any reaction producing air bubbles. These aggregates are used with or without the addition of sand. By definition these concretes contain no air cells in the paste other than that entrapped by normal mixing and from conventional air entraining agent. These lightweight aggregates will range from the extremely light

materials used for insulative and non-structural concrete all the way to expanded clays and shales used for structural concrete. Since the lightness of these aggregates derives from the air trapped in each individual particle, the more air that is trapped per particle unit, the lighter the weight and the better the insulation, but, conversely, the lower the strength.

Aerated concrete often autoclaved to obtain high strength and commercially named aircrete. Aircrete was developed in Scandinavia in 1924 by Messrs Christiani and Nielson and first used in the late 1950's (H+H 2003) as an alternative to building with timber. In most of the developed countries it is used extensively by major house builders. Aircrete is also known commercially as AAC (Autoclaved Aerated Concrete), Celcon, Durox, Thermalite, Topblock etc. Aircrete blocks are suitable as vertical load-bearing elements and provide the thermal insulation expected. Aircrete blocks may also be used as non load bearing outer leaves of masonry walls, external walls and walls below ground level, where adequate care is essential to ensure their durability and protection from effects of the environment. Lightweight concrete is made from various materials, including ground sand, pulverized-fuel ash (PFA), cement, lime, aluminium powder and water. Other than these common ingredients, numerous materials are recently being identified to be introduced producing lightweight concrete.

Curious study by Stahl et al. (2002) indicated the possibility of wood aggregate as filler in concrete to reduce unit weight. Teo et al. (2006) investigated feasibility of introducing oil palm shell in concrete. Nemes and Józsa (2006) indicated suitability of expanded glass aggregate as potential ingredient of lightweight concrete. Arisoy and Wu (2008) successfully developed high performance fiber reinforced lightweight concrete that showed high flexural strength, high flexural ductility, and excellent toughness. Multi-axial test on lightweight aggregate concrete by Liu and Song (2010) revealed potential of this domain of concrete. Recent study by Al-Jabri et al. (2009) even showed the opportunity to incorporate waste materials like polystyrene beads, vermiculate and cement kiln dust to produce lightweight concrete. These materials are blended together into a mixture, which foams to create

an exceptionally strong and light cementitous matrix with high thermal insulation. It is thermally efficient, environmentally friendly and flexible. Studies (Haug et al. 1996; Hunaiti et al. 1997; Haque and Al-Khaiat 1999; Lo et al. 2003; Steinberg et al. 2003; Ahmed et al. 2004; Sadrekarimi 2004; Lijiu et al. 2005; Lo et al. 2006; Mao and Ayuta 2008; Mouli and Khelafi. 2008; Chen et al 2010; Hussain et al. 2010) investigated vibrant properties of lightweight concrete as both structural and infill material. These in-depth researches indicate wide opportunity of lightweight concrete in respect of performance and durability.

2.2.1 Classification

Two technical committees of (a French acronym for International Union of Testing and Research Laboratories for Materials, Systems and Structures) spearheaded the process of creating a comprehensive source that was published in draft form in 1992, concurrent with a technical symposium on ACC sponsored by RILEM. The RILEM model code incorporates the historical results of European experimental and theoretical studies, and is a definitive source book as well as a testing manual. The code deals mostly with the mechanical aspects of ACC, and the use of ACC in various modes of construction, as well as in conjunction with fasteners and other components. Relatively little is presented concerning the environmental aspects, except as generally related to demolition and disposal of building materials. The variety of use of lightweight concrete is recognized by RILEM (1978) has proposed a classification shown in Table 2.1. Bulk density, thermal conductivity and compressive strength ranges normally associated with each class of concrete.

Table 2.1: Classification of lightweight concretes

Property	**Class and Type**		
	I	**II**	**III**
	Structural	**Structural/Insulating**	**Insulating**
Compressive Strength (MPa)	>15.0	>3.5	>0.5
Coefficient of Thermal Conductivity (W/m-K)	-	<0.75	<0.30
Approximate Density Range (kg/m^3)	1600-2000	<1600	<<1450

Structural Lightweight Concrete

Structural lightweight concretes generally contain aggregates made from pyroprocessed shales, clays, slates, expanded slags, expanded fly ash and those mined from natural volcanic sources. Autoclaving provides better properties to satisfy structural requirements.

Structural/Insulating Lightweight Concrete

Industrial application that call for “fill” concretes often require compressive strengths and densities in the intermediate between structural and insulating concrete. These may be produced with high air content and include structural lightweight aggregate or sanded insulating lightweight aggregate or they may incorporate both structural and insulating lightweight aggregate.

Insulating Lightweight Concrete

Insulating concretes are very light nonstructural concretes, employed primarily for high thermal resistance. This type of concrete seldom 800 kg/m^3 density range having compressive strength range from 0.5 MPa to 3.5 MPa.

Another classification of lightweight concrete is according to their origins and production processes. However, these two types of lightweight concrete can easily overlap as originating from same source or production process can perform different functions.

2.2.2 Lightweight Aggregate Concrete

Lightweight aggregate concrete is produced by replacing the usual mineral aggregate by cellular porous or lightweight aggregate. Lightweight aggregate concrete is more popular than that of other lightweight concretes owing to tremendous advantages. Modern technology and a better understanding of the concrete have also helped much in the promotion and use of lightweight concrete. A particular type of lightweight concrete called structural lightweight concrete is the

one that is comparatively lighter than conventional concrete but at the same time strong enough to be used for structural purposes. It, therefore, combines the advantages of normal weight concrete and discards the disadvantages of normal weight concrete. Lightweight concrete can be classified in two categories namely natural lightweight aggregate concrete and artificial lightweight concrete. A summary of possible lightweight aggregates is given below:

2.2.2.1 Natural Aggregates

Natural aggregates are not found in many places and they are also not of uniform quality. As such, they are not used very widely in making lightweight concrete. Shetty (2001) has thoroughly discussed about the classification of lightweight aggregates and their uses in practice.

Pumice

These are rocks of volcanic origin, which occur in many parts of the world. They are light enough and yet strong enough to be used as lightweight aggragates. Their lightness is due to the escaping of gas from the molten lava when erupted from deep beneath the earth's crust. Pumice usually light colored or nearly white and has a fairy even texture of interconnected cells. Pumice is one of the oldest kinds of lightweight aggregates, which has been even used in Roman structures. Pumice is mined, washed and then used. Pumice may be sintered to the point of incipient fusion when a much stronger aggregate is required. Density of pumice concrete made of pumice having six times cement volume with density 500-800 kg/m^3 can produce concrete of density 1200 kg/m^3. All over world, natural pumice is reserved beneath seabed or near places with past volcanic activity. Typical pumice found in coral reef of Okinawa Islands is shown in figure 2.1 (Kitamura et al. 2006). Porous honeycomb structure of this type of stone is clearly visible with open eye. However, coarser pumice is also available in large scale.

Yasar et al. (2008) prospected the feasibility of introducing natural pumice in lightweight building blocks. Based on the thermal conductivity, strength and density

testing undertaken, it was concluded that aggregate from pumice (Nevşehir, Turkey) can be satisfactory for the production of lightweight concrete. The dry density and unconfined compressive strength of the lightweight concrete was established as 1108 kg/m^3 and 16 MPa, respectively, at 90 days. The test results indicate that the concrete strengths generally increased by some 2.25 times between 7 and 28 days. The tensile strengths were seen to increase by some 3.5 times between 7 and 28 days. In conclusion, the author stated that pumice aggregate could be used in the production of lightweight concrete and lightweight brick, which reduce the loads imposed by buildings and make the structure better to withstand earthquake motion. In addition, they provide good noise and heat insulation and hence are environmentally friendly.

Campione et al. (2001) incorporated pumice in fiber reinforced concrete beam having density of 1800 kg/m^3 and compressive strength of about 20 MPa. He concluded the brittleness of lightweight concrete. Pumice induced concrete beam exhibited very brittle behavior with respect to normal weight concrete having the same compressive strength, ensured by a similar comparison with normal weight and expanded clay aggregate concrete beam.

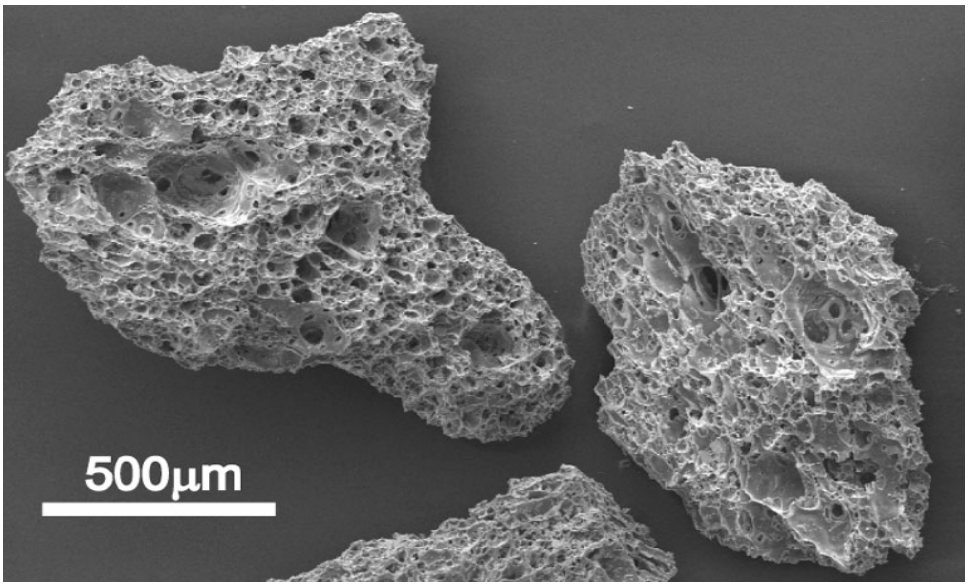

Figure 2.1: Microscopic texture of pumice

Diatomite

This is a hydrated amorphous silica derived from the remains of microscopic aquatic plants diatoms. It is also known as Kieselguhr. The deposits of this aquatic plants are formed beneath the deep ocean bed. Subsequently whiten the ocean bed is raised and becomes continent, the diatomaceous earth becomes available on land. In pure form diatomite has an average weight of 450 kg/m^3. But, due to impurities, the naturally available diatomite may weight more than 450 kg/m^3. Diatomite is used as a workability agent and as one of the good pozzolanic materials. Diatomite or diatomaceous earth can also be sintered in rotary kilns to make artificial lightweight aggregates. Figure 2.2 shows diatomite cited after John J. St. (2010).

Scoria

Scoria is also lightweight aggregate of volcanic origin, which is usually dark in color and contains larger and irregularly shaped cells unconnected with each other. Therefore, it is slightly weaker than pumice. Figure 2.3 shows typical scoria texture (GSI, 2008).

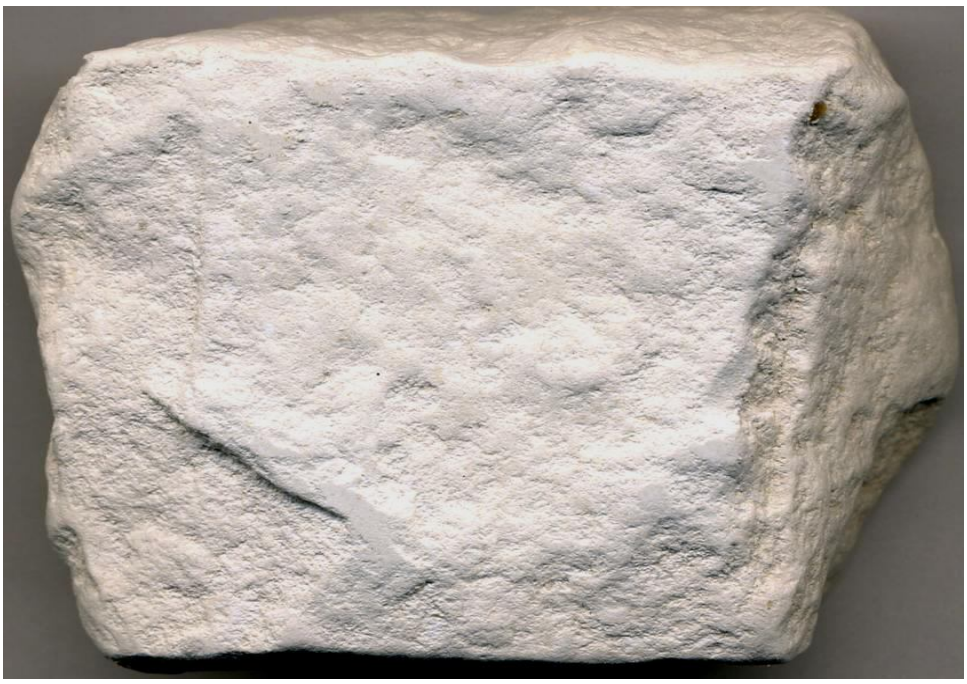

Figure 2.2: Diatomite

Figure 2.3: Scoria

Saw Dust

Sometimes saw dust is used as lightweight aggregate in flooring and in the manufacture of precast products. Curious study by Stahl et al. (2002) indicated the possibility of wood aggregate as filler in concrete to reduce unit weight. The study utilized wood particles from spruce, yellow pine, hard maple, tulip-poplar, and species form the poplar/aspen/cottonwood group mixed with cement, sand and group of admixtures. Density range of 1600-1700 kg/m^3 was attained by resulted concrete of compressive strength ranging 4-9 MPa. A few difficulties have been experienced for its wide spread use. Saw dusts affect adversely the setting and hardening of Portland cement owing to the content of tannins and soluble carbon hydrates. To offset the delay in setting and hardening, addition of calcium chloride to the extent of about 5 percent by weight of cement has been found to be useful. Figure 2.4 shows fibrous saw dust (Wikipedia 2009).

Cork Granules

Another commonly used wood-based lightweight aggregate is cork granules from the bark of Cork Oak trees, which are grown mainly in Portugal, Spain, and Algeria.

The waste cork granules have a density of about 300 kg/m^3, which is lower than that of most of the lightweight aggregates used for making lightweight concrete.

Figure 2.4: Saw dust

It has been found that cork granules do not influence cement hydration much, but cork dust does (Karade et al. 2006; Periera et al. 2006). The composites made using cork and cement have several advantages such as low thermal conductivity, low density and good energy absorption characteristics. The composites can be made of density (400-1500 kg/m^3), compressive strength (1-26 MPa) and flexural strength (0.5 – 4 MPa). Concrete often produced using cork or wood dust is called *nailable concrete*. Saw dust concrete and cork can be used in the manufacture of precast concrete products, jointless flooring and roofing tiles. It is also used in concrete blocks for holding the nail well. The wood wool concrete is made by mixing wood shavings with Portland cement or gypsum of the manufacture of precast blocks. This has been used as wall panels for acoustic purposes. Untreated cork granules shown in Figure 2.5 (Wikipedia, 2000).

Figure 2.5: Cork granules

Husk

Limited use of rice husk, groundnut husk have been used as lightweight aggregate for the manufacture of lightweight concrete for special purposes. Rice husk is an agricultural by-product worldwide in large quantities available. This is a suitable biomass source for energy production. Compared to other agricultural by-products, the burned rice husk presents a high yield of ash (about 20 percent) mainly composed of silica that will be mostly amorphous when properly incinerated. Extensive research in the past three decades has allowed the introduction of rice husk ash as a supplementary raw material in cement-based products, whereby significant improvements in strength and durability can be achieved, also contributing to ecological demands.

Results from Rodrigues et al. (2010) revealed that partial replacement of ordinary Portland cement by up to 30 percent of rice husk aggregate had not impaired the mechanical behavior of the composites. Further, use of low-carbon-content rice husk concrete decreased porosity in the matrix and enhanced interfacial bonding of the composites. Since the deterioration of cellulose-cement composites is closely related to moisture movement and alkalinity, it was concluded that introduction of low-

carbon content rice husk concrete can lead to improved durability performance of these composites. Figure 2.6 provides stacking of rice husk (Wikimedia C., 2009).

Figure 2.6: Rice husk

Teo et al. (2006) investigated feasibility of introducing oil palm shell in concrete. Oil palm shell includes empty fruit bunches, fiber, shell and effluent. The investigation revealed that the flexural behavior of reinforced oil palm shell concrete beams was comparable to that of other lightweight concretes and the experimental results compare reasonable well with the current serviceability requirement. Detail study by Teo et al. (2010) suggested volume of permeable void of oil palm shell concrete at 28 days was found to be in the range of 20.1-21.2 percent. The sorptivity of concrete of this kind at an age of 28 days was found about 0.06-0.14 mm/$\sqrt{\text{min}}$, permeability coefficient ranged from 6.4 X 10^{-12} to 57.5 X 10^{-12} m/s and chloride diffusion coefficients range from 5.86 X 10^{-8} to 12.02 X10^{-8} cm^2/s.

2.2.2.2 Artificial Aggregate

Scarcity of natural aggregate has leaded the engineers to seek for alternative materials for production of lightweight concrete. Not necessarily, all these options are intentionally manufactured for lightweight aggregate concrete, rather may be, by

product of other production process. Numbers of possible artificial aggregate that were incorporated in lightweight concrete is summarized below:

Brick Bats

Brick bats are one of the types of aggregates used in certain places where natural aggregates are not available or costly. The brick bat aggregates cannot be really brought under lightweight concrete. However, since the weight of such concrete will be less than the weight of normal concrete it is included here. Wherever, brick bat aggregates are used, the aggregates are made from slightly over burnt bricks, which will be hard and absorb less water. Brick bat aggregates are also sometimes used in conjunction with high alumina cement for the manufacture of heat resistant cement. Over burnt brick or Jhama brick is lighter in weight but its production is not controlled, rather produced in local brick kiln as waste by product. Ahmed and Amin (1998) investigated on brick aggregate concrete incorporating crushed brick aggregate having unit weight about 1100 kg/m^3. Rashid et al. (2009) carried out intensive study on brick aggregate having 1080 kg/m^3 of Bangladesh origin and concrete produced from brick aggregate with proper vibration was reported of density 2080 kg/m^3. Compressive strength gained from above type of concrete can be as high as 45 MPa. However, crushed brick aggregate have high prospect in producing lightweight concrete for its low density. Figure 2.7 shows brick crushed aggregate.

Cinder, Clinker and Breeze

A cinder is a pyroclastic material. Natural cinders are extrusive igneous rocks. Cinders are similar to pumice, which has so many cavities and is such low-density that it can float on water. Typical cinder originated from volcanic irruption is shown in Figure 2.8 (Wikipedia, 2010). The color of cinder is brown. The term cinder, clinker and breeze are used to cover the material partly fused or sintered particles arising from the combustion of coal. Attempts have been made to use cinder of acceptable quality as lightweight aggregates in the form of fine aggregate or coarse

aggregate. Cinder aggregate undergo high dying shrinkage and moisture movement. Cinder aggregates have been also used for making building blocks for partition walls, for making screeding over flat roofs and for plastering purposes. The unsoundness of clinker or cinder aggregates is often due to the presence of excessive unburnt coal particles. High proportion of coal expand on wetting and contract on drying which is responsible for the unsoundness of concrete made with such aggregates.

Figure 2.7: Brick bat aggregate

Figure 2.8: Igneous cinder

Foamed Slag

Foamed slag is one of the most important types of lightweight aggregates. It is made by rapidly quenching blast furnace slag, a by-product, produced in the manufacture of pig iron. Then the cooling of the slag is done with a large excess of water, granulated slag is formed which is used in the manufacture of blast furnace slag cement. If the cooling done with a limited amount of water, in such a way as to trip steam in mass, it produces a porous, honeycombed material, which resembles pumice. Sometimes, the molten slag is rapidly agitated with a limited amount of water and the steam and gas produced are made to get entrapped in the mass. Such a product is also called foamed slag or expanded slag.

The texture and strength of foamed slag depends upon the chemical composition and method of production. In general, the structure is similar to that of natural pumice. Ready made building blocks and partition wall panels are produced from foamed slag. Such prefabricated items being lighter in weight, could be transported at comparatively low cost. Foamed slag is also used of the manufacture of precast RCC lintels and other small structural numbers. By controlling the density, foamed slag can be used for load bearing walls and also for the production of structural lightweight concrete. Figure 2.9 exhibits surface of hardened slag (http://www.engr.wisc.edu).

Bloated Clay

When certain glass and shale are heated to the point of incipient fusion, they expand or what is termed as bloat to many times their original volume because of the formation of gas within the mass at the fusion temperatures. The cellular structure so formed is retained on cooling and the product is used as lightweight aggregate.

Figure 2.9: Blast furnace slag

Sintered Fly Ash (Sintered Fuel Ash)

Fly ash is finely divided residue, comprising of spherical glassy particles, resulting form the combustion of powdered coal. By heat treatment, these small particles can be made to combine, thus forming porous pellets or nodules, which have considerable strength. Sintered fly ash is one of the most important types of structural lightweight aggregate used in modern times. Fly ash can occupy up to 40-70 percent of volume of concrete.

Numerous studies have been carried out on the prospect of fly ash in concrete. Long-term compressive strength and durability of concrete are well known to be improved by addition of fly ash. Relationship between reaction ration of fly ash, characters and performance of hardened fly ash cement system was observed by Hanehara and Kobayakawa (2010).

Similar observation was found by the study carried out by Pofale et al. (2010). From this investigation, it was found that about 20 percent increase in the compressive strength and about 15 percent increase in flexural strength of concrete by the inclusion of fly ash as a partial replacement of sand as compared to control concrete. Sand was replaced by fly ash by Maximum density method and Minimum voids

method. Results indicated increase in workability over control concrete. Concrete with fly ash was also found to be about 25 percent economical when cost per N/mm^2 was compared.

Another important by-product of fly ash that can be used as lightweight aggregate is *cenospheres*, relatively large (10–300 µm) thin-walled microspheres produced during fly ash formation. Cenospheres are formed during the coal burning process by evolution of gas becoming trapped in a viscous molten glass matrix. These cenospheres can be reclaimed from fly ash readily and are relatively inexpensive as a bulk product. They are also considered a waste product, so any use of them decreases the strain on the environment and can be used as fillers in polymers and concrete. Mcbride et al. (2002) studied mechanical properties, including compressive strength, tensile strength, flexural strength and fracture toughness of cenospehere concrete of density about 1800 kg/m^3 and were tested and cataloged. It was determined that the addition of high volumes of cenospheres significantly lowered the density of concrete but was also responsible for some strength loss. This strength loss was recovered by improving the interfacial strength between the cenospheres and the cement.

Most rigorous study in the characterization of effect of fly ash on foam behavior producing foamed concrete was done by Nambiar and Ramamurthy (2008a, 2008b and 2009). These studies revealed in depth behavior of fly ash when mixed with cement and foam mix matrix. Side by side, outcome of these studies open new opportunity for fly ash as potential ingredient of foamed concrete.

Role of fly ash as potential binder was examined by Komljnovic et al. (2009). Results of this study showed that fly ash, as a component of raw mixture for Portland cement clinker synthesis, has a positive influence on decreasing of the softening temperature of the raw mixture that is on the earlier appearance of liquid phase. By sintering in the presence of liquid phase, the rate of reaction is increasing and more homogeneous mineral composition and other characteristics of the clinker can be achieved.

Arisoy and Wu (2008) successfully developed high performance fiber reinforced lightweight aggregate concrete using fly ash and that showed high flexural strength, high flexural ductility, and excellent toughness.

Pozzolanic action of fly ash was investigated by Rahhal and Talero (2004). The out comes suggested that incorporation of fly ashe to Portland cements of different mineralogical composition stimulated the hydration reactions of Portland cements components. Thus, for Portland cements with high C_3A contents, the incorporation of these fly ashes stimulated the hydration reactions up to a specific cement replacement (between 20 and 40). However, for portland cements with low C_3A contents, the reactions slowed down with the rise of fly ash percentage. As part of the above mentioned research investigation, SEM of fly ash was taken as shown in Figure 2.10.

In Bangladesh perspective, Alam et al. (2006) carried out a study on feasibility of using fly ash generated from Barapukoria power plant in cement production. Laboratory test for different parameters such as compressive strength, workability of showed almost no sacrifice for the strength of cement due to mixture of fly ash with a proportion of 10 percent. Now a day, Portland composite cement containing fly ash is extensively used in Bangladesh.

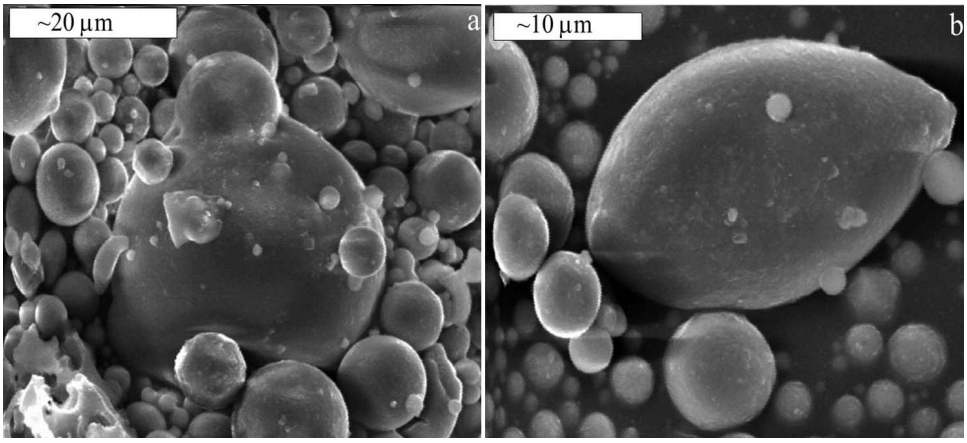

Figure 2.10: Microscopic view of fly ash

Exfoliated Vermiculite

Raw vermiculite is a micaceous mineral and has a laminar structure. When heated with certain percentage of water it expands by delamination in the same way as that of slate or shale. This type of expansion is known an exfoliation. Due to exfoliation, the vermiculite expands many times its original volume. The fully exfoliated vermiculite that may have expanded even as much as 30 times will have a density of only 60-130 kg/m^3.

Study by Hugo et al. (2002) suggested the concrete made with vermiculite as aggregate, therefore, will have very low density and hence very low strength. This concrete is used for insulating purposes, it is also used for in site roof and floor screeds or for the manufacture of blocks, slabs and tiles which are used for sound insulating and heat insulation. Vermiculite concrete can be cut, sawn, nailed or screwed. Figure 2.11 is taken from the website (http://www.vermiculite.cn) of leading vermiculite mining and processing company of china: Vermiculite Mining Ltd.

Figure 2.11: Exfoliated vermiculite

Expanded Perlite

Perlite is one of the natural volcanic glasses like pumice. This when crushed and heated to the point of incipient fusion at a temperature of about 900-1000^{0}C it expands to form a light cellular material with density of about 30-240 kg/m^3. In appearance, it resembles “popcorn”. Due to its very low density, this can be used for insulation grade concrete. Other than expanded perlite, raw perlite is reported to reduce low density and thermal conductivity (Tandiroglu 2010).

Insight of perlite expansion was studied by Varuzhanyan et al. (2006). The results of this study demonstrated that during heating, perlite expansion begins in the central part of the sample. The process is accompanied by a marked strength gain. The heating-induced strengthening impeded the removal of water. Water release from perlite sharply raises its viscosity, preventing the material from softening, sticking to the reactor wall, and agglomeration. Samples of the same bulk density have identical viscosities, independent of the process temperature and pressure. At elevated water vapor pressures, increasing the heating rate shifts the viscosity of perlite to lower temperatures. Expanded perlite in above mentioned study by Varuzhanyan et al. is shown in figure 2.12.

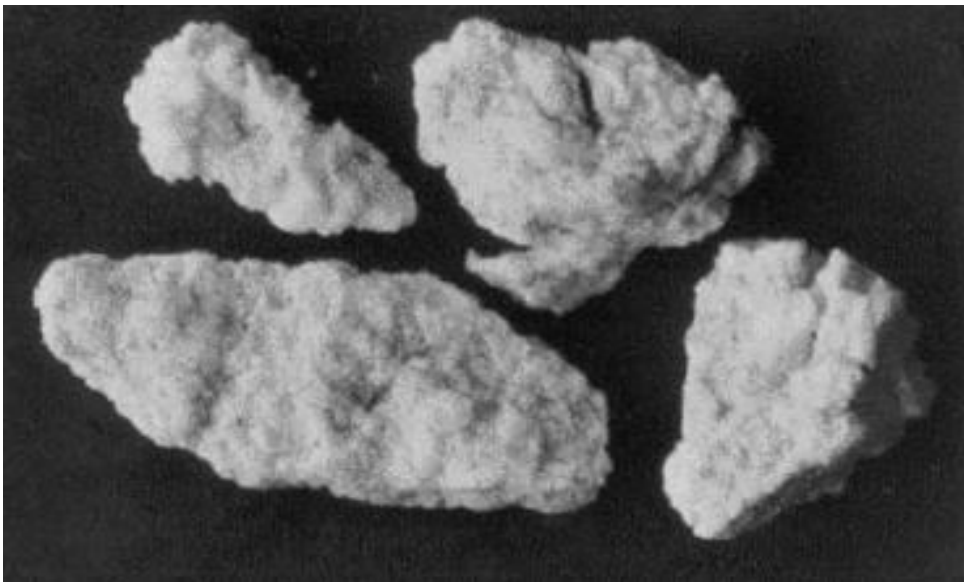

Figure 2.12: Expanded perlite

Expanded Glass Aggregate

Expanded glass aggregates are made of waste materials so an environmental advantage can be achieved. Nemes and Józsa (2006) indicated suitability of expanded glass aggregate as potential ingredient of lightweight concrete. In this study, lightweight concrete from expanded shell was reported to be found with density 1500-2000 kg/m^3 and compressive strength 15-50 MPa.

Expanded glass aggregate prebroken glass is fed into a mill, producing a fraction, which is smaller than 3 mm in size. Then, knowing the chemical composition, gas-forming, structure-shaping, and melting-point-reducing agents are added. These are also industrial waste materials, the main components of which are used as additives in glass production. The mixture is then milled in a ball mill until the size of 50-120 µm is reached. The diameter of the bubbles made in the granulator depends on the added melting-point-reducing and viscosity-controlling additives. Next, the water in the unfired pellet is removed on a belt drier by heating. Then, the granulate is fed into the final drier, and mixed with an additive that prevents the cohesion of the melted glass grains. The upper limit of the raw pellets is 14-16 mm. Controlling the temperature and altering the angle of the rotary furnace and the number of rotations of the tube per minute all make it possible for the grains of different sizes to have the same physical parameters. The pellets form a semi molten mass, which melts and increases in volume to two to ten times their original size, and then an alkali-resistant layer is formed on the pellet surface in one step, at a temperature of 750-950°C. The grains have low particle density. If the surface is closed, they have good thermal insulating properties and low water absorption; or if the surface is open, they have good sound insulating properties as well as high water absorption and are ideal for extended moist curing of the concrete. Grains have good bond capacity when embedded in gypsum, cement, bitumen, or resin matrix. The production process expanded glass aggregate, as shown by Nemes and Józsa (2006), is shown in Figure 2.13.

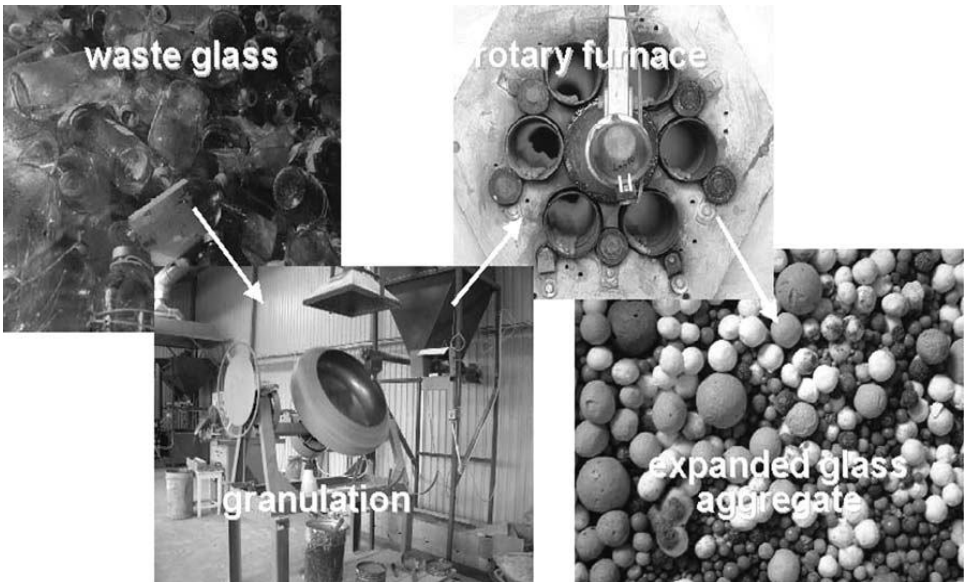

Figure 2.13: Manufacturing of expanded glass aggregate

Polystyrene

Polystyrene is a lightweight cellular plastic foam material composed of carbon and hydrogen atoms. It is produced from petroleum and natural gas by-products. Over the years, the outstanding physical properties of this material have been proven. Properties include excellent vapor diffusion and fire resistance, frost proof, lack of toxic components and out gassing, and vermin and insect proof. Nowadays, expanded polystyrene beads light concretes have been used in various structures such as cladding panels, curtain walls, composite flooring systems, load-bearing concrete blocks, sub-base material for a pavement; floating marine structures, and protected layer of structure for impact resistance due to its good energy-absorbing characteristics. The polystyrene beads used as lightweight aggregates are that have a density ranging from 12 to 25 kg/m^3 and a diameter ranging from 1-6 mm. Polystyrene beads are a widely used aggregate and can be easily incorporated into concrete or mortar to produce lightweight concrete with a wide range of densities (Babu et al. 2006).

Expanded polystyrene beads are classified as an artificial ultra-lightweight aggregate (density less than 33 kg/m^3) with a non-absorbent, hydrophobic and closed cell

nature. Xiaoyan et al. (2009) utilized expanded polystyrene to produce homogeneous and compact lightweight concrete with higher strength and heat-insulating property through the surface modification by polyvinyl acetate emulsion.

Study by Al-Jabri et al. (2009) even showed the opportunity to incorporate waste materials like polystyrene beads, vermiculite and cement kiln dust to produce lightweight concrete. These materials are blended together into a mixture, which foams to create an exceptionally strong and light cementitous matrix with high thermal insulation. It is thermally efficient, environmentally friendly and flexible.

Polystyrene can be incorporated with solid waste like ash produced from thermal power station along with turf, glass sand to produce lightweight concrete. Using this concept, Hadi et al. (2009) demonstrated production of mortar with density ranging from 1600-1900 kg/m^3 and compressive strength 18-92 MPa.

Recently, Chen et al. (2010) claimed to produce a new structural lightweight concrete by totally or partially replacing coarse and fine aggregates in high performance concrete by expanded polystyrene beads. Lightweight expanded polystyrene concretes with a wide range of concrete densities and compressive strengths were successfully developed. Additionally, fine silica fume and polypropylene fibers were added to improve the mechanical and shrinkage properties of lightweight concretes. The results show that fine silica fume greatly increases the bond strength between the expanded polystyrene beads and cement paste, thus increasing the compressive strength. With inclusion of polypropylene fibers, drying shrinkage properties are significantly improved. Figure 2.14 shows expanded polystyrene beads (www.antenocitisworkshop.com).

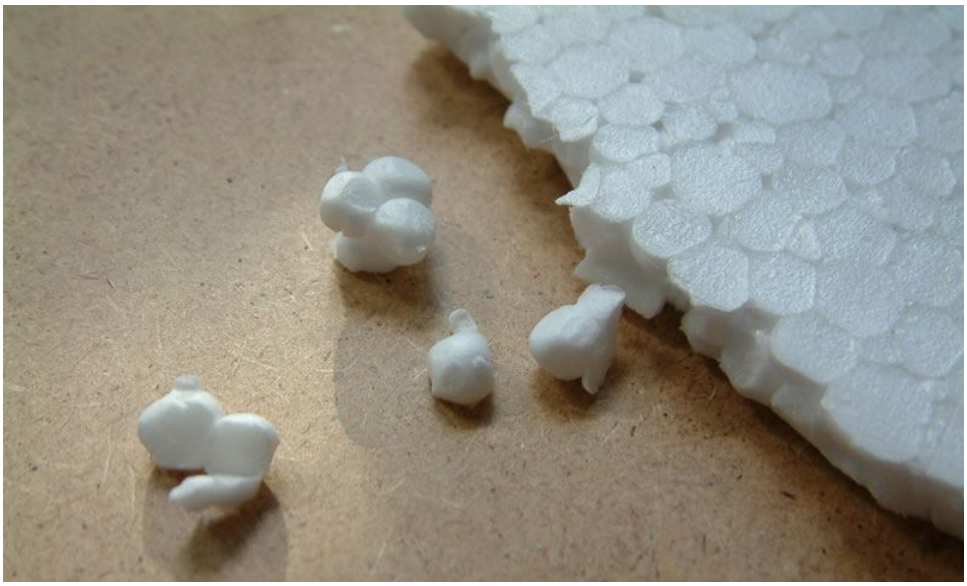

Figure 2.14: Polystyrene beads

Waste Sludge Residues

Sludge is an inevitable by-product of wastewater treatment. Its abundance poses disposal problems that can be drastically reduced if sludge can be converted for economical uses in construction as substitute materials. Digested and dewatered sludge, after incineration at a high temperature, yields a hard, cellular, porous mass with low unit weight. This hardened mass of sludge ash can be crushed to smaller-sized aggregates, which, when graded in suitable proportions, manifest the basic attributes required of lightweight aggregates.

Alleman and Berman (1984) reported the use of sludge mixed with clay-shale material for “Biobrick” production. Study by Tay and Yip (1989) incorporated incinerated sludge having density 600-900 kg/m^3 in concrete and obtained concrete product of density 1500-1900 kg/m^3 and compressive strengths 7-20 MPa. He also concluded that lightweight concrete made with sludge ash aggregates has low thermal conductivities and high fire resistance and thus are suitable for application in thermal insulation and fire protection.

2.2.3 Cellular Concrete

The name cellular concrete contains a wide range of concrete product. Cellular concrete contains voids that can be generated by a number of processes. ACI practice guide ACI 523 (1996) has defined *cellular or aerated concrete* as: *"A lightweight product consisting of Portland cement and/or lime with siliceous fine material, such as sand, slag, or fly ash, mixed with water to form a paste that has a homogeneous void or cell structure. The cellular structure is attained essentially by the inclusion of macroscopic voids resulting from a gas-releasing chemical reaction or the mechanical incorporation of air or other gases (autoclave curing is usually employed)."*

History

A brief history of cellular concrete and autoclaving is narrated at website (www.hebel.co.nz) of famous autoclave producing company Hebel; named after Josef Hebel, one of the pioneers in autoclave technology. Since Roman times, lightweight aggregates and foaming agents have been employed to reduce the weight of concrete. However, unlike these foamed or light aggregate mixes, true aerated concrete relies on the alkaline binder (lime and cement) reacting with an acid to release gases, which remain entrained in the material.

The first attempt to produce aerated concrete was a method patented by a Czechoslovakian, Mr E. Hoffman, in 1889. The aeration was produced by carbon dioxide generated in the reaction between hydrochloric acid and limestone. Powdered aluminium and calcium hydroxide were used as aeration agents in cementicious mixtures by Aylsworth and Dyer in the USA in 1914. In 1917, a Dutch patent was registered using yeast as an aerating agent. Later patents involved the reaction between zinc dust and the alkalis in the cement mixture, hydrogen peroxide, sodium or calcium hypochlorite and air foaming. The use of metal powders as a hydrogen gas forming agents was developed further by Grosahe in Berlin in 1919. Aluminium powder was settled upon as the medium that produced the most even,

controllable aeration by the release of hydrogen bubbles in a consistent size range. Most of these air cured aerated concrete techniques resulted in low compressive strength, crumbly material, generally unfit for structural applications.

The first documented attempt at autoclaved aerated concrete was in 1923 in Sweden. The discovery was almost accidental. An architectural science lecturer, Dr Johan Axel Eriksson, then assistant professor for Building Techniques at the Royal Institute of Technology in Stockholm, was working on a variety of aerated concrete samples. Running short of time, he decided to speed up the curing process on a porous mass of burnt shale limestone, water and aluminium powder by placing the sample in the laboratory autoclave. The porous mass survived the overnight autoclaving and the resulting cured brick possessed greatly increased strength and a new, stronger crystalline composition called tobermorite. Tobermorite is usually found in conjunction with basalt and was named after the spot where it was first found, on the Scottish Island of Mull near the village of Tobermory. Dr. Eriksson patented his ‘gas concrete’, known locally as ‘poren betong’, in 1924. It took a few years for him to find a manufacturer prepared to invest in a plant and in November 1929, Y-Tong was first licensed and manufactured by building product producer, Karl August Carlen, in the town of Yxhult, Sweden. Y-Tong is an abbreviation of the town’s name and the Swedish word for concrete ‘betong’. This plant was operational until the late 1960’s. The development of an autoclaved aerated concrete industry, using local raw materials, began producing what were known as ‘warm stones’ due to the thermal resistivity provided by the aerated material. A bricklayer in his first life, Josef Hebel further adjusted the AAC manufacturing process by incorporating cutting wires to slice the large slabs into panels for making reinforced elements and further mechanized the process with various machines for lifting, trimming and packaging the material. Recent development in aircrete industry has allowed producing lightweight concrete for moderate structural purposes and improving day by day towards perfection.

Void Intrusion

Generally, weaker cellular concrete is produced by introducing stable voids within the hardened cement paste or mortar. The void can be produced by gas or by air; hence the name *gas concrete* or *aerated concrete* or *foam concrete* or *aircrete*. Arerated concrete can be manufactured in several ways:

i. By the formation of gas by chemical reaction within the mass during liquid or plastic state. By using finely powdered metal (usually aluminium powder) with the slurry and made to react with the calcium hydroxide liberated during the hydration process, to give large quantity of hydrogen gas. This hydrogen gas when contained in the slurry mix, gives the cellular structure.

ii. By mixing preformed stable foam with the slurry.

iii. By using durable starch based gels comprised of water and a gelling agent, commercially called *aquagel*. The aquagel must have the shear strength to remain intact during the mixing process to be most effective. Once the aquagels are uniformly interspersed in a concrete mixture, the concrete is poured into place where it hardens and encases the aquagels. Void spaces develop around the encased aquagels as the cement cures and dries.

Foam can also be produced usually by the use of finely ground zinc powder, which reacts with hydroxide of calcium or alkalis or water and liberates bubbles of hydrogen. Hydrogen peroxide and bleaching powder have also been used instead of metal poser. However, this practice is not widely followed at present.

In the second method preformed, stable foam is mixed with cement and crushed sand slurry thus causing the cellular structure when this is set and hardened. Most of the foaming process is done through mechanical foaming process. Mechanical foaming processes introduce a foaming agent into the cement slurry in one of two

ways: the foaming agent can be added directly to the cement slurry which is then agitated to form a stable mass, or a preformed foam, made by pressurizing an aqueous solution of the foaming agent with compressed air, can be introduced into the cement slurry and mixed.

Ranjini and Ramamurthy (2010) discussed that foam usually produced by aerating four commercially available synthetic surfactants viz; sodium lauryl sulfate, sodium lauryl ether sulfate, sulfanol (ionic surfactants) and cocodiethanolamide (non-ionic surfactant). The preformed foams typically provide better control of density and foam cell structure and are more suitable for making low-density foams. In a similar way, air entrained agent in large quantity can also be used and mixed thoroughly to introduce cellular aerated structure in the concrete. However, this method cannot be employed for decreasing the density of the concrete beyond a certain point an as such, the use of air entrainment is not often practiced for making aerated concrete. Tonyan and Gibson (1992) used preformed pressurized foam generator as shown in Figure 2.15.

Gasification method is of the most widely adopted methods using aluminium powder or such other similar material. This method is adopted in the large-scale manufacture of aerated concrete in the factory wherein the whole process is mechanized and the production is subjected to high pressure steam curing. Such products will suffer neither decline of strength nor dimensional instability. Lightweight concrete had been directed towards a new direction when autoclaving was introduced to achieve better product performance.

Other than traditional lightweight concrete production technique, Glenn et al. (2004) demonstrated detail of starch-based lightweight concrete made by aquagel. Glenn made lightweight concretes with aquagel having oven dry density 1100-1400 kg/m^3 and compressive strength 2.5-7.0 MPa. Effort was made to improvise the demerits like low strength, high absorption capacity and aquagel instability in alkaline matrix. Starch-based aquagels are unstable in the alkaline conditions that are typical in Portland cement based concrete. Aquagels affect the time of setting concrete by

changing the water availability in a concrete mixture. Moisture levels 60 percent or lower accelerated the time of setting while levels 75 percent and greater progressively delayed the setting. Trial blends of starch and 30 percent wheat based starch absorbed less moisture and was more resistant to alkaline dissolution than the other blends tested making it a more suitable material for aquagel-based concrete.

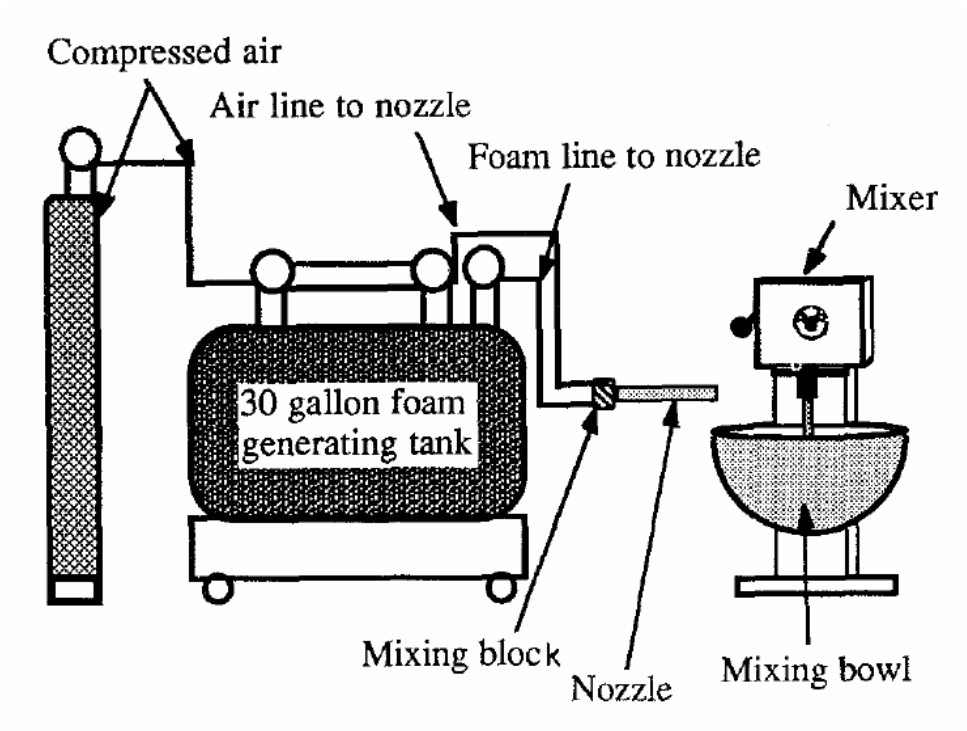

Figure 2.15: Typical preformed foam generator

The bubbles expand the cement paste or the mortar, which must have such consistency as to prevent their escape. Cellular concrete is free flowing and can be easily pumped and placed without compaction. The material can be used for floors, trench fills, roof insulation and other insulating purposes, as well as to make masonry units. Nowadays, in China and other countries, medium entrepreneurs can avail a foam generator to produce lightweight cellular concrete without autoclaving. However, technical knowhow on the production process is necessary before going for commercial production.

Past Experimental Investigations

Neville (2000, p. 708) commented on this type of lightweight concrete such, "*the term 'concrete' is inappropriate because no coarse aggregate is present*". However, researchers are confident to call it so as it is performing the functions of a concrete and thus it can be treated as concrete.

BCA (1991) has provided with a range of properties for cellular concrete. For a range of oven-dry density of 360-1180 kg/m^3, compressive strength ranges within 1-5 MPa and thermal conductivity within 0.1-0.4 W/m-k.

Aluminium based aeration was done by Hussin et al. (2010) integrating palm oil fuel ash to produce lightweight concrete with density less than 1000 kg/m^3. Results suggested that palm oil fuel ash cement-based aerated concrete exhibit higher strength development compared to ordinary Portland cement aerated concrete due to the function of finer particles and occurrence of pozzolanic reaction which makes its microstructure become dense in the case where constant amount of superplasticizer was added, standard proportion of aluminum powder used, or same size of sand is incorporated in the mix. Palm oil fuel ash physical characteristic in terms of fineness and chemical composition plays vital role in determining the strength development of agro blended cement-based aerated concrete through modification of it microstructure. From this intense study it was also seen that increasing sand sizes used for a given water dry mix ratio leads to higher workability mix due to existence of more water because of the small surface area of the sand, which leads to creation of more porous structure as compared to aerated concrete mixture with smaller sized sand. Compressive strength and density of palm oil fuel ash cement-based aerated concrete are also influenced by aluminum powder content used at a constant water dry mix ratio whereby both the density and strength reduce with the increment of aluminum powder content due to higher volume of voids created within the material.

Most intensive study for foam characterization was done by Nambiar and Ramamurthy. Nambiar and Ramamurthy (2008a) suggested strength of cellular

concrete depends on porosity. Strength is not often the desired property as far cellular concrete is concerned rather thermal property is. This study showed that other than air void volume, air-void size and its distribution and its spacing affects the strength of foam concrete. In addition, it was observed that the addition of fly ash helps in achieving a more uniform and narrower distribution of air-voids than sand as the finer filler provides a good uniform coating on each bubbles thus preventing it from merging and overlapping. Another research by Nambiar and Ramamurthy (2008b) appraised that the consistency of the base mix was reduced considerably when foam was added. This reduction in consistency of foam concrete is probably due to the reduced self-weight and greater cohesion resulting from higher air content. Recent work by Nambiar and Ramamurthy (2009) concluded that the higher the fly ash content in the foam concrete mix replacing sand, the higher the shrinkage. This phenomenon lead to low shrinkage resisting capacity of fine fly ash than sand, greater volume water-solids ratio requirement with fly ash for a stable and workable mix, and greater volume of shrinkable paste with fly ash replacement due to reduced foam volume requirement at a given density. Even though addition of fly ash causes a small increase in shrinkage, it has a major contribution toward increasing the strength of foam concrete of comparable density. It was also seen that, irrespective of type of mixes, low-density products are stable for drying shrinkage in spite of its low strength. Artificial air voids may have an effect on volume stability by allowing some shrinkage; this effect increases with increase in foam volume.

Zhihua et al. (2006) produced high performance foamed concrete from Portland cement, ultra fine granulated blast-furnace slag, pulverized fly ash and condensed silica fume by means of pre-foaming process. The resultant foamed concrete presents its thermal conductivity of about 0.16-0.75 W/m-K) and compressive strength of about 1.1-23.7 MPa.

Wang et al. (2005) concluded that anti-permeability of lightweight concrete could be improved by the addition of fly ash, granulated blast furnace slag or silica fume. The improvement magnitude by the addition of fly ash and granulated blast furnace slag used together as a partial replacement of cement each 10 percent or by the addition

of silica fume 10 percent cement was the most significant. It was also that the pore-rate and medium pore-size in cement paste around lightweight aggregate were significantly decreased through the self-curing effect of lightweight aggregate and pozzolanic reaction of the assistant binder, and then, a layer of harden paste with a dense structure and a low pore rate appeared around lightweight aggregate.

Autoclaved Aerated Concrete

The porous cellular structure is produced by the addition of finely divided metallic aluminum late in the mixing step, and results from the generation of hydrogen gas or water vapor during the subsequent molding stage. Autoclaving is a process of curing concrete under elevated temperature and pressure. Aerated concrete produced by the addition of an air-entraining agent to the concrete is sometimes called *Aircrete*. It is also often termed, as *Autoclaved Aerated Concrete (AAC)* or otherwise *Autoclaved Cellular Concrete (ACC)*, is a lightweight, precast building material. AAC provides structure, insulation and fire resistance in a single material. AAC products include blocks, wall panels, floor and roof panels, and lintels. Blocks made by AAC can be used in both reinforced and nonreinforced applications.

Autoclaving is the process of gaining high strength utilizing high pressure (1.0-1.2 MPa) and high relative humidity at 170-200^{0}C. However, steam curing is also practiced with pressure. The important strength-producing phase from hydrothermal reactions is crystalline *tobermorite*, a calcium-silicon hydrate (Neufeld et al. 1996 cited Latona et al. 1997).

Blocks for load-bearing internal and external walls and precast panels for floor and roof slabs are among the most common uses, as well as modular prefabricated products of close tolerances. AAC can also serve as a cladding or filler component, thus affording an extra layer of insulation for other composite building materials. This type of concrete is getting popular day by day for reducing dead load on structures. The main basis behind this type of concrete lies within the production of low-density concrete by introducing void or by using lightweight materials. Aircrete

is produced as industrial products all over the world other than produced in laboratory for research purposes. Keeping in mind the growing popularity of concrete block and its vast utility, research carried out on lightweight concrete properties and aircrete blocks all over the world.

Developed countries are producing wide range of AAC to ensure safe and quick construction. World's largest AAC producing company H+H Celcon Ltd of United Kingdom is producing concrete blocks of density 460-750 kg/m^3, compressive strength 2.9-8.7 MPa and thermal conductivity 0.11-0.19 W/m-K (H+H 2008).

Gutovic et al. (2005) was successful to achieve compressive strength of about 85 MPa by applying autoclaving through mixing of Portland cement and clay-brick waste. However, despite of suitability of product performance, small change in dimension was observed in the study by Gottfredsen et al. (1997). It is demonstrated that initial drying from the moisture content on delivery to equilibrium at approximately 80 percent relative humidity results in a length increase up to 0.4 percent for produced AAC.

Prospect of cellular concrete is not limited to infill or thermal or structural purposes only. Research by Doniec (2007) showed that heavy metals like Cu, Zn, Cr and Ni ions could be removed from aqueous media using cellular concrete. The results suggested the bed of 1 m^3 volume has ability to uptake 25 to 50 kg of metal from a solution, which means cleaning capacity ranging 2500–5000 m^3 of waste water containing 10 mg/m^3 of metals. He concluded that, as the AAC had appeared very effective in a treatment of effluents coming from electroplating facilities, so that it could also be used successfully in other processes generating similar wastewaters (e.g., tanneries).

All over the world, ACC blocks are produced and categorized locally as per their performance. AAC is used extensively in Europe and other parts of the world with the notable exception of North America. Worldwide ACC production exceeds 800000000 ft^3, with Germany and the United States accounting for most of the

world's production (Neufeld et al. 1994). Typical physical properties of AAC blocks are shown in Table 2.2 (after Ahmed et al. 2004).

Table 2.2: Physical properties of AAC blocks

Aircrete Density	Density (kg\m^3)	Compressive Strength (MPa)	Thermal Conductivity (W/m-K)
Low	450	2.0 – 3.5	0.09 - 0.11
Medium	620	4.0 – 4.5	0.15 – 0.17
High	750	7.0 – 8.5	0.19 – 0.20

Neufeld et al. (2004) thoroughly investigated physical properties of ACC blocks containing high fly ash content about 60 percent by weight, collected from random sources and compared the properties in respect of ASTM and RILEM. He summarized compressive strengths of the foamed product to the range of 2-4 MPa, with dry weight densities approximately 500-600 kg/m^3. The pore structure of high fly ash showed a uniform distribution of relatively unconnected pores. The lack of pore interconnection was reported to be used to explain the tendency of ACC to float even when submerged in water for prolonged period. Similarly, the lack of pore interconnection expected to leads to superior thermal insulation properties of block and panel materials. Side by side, Latona et al. (1997) searched for harmful toxicity in ACC where no toxic effects attributable to soluble species was reported.

2.2.4 Pervious concrete

Pervious concrete is sometimes specified by engineers and architects when porosity is required to allow some air movement or to facilitate the drainage and flow of water through structures. Pervious concrete is referred to as "*no-fines*" or "*sand-free*" concrete because it is manufactured by leaving out the sand or fine aggregate. A pervious concrete mixture contains little or no sand (fines), creating a substantial void content. Using sufficient paste to coat and bind the aggregate particles together creates a system of highly permeable, interconnected voids that drains quickly. The

single sized aggregates make a good no-fines concrete, which in addition to having large voids and hence light in weight, also offers architecturally attractive look. The bond strength of pervious concrete is very low and therefore is not used in conjunction with pervious concrete. Narayanan and Ramamurthy (2010) characterized the porosity-permeability relation and thereby optimizing aggregate gradation for pervious concrete.

Study by Zhifeng et al. (2008) showed that more than 25 percent voids and flow rates for water typically around 0.183-0.325 mm/s could be achieved in the hardened concrete. Both the low mortar content and high porosity also reduce strength compared to conventional concrete mixtures, but sufficient strength (5-7 MPa) for many applications can be readily achieved.

Pervious concrete with density and porosity ranging from about 18-30 percent and 1550-1650 kg/m^3 respectively was produced by Mahboub et al. (2009) where flow rate was found 0.243-0.259 mm/sec. This research specially focused on improvisation by aggregate orientation.

2.3 Curing of Concrete

Curing is the maintenance of a satisfactory moisture content and temperature in concrete for a period of time immediately following placing and finishing so that the desired properties may develop. The need for adequate curing of concrete cannot be overemphasized. Curing has a strong influence on the properties of hardened concrete; proper curing will increase durability, strength, water tightness, abrasion resistance, volume stability, and resistance to freezing and thawing and deicers. Exposed slab surfaces are especially sensitive to curing as strength can be reduced significantly when curing is defective.

2.3.1 Mechanism and Necessity

Curing is the name given to procedures used for promoting the hydration of cement, and consists of a control of temperature and of the moisture movement from and into

concrete. The maintenance of proper conditions during this time is known as curing. More specifically, the objective of curing is to keep concrete saturated or as nearly saturated as possible, until the originally water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement. Fresh concrete gains strength most rapidly during the first few days and weeks. In this process, concrete should be protected from loss of moisture for at least 7 days and in more sensitive work up to 14 days. Curing can be achieved by keeping exposed surfaces continually wet through sprinkling, ponding or covering with plastic films or by the use of sealing compounds. In the case of site concrete, active curing stops nearly always long before the maximum possible hydration has taken place.

Type of water available inside hydrated cement can be categorized under evaporable and non-evaporable. Evaporable water can be determined by loss upon drying at a higher temperature, usually 105°C or by freezing out, or by removing with a solvent. The amount of non-evaporable water increases as hydration proceeds but, in a saturated paste, non-evaporable water can never become more than one-half of the total water present. In well-hydrated cement, the non-evaporable water is about 23 percent in fully hydrated cement. Hydration at a maximum rate can proceed only under condition of saturation. As stated by Neville (2000), a minimum relative humidity of 80 percent is required to continue hydration inside concrete. If the relative humidity of the ambient air is at least that high, there will be little movement of water between the concrete and the ambient air, and no active curing is needed to ensure continuing hydration if no other factors intervene, e.g. wind, temperature difference, solar radiation etc. In practice, therefore, active curing is unnecessary only in a very humid climate with a steady temperature. Prevention of the loss of water from the concrete is of importance not only because it adverse affects the development of strength, but also because it leads to plastic shrinkage, increased permeability, and reduced resistance to abrasion. This is why loss of water by evaporation from the capillaries must be prevented. Furthermore, water lost internally by self-desiccation has to be replaced by water form outside. Hydration of sealed specimen can proceed only if the amount of water present in the paste is at

least twice that of the water already combined. Self-desiccation is thus of importance in mixes with water-cement ratios below about 0.5; for higher water-cement ratios, the rate of hydration of a sealed specimen equals that of a saturated specimen. Thus, curing needs in situations where, only loss of water form the concrete needs to be prevented and, on the other, situations where water ingress form outside is necessary for hydration to continue. The dividing line is approximately at a water-cement ratio of 0.5. With many modern concretes having a water-cement ratio below 0.5, the promotion of hydration by the ingress of water into concrete is desirable. From the hydration mechanism, it can be commented that the quality of concrete depends primarily on the gel-space ration of the paste. If, however, the water-filled space in fresh concrete is greater than the volume that can be filled by the products of hydration, greater hydration will lead to a higher strength and a lower permeability.

2.3.2 Curing Practices

The method or combination of methods chosen depends on factors such as availability of curing materials, size, shape, and age of concrete, production facilities (in place or in a plant), esthetic appearance, and economics. As a result, curing often involves a series of procedures used at a particular time as the concrete ages. Concrete can be kept moist (and in some cases at a favorable temperature) by three curing methods:

Wet Curing

It is the method of providing water, which can be taken by the concrete. This requires that the surface of the concrete is continuously in contact with water for a specified length of time, starting as soon as the surface of the concrete is no longer liable to damage. Such conditions can be achieved by continuous spraying or flooding, or by covering the concrete with wet sand or earth, sawdust or straw. Periodically wetted clean hessian or cotton mats may be used, or alternatively an absorbent covering with access to water may be placed over the concrete. Special care is required when hessian is used in sunny weather or hot temperature. Hessian

not watered for long time may act adversely by taking away moisture from the concrete covered. Intermittent wetting of hessian in essential in case of hessian materials where used. Wet curing should be used for water-cement ratio lower than 0.5 and certainly for water-cement ratio less than 0.4, but only if can be applied thoroughly and continuously.

Membrane Curing

This method relies on the prevention of loss of water from the surface of the concrete, without the possibility of external water ingression. This can be called water-barrier method. The techniques used include covering the surface of the concrete with overlapping polyethylene sheeting, laid flat, or with reinforced paper. The sheeting can be black, which is preferred in cold weather, or white, which has the advantage of reflection of solar radiation in hot weather. Paper with a white surface is also available. Sheeting can cause discoloration because of non-uniform condensation of water on underside.

Another technique uses spary-applied curing compounds which from a membrane. The common ones are solutions of synthetic hydrocarbon resins in high-volatility solvents, sometimes including a fugitive bright colored dye. A white or alumina pigment can be included to reduce the solar heat gain; this is very effective. Other resin solutions are available: acrylic, vinyl or styrene butadiene, and chlorinated rubber. Wax emulsions can also be used.

Rapid drying on the exposed surface of concrete may result in finishing problems such as stickiness, sponginess, and unevenness; plastic shrinkage and cracking / or a compacted surface which creates a layered structure subject to scaling. Cordon and Thorpe (1965) suggested application of monomolecular film on the surface of bleeding water. Monomolecular had a long hydrocarbon chain, which is hydrophobic, attached to a hydrophilic alcohol terminal group. The evaporation retarder material had been proven especially effective on concrete placed over plastic sheets or suspended forms. Concrete placed on these materials generally

exhibited extreme differentials in drying rates between the top surface and that at the bottom, since bleed, water cannot escape into the base. The use of an evaporation retarder maintained more uniform moisture conditions from the top to bottom.

It is obvious that membrane must be continuous and undamaged. The timing of spraying is also critical. The curing spray should be applied after bleeding has stopped bringing water to the surface of the concrete but before the surface has dried out the optimum time is the instant when the free water on the surface of the concrete has disappeared so that the water sheen is no longer visible.

Steam Curing

A rise in the curing temperature speeds up the chemical reaction of hydration and thus affects beneficially the early strength of concrete without any ill effects on the later strength. Higher temperature during and following the initial contact between cement and water reduces the length of the dormant period so that the overall structure of the hydrated cement paste becomes established very early. Although a higher temperature during placing and setting increases the very early strength, it may adversely affect the strength from about 7 days onwards. The explanation is that a rapid initial hydration appears to form products of a poorer physical structure, probably more porous, so that a proportion of the pores will always remain unfilled.

Because an increase in the curing temperature of concrete increases its rate of development of strength, the gain of strength can be speeded up by curing concrete in steam. When steam is at atmospheric pressure, the process can be regarded as a special case of moist curing in which the vapor-saturated atmosphere ensures a supply of water. In addition, condensation of the steam releases latent heat. This curing can be a good solution for precast sections where high pressure steam curing is an application of financial burden or technical and instrumental knowhow are limited.

Often steam curing is applied to obtain a sufficiently high early strength, so that the concrete products may be handled soon after casting: the moulds can be removed, or

the prestressed bed vacated, earlier than would be the case with ordinary moist curing, and less curing storage space is required; all these mean an economic advantages. For many applications, the long-term strength of concrete is of lesser importance. Low-pressure steam curing is normally is applied in special chambers or in tunnels through which the concrete members are transported on a conveyor belt. Alternatively, portable boxes or plastic covers can be placed over precast members, stream being supplied through flexible pipes.

Gebler (1983) summarized a number of curing methods applied to concrete piping industry. Concrete piping industry utilized steam curing (about 66^0C) for both primary and secondary curing. Some pipe in moderate climate were able to reduce the cost of curing by using water curing in place of steam curing. Precasters had reported 65 percent reduced curing cost using water curing. However, water curing was difficult due to the unevenness of coverage because of clogged nozzles, wind and pipe shapes. Also, water curing might be expensive in some areas unless water was recirculated. A recirculation system required expenditure for pumps, sumps and piping. Some of the industries had used insulation of curing bins and provided a better seal to reduce thermal losses. Some pipe producers used direct-fired-moist-cured method. This method forced circulation of generated steam in the curing chambers. This system had the advantages of being energy efficient as it circulated vapor in closed circular system. Another system being used was vapor energy system (steam generator) which utilized the exhaust heat to minimize the distribution losses. Solar energy was also utilized for effective curing.

Yazdani et al. (2008) investigated effect of silica fume in concrete when associated with accelerated curing. The maximum temperature reached beyond the maximum specified temperature of 71°C. He concluded that the steam-cured samples displayed lower compressive strengths at all ages than their moist-cured counterparts. This was consistent with previous research finding on silica-fume concrete. He also commented that steam-curing times of 12, 18, and 24 hours did not seem to play a major role in controlling concrete compressive strengths. There was no consistent

pattern of maximum strength displayed by samples from a single source of steam-cured duration.

Mathematical model of process of heat and moist treatment of concrete and reinforced-concrete products in pit-type, steam-curing chambers constructed by Frolov and Lagutin (2002) explained the behavior of the technological parameters and their kinetics. The temperature of isothermal curing exerted the greatest influence on the ultimate strength of products. However, the increase in the temperature had the most substantial effect on the increase in the steam flow rate and in the expenditure of electric energy. It should also be taken into account that an increase in the temperature of isothermal curing can lend to the overheating of products (as a result of which low-strength compounds are formed) and to a decrease in the mechanical indices of the products.

Detail study by Higginson (1961) revealed the effect of curing method on properties like strength, modulus of elasticity and durability. He concluded that concrete that had been steam cured and then air-dried was not as good as concrete that had been continuously moist cured for 7 days. Supplementary moist curing after steam curing improved the quality of steam cured concrete. However, concrete of high quality could be achieved using proper steam curing.

ACI Committee 517 (1963) had reported advantage of low pressure steam curing as rapid strength gain. Assuming proper curing was provided about 60 percent strength of moist cured concrete could be achieved within 24 hours.

Hanson (1965) had reported detailed effect of curing conditions on strength of lightweight concrete. He concluded that lightweight concrete differed little from that of normal weight concrete. Initial delay of steaming aided gaining more strength than that of curing from the beginning of cast. Effect of delay of steaming was reported as shown in Figure 2.16 (after Hanson, 1965).

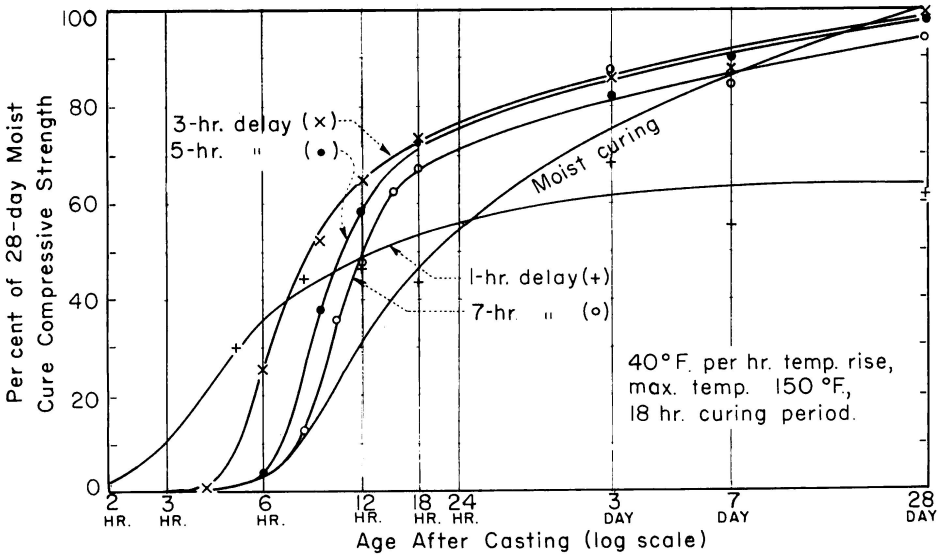

Figure 2.16: Relative compressive strength of steam cured lightweight concrete

Steam curing has been used successfully with different types of Portland cement, as well as with blended cements, but must never be used with high-alumina cement because of the adverse effect of hot, wet conditions on the strength of that cement. Steam curing of concrete made with fly ash accelerates the pozzolanic reaction with $Ca(OH)_2$ but only above a temperature of 88°C. Study by Dan et al. (1991) cited in Neville (2000) suggested that ground granulated blast furnace slag in the mix above 60°C. The slag also leads to a reduction in the average pore size in the steam-cured cement paste.

Ke-fang and Nichols (2004) reported performance of concrete under elevated temperature when concrete was cured at elevated temperature, a harmful consequence occurred. That was the later strength of concrete decreases significantly compared to that under normal curing condition, especially for the higher water-cement ratio concrete. The later strength reduction caused by elevated curing temperature decreased as water-cement ratio of concrete decreased. Incorporation of silica fume, fly ash and slag could reduce the later strength reduction of concrete. Among those, silica fume was the most efficient material to decrease the later strength reduction of concrete. The later strength reduction of concrete was not caused by the difference in degree of hydration of cement between the two curing

conditions. It was caused by the uneven distribution of hydration products when concrete was cured at elevated curing temperature.

As suggested by Cervera et at. (1999), the effect of the curing temperature was two fold. First one was the thermo activated character of the hydration reaction was very evident, as the process of hardening was accelerated by the increase in curing temperature; and second one was the significant loss of strength with increasing curing temperature was clear. The first effect was particularly evident at the initiation of the hydration process, with an activation phase being shortened as the curing temperature was increased. Among two set of tests by Canvera et al., first one demonstrated that mortar cured at 50^0C showed a loss of attainable strength of 23 percent, compared with that cured at 12.5^0C. This demonstrated the necessity of accounting for the effect of the temperature in a realistic chemo-aging model, particularly for higher curing temperatures. Concrete cured at 50^0C showed a loss of attainable strength of 6 percent, compared with that cured at 20^0C, which was significantly less than the percentage measured for the mortar above set. Even though, the trend of strength reduction due to elevated temperature curing was evident.

Gesoğlu (2010) investigated a special case of moist curing in which the vapor-saturated atmosphere ensures a supply of water. In that study, influence of steam curing on the compressive strength, ultrasonic pulse velocity, water sorptivity, chloride ion permeability, and electrical resistivity of metakaolin and silica fume blended concretes were investigated. Steam was generated at atmospheric pressure and temperature being below 100^0C. Compressive strength of the concrete mixtures increased with the increasing curing period. Although, the steam cured concretes had higher compressive strength at the very early ages, the strength at 7 days onwards seemed to be lower. Using metakaolin and silica fume increased the compressive strength of concrete for both curing conditions, the effect being more influential with increasing metakaolin and silica fume contents.

Chini and Acquaye (2005) showed that when the pure cement concrete specimens were placed in preheated curing tanks as soon as they were molded and cured under constant temperatures of 71^0C and 93^0C, their compressive strengths were significantly decreased to 34 percent and 62 percent respectively and their permeability were increased. Blending the cement with fly ash and slag, resulted in increased strength and durability when compared to the plain cement mixes. This showed the importance of the age of precast concrete members when they were exposed to steam curing regimen to accelerate their strength gain.

Special curing treatment was reported after Hermawan et al. (2001, 2002a, 2002b). These reports documented treatment with gaseous or supercritical CO_2. The specimens were placed in a reaction cell surrounded by a water jacket set at 60^0C. In these experiments, the specimens were subjected to a CO_2 pressure of 1.0 MPa in the gas phase and 7.5 MPa in the supercritical phase at about 50^0C. Following curing times of 10, 30, and 60 minutes, they were placed in an oven set at 80^0C for 10 hours. Later the specimens were conditioned at ambient temperature prior to property evaluation. The mechanical and dimensional properties of oil palm fronds cement-bonded board manufactured by the conventional cold-pressing method followed by curing treatment using either gaseous or supercritical CO_2 were improved significantly, and the curing was accelerated dramatically between 10 and 60 minutes. Rapid carbonization might enhance cement hydration and inhibitors; for example, free carbohydrates that retard the hydration of cement lose their effect. The improvement effect of the CO_2 curing method might be due to the accelerated formation of the hydration products (e.g., calcium carbonate and calcium silicate), which were responsible for the strength development of cement. The addition up to 5.0 percent $MgC1_2$ to accelerate the setting of cement did not affect the properties of oil palm fronds cement-bonded board when the board was cured with either gaseous or supercritical CO_2. Therefore, CO_2 curing technology does not need any setting accelerators, which produce a decrease in the dimensional stability of cement-bonded board. CO_2 induced curing was also reported by Jorge et al. (2004). CO_2 injection into the wood-cement furnish provides a method of reducing the pressing

time. Exposure of Portland cement to carbon dioxide reduces the duration of the initial hardening stage.

Bhutta (2010) studied strength properties of epoxy modified concrete cured by steam and heating in different combinations. The effects of accelerated curing on the strengths of hardener-free epoxy-modified mortars were significantly marked. The strengths of accelerated-cured hardener-free epoxy-modified mortars were increased with increasing polymer–cement ratio. The application of heat curing to autoclave- or steam-cured hardener-free epoxy modified mortars caused a significant improvement in their strengths because of the acceleration of epoxy resin hardening reaction in the presence of alkalis or hydroxide ions and the elimination of water in the mortars.

Internal Curing

Kovler and Jensen (2005) reported another two new techniques of curing called internal sealing contributed by Dhir et al. (1994, 1996) and superabsorbent polymers (SAPs) by Jensen and Hansen (2001, 2002). The first method involved curing concrete that did not need externally applied curing, but was not based on adding water to the concrete. These “self-cure chemicals” involved the addition of a water-soluble chemical during mixing that reduced water evaporation from the hardening concrete and also water loss to underlying concrete. These admixtures consisted of water-soluble polymers, having hydroxyl and ether functional groups that enhance water retention in the concrete and thereby increase the degree of hydration. Hydrogen bonding that occurred between these functional groups reduced the vapor pressure of water and decreased evaporation. These admixtures altered the C-S-H gel morphology, reducing the absorptivity of the concrete.

The second method was for prevention of self-desiccation that had been proposed is the use of superabsorbent polymers (SAPs). Most SAPs were cross-linked polyelectrolytes. Because of its ionic nature and interconnected structure, an SAP was able to absorb a significant amount of liquid from its surroundings and retained

the liquid within its structure without dissolving. With present polymer types, the theoretical maximum water absorption was about 5000 times its self-weight. The absorbency of commercially produced SAPs, however, might be around 20 times their own weight in highly ionic solutions such as cement paste pore fluid. The absorption of water in the SAP was based on secondary chemical bonds. The water is so loosely held that essentially all of it could be considered bulk water. During concrete mixing, the particles of SAP formed macro-inclusions containing free water. This free water was consumed during cement hydration, providing internal curing to the surrounding paste matrix and preventing self-desiccation.

2.4 Conclusion

Among the categories of lightweight concrete, lightweight aggregate concrete is subjected to availability of lightweight aggregate in a particular geographical area. However, in some cases artificial lightweight aggregates are also used. Nowadays cellular concrete is getting more and more popular in concrete industry. Aluminium and mechanized foaming is used to produce aircrete all over the world. Previous studies also suggest that improved curing is required to enhance performance of lightweight concrete.

Numerous studies have been carried out all over the world in the field of lightweight concrete and cellular concrete. However, it can be seen from literature review that the new approach applied in this study involving indigenous materials in Bangladesh is perhaps hardly utilized before in the field of cellular concrete.

Chapter 3
IDENTIFICATION OF POTENTIAL INGREDIENTS

3.1 General

As first of this kind in Bangladesh, the effort in this research was focused on the step-by-step progress for the production of lightweight concrete from locally available materials or any other admixture required. First approach was to find out locally available material to produce lightweight concrete. This chapter is aimed to describe the sequential scheme through which the potential ingredients producing aircrete were identified. A database was formed containing all major lightweight concrete research and production since last two decades. Materials in the category of binder, fine aggregate, coarse aggregate, foaming agent, and admixture were identified and tabulated for ease of selection. Potential ingredients for aircrete production were selected in respect of availability, applicability, performance and other technical limitations.

3.2 Lightweight Concrete Practices

Numerous studies have been carried out on lightweight concrete especially in the field of cellular concrete without autoclaving and with autoclaving. From literature, it can be easily concluded that lightweight aggregate concrete can merely achieve density less than 1000 kg/m^3. However, the primary objective of this study is to identify the possible ingredients for producing aircrete. For ease of selection, Table A3.1 of Appendix-1 has been constructed extracting from previous works done in this field. However, production process have not been discussed in the table, rather material options are summarized to compare the past practices. The names of the material are written as cited in the source and categorized in four groups: binder, fine aggregate, course aggregate and admixture.

3.3 Selection of Ingredients

Basic raw materials of aircrete consist of two major types of components: CaO-rich, or calcareous materials including cement, lime, or a combination of the two; and SiO_2-rich, or siliceous materials including sand, sandstone, shale ash, fly ash, or a combination. There are many types of aircrete produced in the world, of which the cement-lime-fly ash and cement-lime-sand products are the most widely manufactured and utilized. Above-mentioned categories are more specifically cover autoclave aerated concrete practices. As first of this kind in Bangladesh, this research was initiated with careful screening of possible options. During selection of ingredients, it was kept in mind that density to be kept close to 1000 kg/m^3.

Among all potential binders, air-setting binders were not suitable due to nonavailability and special preprocessing either in the form of heating or chemical reaction. Best suitable option for our country was to use of hydraulic binder specially Portland cement. Both ordinary and composite Portland cement were suitable for binding the ingredients.

Potential natural aggregates such as pumice, diatomite, scoria were rare in Bangladesh for geographical location. Major geographical land feature of Bangladesh is either sedimentary or metamorphic in nature. Alternative, saw dust was easily available in Bangladesh. Saw dust when combined with cement a number of problems arose such as efflorescence, requirement of special curing environment, compatibility with cement, lower strength than expected etc. (Stahl et al. 2002).

Cork granules were inert with cement but require uniform mixing in the matrix and were not available as abundant; to be imported in large quantity. Husk could be used as filler but its ash was mostly used with cement for its pozzolanic action as binder (Rodrigues et al. 2010). Raw rice husk was not enough to minimize density to obtain the goal.

Crushed brick bats were typically used as coarse aggregate in local construction. It is perhaps the only aggregate of Bangladesh origin having low density than that of other aggregates used in concrete. However, the density of brick aggregate was not that low enough to reduce the concrete density below target level. Cinder, clinker and breeze, foamed slag, boated clay, sintered fly ash, exfoliated vermiculite, expanded perlite, expanded glass aggregate were not the best options of indigenous origin and require processing (sintering, quenching, grinding, cooling etc.) which was not currently available. If used, they should be imported from abroad. Polystyrene fibers provide good filler performance but if used, should be associated with number of admixtures and prefoaming process to stabilize them inside matrix. Furthermore, they were to be imported in large quantity for mass production. Use of waste sludge residue might prove complicated as it requires incineration and/or dewatering and associated with the similar problem as saw dust such as efflorescence, requirement of special curing environment, compatibility with cement, lower strength than expected etc.

From the previous studies discussed in chapter 2, it was evident that natural lightweight aggregates were not the suitable option for making aircrete. All studies involving lightweight cellular concrete (LWACC) discussed so far are Tonyan and Gibson (1992), Latona et al. (1997a, 1997b), Neufeld et al. (1994), Hu et al. (1997), Hunaiti et al. (1997), Huang et al. (2001), Zhihua et al. (2005), Qingjun et al. (2005), Dunaeva et al. (2006), Doniec et al. (2008), Nambiar and Ramamurthy (2008a, 2008b, 2009) and Rodrigues et al. (2010). Other than Qingjun et al. (2005), all studies were reported to exclude coarse aggregate in their respective mix designs. Qingjun integrated expanded shale and expanded clay as coarse aggregate in mix design. Aircrete or cellular concrete is by definition lighter than lightweight aggregate concrete. Cellular concrete mostly associated with mechanically/chemically induced voids. Complexity might arise due to use of large size aggregates in low viscous foamy or honeycomb matrix. Resistance to fracture line propagation by course aggregate had a little to do in this scenario. As cited in Nambiar et al. (2008a), the strength prediction models by researchers are shown in

Table 3.1. It could be seen that course aggregate is not in the composition list of foam concrete and aerated concrete.

Fine aggregate used in the past practices is limited to very fine sand/microsilica, fly ash, cenospheres, silica fume for lightweight aggregate concrete. Previous practices suggest no fine or small sized quartz was used to produce lightweight cellular concrete.

Table 3.1: Summary on strength prediction models on aerated and foam concrete

Author	Type of Concrete	Material composition	Remarks
Hoff	Foam Concrete	Cement paste	Based on Balshin's model Single strength-porosity relation is possible by combining space occupied by evaporable water and the air voids
Kearsley and Wainwright	Foam Concrete	Cement paste with and without fly ash replacement	Based on Hoff's model (extension of Balshin's model). Hoff's model can be effectively used to predict the compressive strength of foam concrete made of different fly ash replacement levels and densities at different ages.
Narayanan and Ramamurthy	Aerated Concrete	Cement mortar with and without fly ash replacement for fine aggregate	Based on Balshin's model and Powers' gel-space ratio equation. Separate relations have been proposed for nonautoclaved and autoclaved aerated concrete.
Tam et al.	Foam Concrete	Cement mortar	Based on Feret's and Powers' equation Feret's formula provides a good relationship with strength. The relationship is improved when degree of hydration is introduced through Power's gel space ratio.
Durack and Weiqing	Foam Concrete	Cement mortar with sand and fly ash as fine aggregate	Based on Power's gel-space ratio concept. For mixes with lower density ranges

Latona et al. (1997a, 1997b), Neufeld et al. (1994) and Hu et al. (1997) practiced inclusion of lime with cement and sand to produce cellular concrete. Lime being

calcium rich oxide forms calcium silicates along with silica in pressure curing situation. In addition, property of lime to exhibit volumetric expansion can be utilized in this study. Product of hydration of lime; calcium hydroxide can be used to react with foaming agent (aluminium powder) to produce hydrogen gas.

Two types of foaming agents are used in past practices. First ones are surfactants which when present in small amounts in solution facilitate the formation of foam and ensures stability by preventing collapse. These surfactants can be either natural or synthetic based, and ionic or non-ionic. Applicability of these foaming agents was subjected to mechanical preprocessing that required adoption of new equipments. The scheduled time and scope of this study did not allow the procurement of foam generator.

Second option that was used by Latona et al. (1997a, 1997b), Neufeld et al. (1994) and Hu et al. (1997) was generation of the cellular structure in aircrete with aluminum powder being most popular now in aircrete industry. It was used widely throughout the world for purposes of product density modification.

Almost all practices earlier in this field incorporated number of admixtures. Most commonly used ones were plasticizer and viscosity modifying admixture. Tonyan and Gibson (1992) suggested the use of a plasticizer to reduce the water/cement ratio of the mix while maintaining stable foam. Cellular concretes involve low viscosity that may lead to segregation of ingredients. Thus, it was necessary to increase paste’s viscosity with a viscosity-modifying admixture.

It can be concluded that a binder (OPC or PCC), local sand (Local sand and Sylhet sand), lime to enhance performance of aluminium, a foaming agent preferably aluminium as non-mechanized foaming process would be applied and any other admixture if required were main ingredients of this study.

3.4 Laboratory Investigation of Ingredient Properties

Materials identified from previous discussion and literature review were tested for properties in the laboratory. ASTM and British standards were utilized while investigating the materials properties. Furthermore, if test of any parameter was beyond laboratory capability, standard reference sources were mentioned as provided by the manufacturer or import authority. Detail investigation of materials used in this study is described below:

3.4.1 Binder

Lightweight concrete can be prepared from all kinds of binding materials discussed in the preceding chapter, their choice being governed by a host of factors: required strength of concrete, specified durability under given working and hardening conditions and availability. Due to availability and performance suitability, Portland cement and its varieties were used as potential binder for lightweight concretes for almost all autoclaving and non-autoclave hardening. Other binding materials (lime-slag, lime-pozzolana, and lime-cinder) were used chiefly for non-autoclaved products. Binding materials were chosen with due regard for hardening conditions of items (natural hardening, steam curing, autoclaving, etc.).

As prime binder in this investigation, commonly available cement CEM I (BDS EN 197-1); Ordinary Portland Cement (OPC) and CEM II (BDS EN 197-1); Portland Composite Cement (PCC) were used. Both cements were tested for initial setting and final setting time (ASTM C 191), fineness (ASTM C 204) and compressive strength (ASTM C 109). Initial setting time of OPC and PCC were 120 and 135 minutes respectively whereas final setting time was 285 and 295 respectively. Specific gravity of cement was 3.0. Fineness value of OPC and PCC by Blaine's Apparatus was 330 and 305 m^2/kg respectively. 3-days, 7-days and 28-days compressive strength were 18, 25 and 34 MPa for OPC and 17, 21 and 30 MPa for PCC respectively. Variation of strength of OPC and PCC is shown in Figure 3.1.

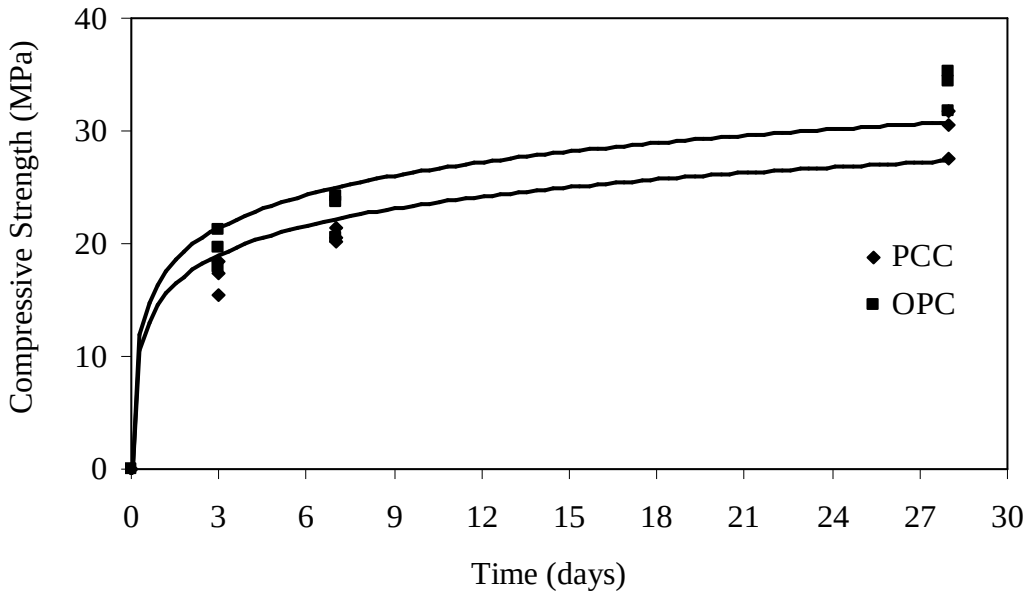

Figure 3.1: Compressive strength of OPC and PCC

3.4.2 Fine Aggregate

Among the available sands of Bangladesh, Local sand is widely used as finer contribution in concrete. It is chiefly river sand dredged up commercially. This variety of sand is fine, round and polished. It is white in color and most suited for plastering and mortar works.

Sylhet sand is relatively coarser than that of Local sand or any other sand available in Bangladesh. This type of sand is sharp, angular, porous and free from salts. It is brown or yellowish in color. This sand is widely used in concrete for higher strength with coarse stone aggregate.

Along with Local sand, basic physical properties were determined for Sylhet sand used for this research. Unit weight was measured as per ASTM C 29, specific gravity and absorption capacity were determined conforming ASTM C 128 and sieve analysis was conducted conforming ASTM C 136 (see Table 3.2). Sands were washed before use in experiments to remove impurities. Grading of Local sand and Sylhet sand are shown in Figure 3.2.

Table 3.2: Physical properties of Sylhet Sand and Local Sand

Property	Local Sand	Sylhet Sand
Specific Gravity (OD)	2.14	2.43
Specific Gravity (SSD)	2.33	2.56
Apparent Specific Gravity	2.63	2.80
Absorption Capacity (percent)	8.67	5.4
Loose Unit Weight(kg/m^3)	1346	1464
Compact Unit Weight (kg/m^3)	1484	1583
Fineness Modulus	1.02	2.69

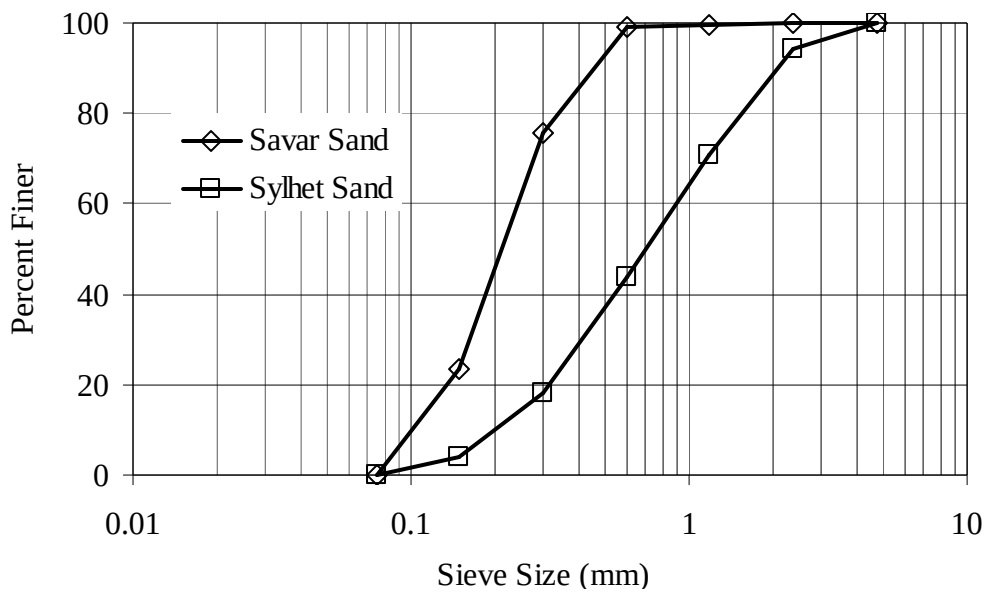

Figure 3.2: Gradation curve of Local Sand and Sylhet sand

3.4.3 Coarse Aggregate

Main source of coarse aggregate in our country is crushed natural stone obtained from local sources like Jafflong and Volaganj in Sylhet and crushed brick aggregate. Study by Shamsuddoha et al. (2009) showed that Volagonj crushed stone has specific gravity of 2.59. Due to low specific gravity, crushed brick has an upper hand over crushed stone as potential ingredient of lightweight concrete. Furthermore, use of high-strength and high-density stone chips in low-density and low-strength concrete is not a justified option.

Crushed brick aggregate of specific gravity 2.15 and absorption capacity 21 percent (ASTM C 127), abrasion value 54 percent (ASTM C 131) and crushing value 53 percent (BS 812: 110) was used by grading it between 19 mm and 12 mm with a ratio of 1:1.

3.4.4 Lime

Hydrated lime appears to have fineness (particle size) not unlike that of flour. Limestone (calcium carbonate), which is used to produce quicklime (calcium oxide), has a rhombohedral crystal structure. Quicklime when reacts with water takes away 32 percent water by the mass of CaO (Komar 1979). This process is called slaking of lime. Reaction of slaking is given in Equation 3.1. The rate of slaking is increased by elevated temperature. The resultant hydrated lime (calcium hydroxide) has a hexagonal crystal structure, which expand volumetrically than the original cubic structure of quicklime (Ghosh, 1991). As the quicklime-water reaction takes place, quicklime swells and occupies more volume. On the other hand, cementation property is reduced when lime content is increased in concrete. As discussed by Aziz (1995), cementation index is a parameter stating cementation capability. Cementation Index = (2.8 Silica +1.1 Alumina + 0.7 Oxides of Iron) / (Lime+1.4 Magnesia). Thus, if strength is compromised, at some extent volume can be increased which may be useful to produce cellular concrete.

$$\underset{Unslaked\ Lime}{CaO} + \underset{Water}{H_2O} = \underset{Slaked\ lime}{Ca(OH)_2} + \underset{heat}{65.5kJ} \tag{3.1}$$

Locally available unslaked lime is used as an option for volumetric expansion. Unslaked local lime was finely ground to get fine powder. Specific gravity of lime was 2.4 (ASTM C 110). To ensure uniform fineness, ground lime was screened through #200 ASTM sieve.

3.4.5 Aluminium Powder

Aluminium is non-toxic, non-magnetic, low-dense, corrosion resistant, non-combustible, easily workable and decorative metal. It is a Group IIIA metal with atomic number of 13. Aluminium is a light metal with a specific weight of 2.7 g/cm^3, about a third that of steel. Aluminium powder was the prime void intruder in this research. Pure aluminium reacts with water to produce hydrogen gas (Haque and Alam 2007, Rosa 2009). Reaction of aluminium powder with water is shown in Equation 3.2. At elevated temperature, usually more than 280^{0}C, Aluminium Hydroxide can be activated to produce hydrogen gas.

$$\underset{\textit{Aluminium Powder}}{2Al} + \underset{\textit{Water}}{6H_2O} = \underset{\textit{Aluminium Hydroxide}}{2Al(OH)_3} + \underset{\textit{Hydrogen Gas}}{3H_2(\uparrow)} \tag{3.2}$$

As mentioned by Tonyan and Gibson (1992), another useful reaction producing hydrogen gas can be triggered if product of Equation 3.1 is mixed with aluminium powder as shown in Equation 3.3.

$$\underset{\substack{\textit{Aluminium}\\ \textit{Powder}}}{2Al} + \underset{\textit{Hydrated Lime}}{3Ca(OH)_2 + 6H_2O} = \underset{\substack{\textit{Tricalcium}\\ \textit{Aluminate Hydrate}}}{3CaO\ Al_2O_3\ 6H_2O} + \underset{\textit{Hydrogen Gas}}{3H_2(\uparrow)} \tag{3.3}$$

Thus, hydrogen gas can be produced if aluminium powder is used and the production of hydrogen can be enhanced if lime (slaked/unslaked) is added. Unslaked lime is expected to contribute to volumetric expansion in the form of swelling caused by hydration of lime.

Aluminium powder containing 99.9 percent assay of MERCK (Germany) and Lubachemie (India) were used to get desired void intrusion. This Hydrogen gas bubbles when entrapped in fresh concrete occupies spaces. After a concrete hardens, they form permanent voids resulting low unit weight. However, strength reduces due to formation of Aluminium Hydroxide and void intrusion.

3.4.6 Plasticizer

Zhihua et al. (2006) has successfully introduced plasticizer to produce high performance foamed concrete. Plasticizer was used to reduce water-cement ratio and to stabilize the bubbles produced by reaction between aluminium powder and water. As available plasticizer, Sika Plastiment R-1 of Sika India Pvt. Ltd. was used.

3.4.7 Viscosity Modifying Admixture

Study by Morency and Paradis (2006) showed that Viscosity Modifying Admixture (VMA) could aid to produce lighter mix with desired workability. This property of viscosity modifying admixture can stabilize the bubbles inside the matrix. Due to low viscosity as associated with high water content, a viscous modifying admixture from BASF, UK; Glenium Stream 2 was used. This admixture conform guideline by EFNARC (2006).

Chapter 4
FEASIBILITY OF AIRCRETE PRODUCTION

4.1 General

By definition, aircrete should contain cellular distributed voids, which eventually reduces density of concrete. This chapter provides feasibility statement of producing aircrete from previously selected potential ingredients. Ingredients identified in chapter 3 were mixed sequentially to observe intrusion of void. Next approach was to mix above materials to ensure low density concrete mass. To make concrete lighter, void must be included by any means. Lime and aluminum powder were introduced to get desired voids. Any other factors that could be identified for future optimization were also investigated.

4.2 Floating Concrete Bowl Investigation

Before going to sequential feasibility study, based on previous literature, a mixture of cement and water with aluminium powder was prepared and allowed to harden. Weight of cement was 3000 gm (882 kg/m^3) and water was 2400 ml (706 kg/m^3). Aluminium powder mixed was 50 gm (cement-aluminium ratio 60). The resulted aircrete bowl formed a mass that floated on water continuously. Figure 4.1 exhibits the bowl shaped aircrete floating on water and capable of bearing 50 steel mm cubes on it. This optimistic aircrete floating show suggested that cellular concrete with density less than 1000 kg/m^3 was feasible.

However, the investigation was a fancy and arbitrary approach to check the optimistic feasibility. The cement content was too high as no aggregate was included. Even though, this aircrete bowl suggested the possibility of producing concrete lighter than water.

Figure 4.1: Floating aircrete bearing 50 mm cube mortar

4.3 Aircrete with Polystyrene Beads

Polystyrene bead was used by many researchers incorporating with pre-formed foam. Bead was mixed with foam and cement slurry by high-speed mixer. Considering its potential, sample with polystyrene beads was prepared. 1000 gm of cement was mixed with 20 gm bead and thoroughly mixed. Aluminium content was 20 gm (cement-aluminium ratio 50).

Resulted aircrete floated on water but being lighter in weight polystyrene beads pushed upward and occupied upper half of the specimen. This phenomenon suggested that polystyrene beads if not mixed mechanically with foam and viscous admixture might result in non-homogenous mass. Other than above disadvantage, polystyrene beads gave soft texture in the surfaces allowing punching by finger or nail. Cross section of resulted aircrete mass with polystyrene beads is shown in Figure 4.2.

(a) Cross section of aircrete containing polystyrene beads

(b) Rough texture caused at top surface of aircrete block by upward heaving of polystyrene beads.

Figure 4.2: Aircrete incorporating polystyrene beads

4.4 Existing Mix Design Guidelines

ACI 213 (2003) provides with proportioning of lightweight aggregate for producing lightweight aggregate concrete. This guideline recommends two proportioning methods: absolute volume method and volumetric method. In using the absolute volume method, the volume of fresh concrete produced by any combination of materials was considered equal to the sum of the absolute volumes of cementitous materials, aggregate, net water, and entrained air. Proportioning by this method requires the determination of water absorption and the particle relative density factor of the separate sizes of aggregates in an as-batched moisture condition. The principle involved was that the mortar volume consists of the total of the volumes of cement, fine aggregate, net water, and entrained air. This mortar volume should be sufficient to fill the voids in a volume of rodded coarse aggregate plus sufficient additional volume to provide satisfactory workability. This is the most widely used method of

proportioning for normal weight concrete mixtures. Displaced volumes are calculated for the cement, air, and net water (total water less amount of water absorbed by the aggregate). The remaining volume is then assigned to the coarse and fine aggregates. This factor may be used in calculations as though it were the apparent particle relative density and should be determined at the moisture content of the aggregate being batched.

Second method recommended is the volumetric method, which consists of making a trial mixture using estimated volumes of cementitious materials, coarse and fine aggregates, and sufficient water to produce the required slump. The resultant mixture is observed for workability and finishability characteristics. Tests are made for slump, air content, and fresh density. Calculations are made for yield (the total batch mass divided by the fresh density) and for actual quantities of materials per unit volume of concrete. Necessary adjustments are calculated and further trial mixtures made until satisfactory proportions are attained. Information on the dry-loose bulk densities of aggregates, the moisture contents of the aggregates, the optimum ratio of coarse-to-fine aggregates, and an estimate of the required cementitous material to provide the strength desired can be provided by the aggregate supplier.

ACI 523 (1993) guided mix proportioning for preformed foam cellular concrete. This mix proportioning begins with the selection of the unit weight of the plastic concrete (wet density), the cement content, and the water-cement ratio (water-cement). The choice of these parameters is usually made after a study of requirements such as compressive strength and thermal conductivity. The mix can then be proportioned by the method of absolute volumes. The sum of the absolute volumes of cement, water, and aggregate for unit volume gives the volume of air required per cubic unit of concrete. The relation between air volume and foam volume is calculated from the foam gun calibration data as the ratio of foam volume per minute to air volume per minute. The weight of water calculated from the cement content and water-cement should be reduced by the weight of the foam volume (considered as water). The amount of foaming agent required varies with

speed of mixing, character of mix ingredients, type of agent employed, and other considerations. Manufacturers' recommendations should be referred to for guidance with the particular agent selected. Detail of mix design by ACI 523 (1993) is illustrated in the form of flow chart in Figure 4.3. ACI 523 (1996) does not provide us with mix design guideline rather practice outlines for design and fabrication of precast reinforced cellular concrete less than 800 kg/m^3.

4.5 Modification of Existing Mix Design

Foam output is expressed in volume per unit time of operation of foam generator. Foam volume generation, being mechanized, can be controlled and exact required volume of void can be introduced in the matrix. For known void volume, its contribution could be incorporated in the matrix. When associated with foam generation by aluminium powder, its limitation lied within uncertain void intrusion by aluminium-water and aluminium-lime reaction. Therefore, mix design guided by ACI 523 (1993) could not be applied for this study. Assumption of modified mix design deals with simple specific volume utilization with cement, aggregate, lime, water and aluminium powder when applicable. Amount of void inside the matrix was not taken into consideration in the fresh density calculation. Void inside fresh mix was treated as volumetric expansion added with post-reaction volume change. Contribution owing to volume change due to entrapped air, volumetric expansion and chemical reactions was expressed by the term 'Expansion Index'. Expansion Index (EI) is the ratio of design density of mixed concrete to hardened density of expanded concrete.

Fresh density of mixed concrete could be found from summation of weights of ingredients contributing to specific volume (unit volume) whereas expanded obtained density of concrete from mass per controlled volume of mold. Actual laboratory mix weights of ingredients can be found form the Equation 4.1.

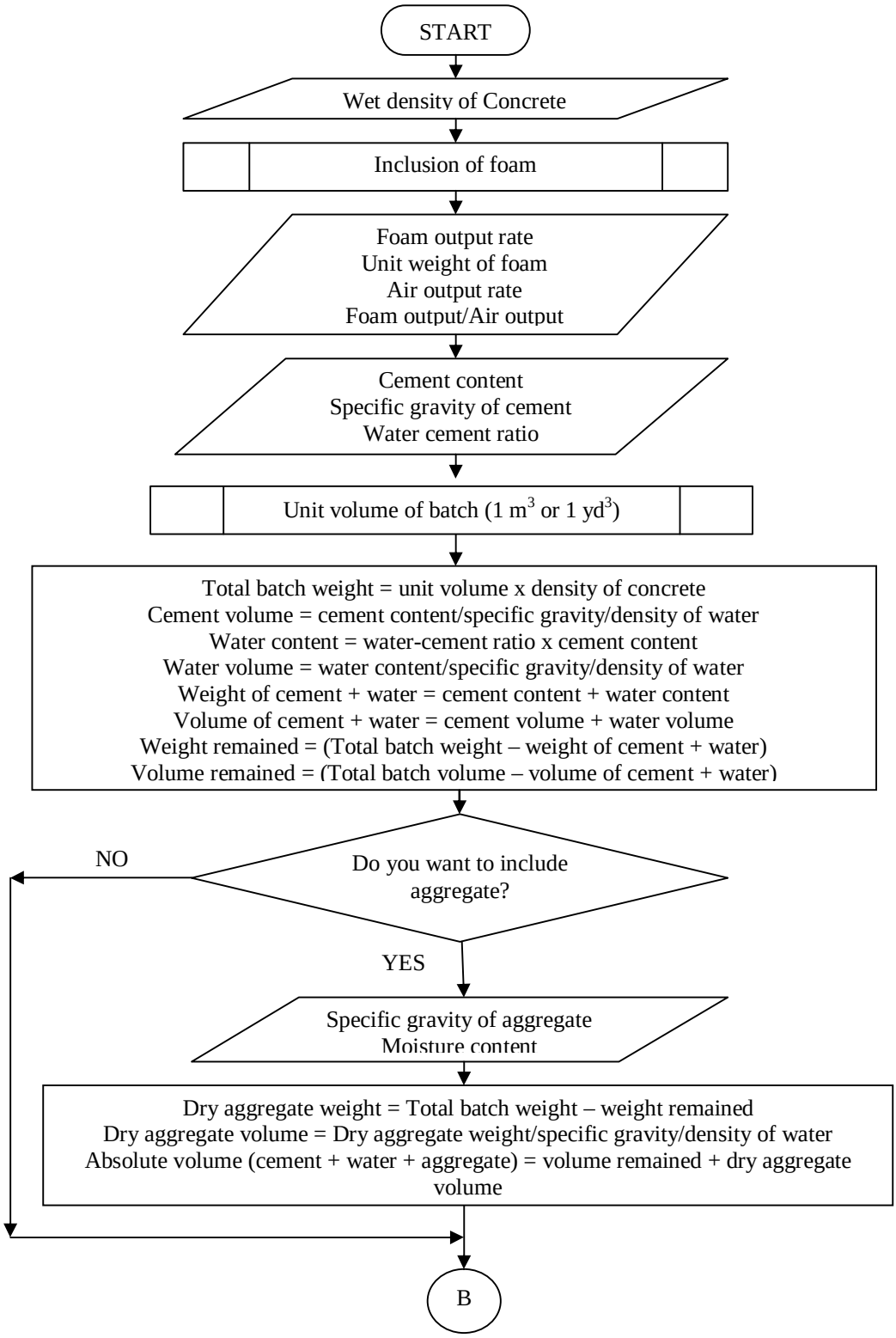

Figure 4.3: Mix design for cellular concrete according to ACI 523 (1993)

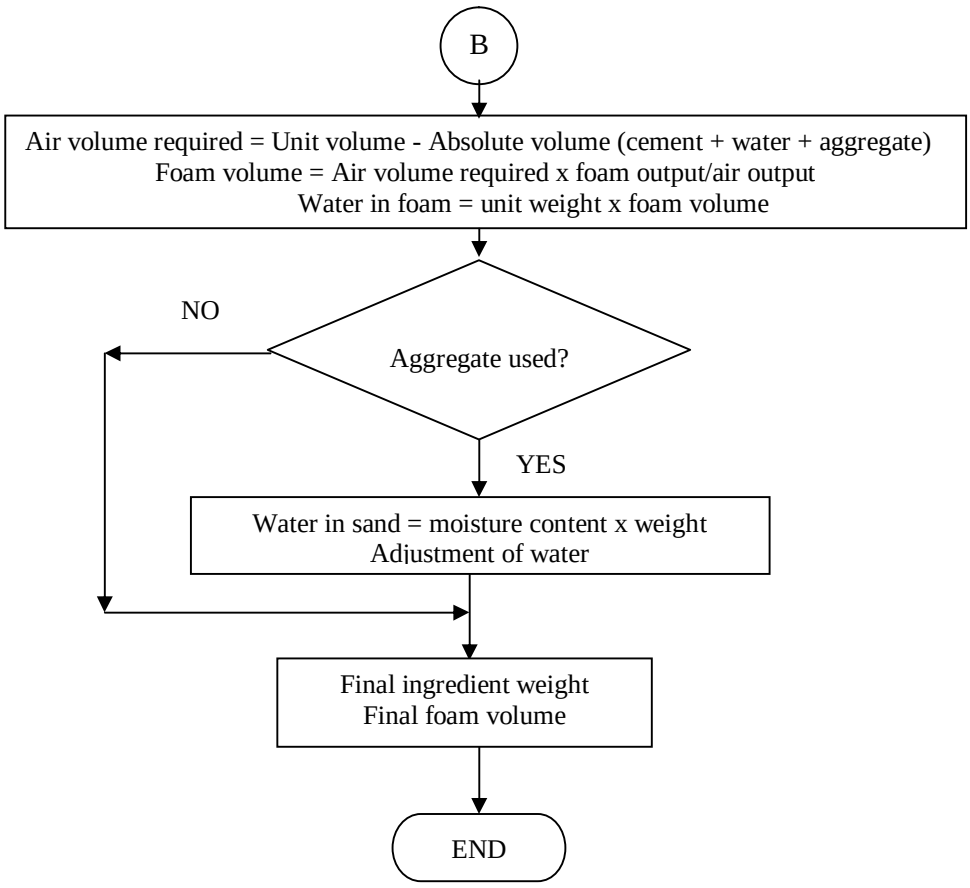

Figure 4.3: Continued…

$$\Sigma \frac{W_i}{S_i \times \rho_{water}} = 1 \tag{4.1}$$

Here,

W_i = Weight of i material in kg and S_i = Specific Gravity of i material.

The generalized equation was used to ease the mixture matrix formation and to obtain more localized material applicability. However, the concept of expansion index was expected to predict the product density for particular mixture matrices. Outline of modified mix design is shown in Figure 4.4 in the form of flow chart.

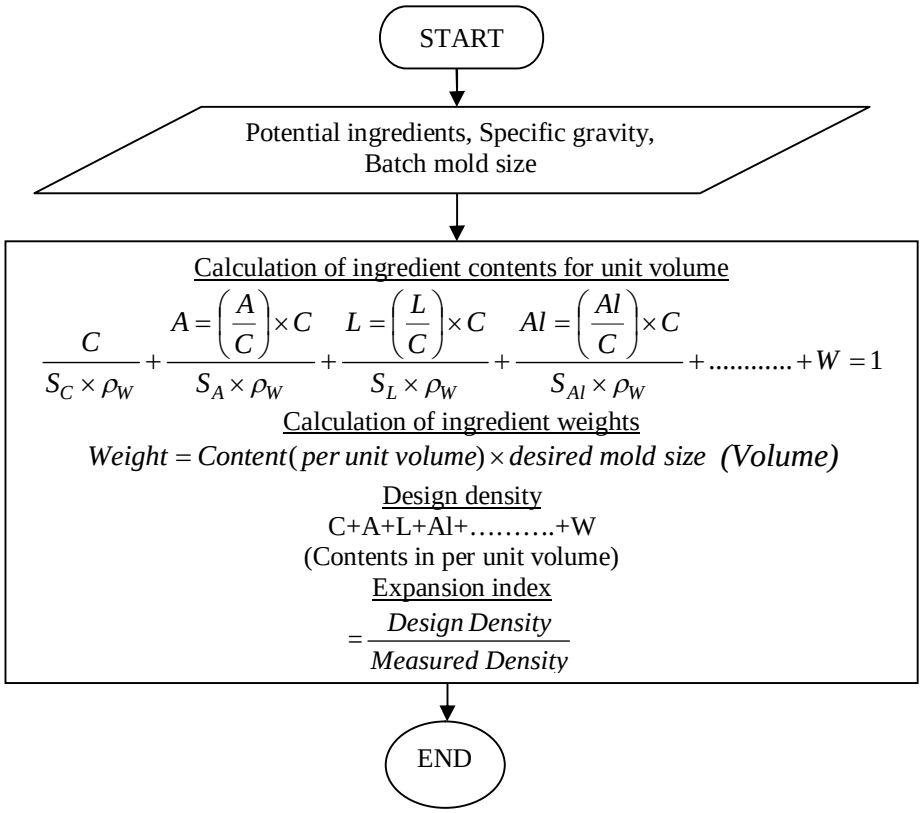

Figure 4.4: Modified mix design

4.6 Feasibility Bands

As mentioned earlier, aluminium reacts with water and lime to form hydrogen gas. “Trial and Error” method was utilized for the production of lightweight mortar from locally available materials. Series of mix combinations were prepared to optimize the goal. No admixture was used in feasibility band to visualize the lower boundary of performance. First band was constructed to observe the void intrusion by aluminium powder in the cement matrix. This band was named FB-1 where FB stands for Feasibility Band. Aluminium content was expressed as percentage of aluminium to cement by weight (A). Water-cement ratio (W/C_1) was kept constant at a value of 0.60 Water and cement were mixed together in absence of other ingredients. Here, W is water content and C_1 is Portland Composite Cement (PCC) in kg/m^3. Owing to absence of other ingredients, water and cement content were

high compared to usual practice of concreting. However, this study was preformed in the aim of identifying aluminium content to get desired void intrusion. Cement-aluminium ratio 50 and 100 was used for these bands. During band formation, specific volume principle was used as mentioned earlier in this chapter. To make a comparison, constant sand-cement ratio (S_1/C) 1.5 was used in this research as this ratio is widely used in normal weight concrete. S_1 expresses local sand content in kg/m^3. Feasibility band; FB-2 was selected to visualize initial condition of mortar mixture without compaction and expansive agent for varying water-cement ratio from 0.40 to 0.85. Mix proportion FB-3 and FB-4 were implemented to observe the effect of aluminium and lime respectively. The detail of mix proportions are reported in Table 4.1.

Table 4.1: Summary of mix designs for feasibility study

Mix Band	S_1/C_1	C_1/L	W/C_1	A (% of cement)	Mold Size
FB-1	-	-	0.60	0.20-3.125	50 mm
FB-2	1.5	-	0.40-0.85	-	50 mm
FB-3	1.5	-	0.40-0.85	2.0	50 mm
FB-4	1.5	4.0	0.40-0.85	2.0	50 mm
FB-5	1.5	4.0	0.60-1.20	1.0	150 mm
FB-6	1.5	4.0	0.75-1.20	2.0	150 mm

To enhance accommodation of volumetric expansion, 150 mm cube mold was used in mix band; FB-5 and FB-6 having cement-aluminium ratio 100 and 50 respectively. FB-4 and FB-6 were containing identical mix proportion with different mold capacity (50 mm and 150 mm cube respectively). Cement-lime ratio (C_1/L) was kept constant at 4.0 for bands FB-4, FB-5 and FB-6. L is the lime content in kg/m^3. Water-cement ratio for the mix bands was dynamic due to trial and error approach. On affirmative test results of a band another band was formed and tested.

4.7 Mixing and Molding

As discussed earlier in chapter 3, cellular concrete ingredients mixed by mechanical stirrer with pre-produced foam added either to it or by regular mixing without

mechanical pre-foaming technique. The foaming agent used in this study was aluminium powder, which did not require pre-foaming; moreover foaming technique was not used in this study. Saturated surface dry ingredients were weighted and thoroughly mixed together by hand to ensure uniform distribution of ingredients. Water was measured and mixed with previously prepared powdered mixture. Water was not added at the beginning. Reason was the affinity of aluminium powder and lime to react with water.

50 mm and 150 mm cube moulds where applicable were prepared to accommodate mixture and post mixture volumetric expansion. For the initial stage of feasibility study (FB-1 to FB-4), 2 inch cube sample was used. 150 mm cube sample was used for testing of FB-5 and FB-6. Corner of the molds were made leak proof using grease. Mixture was poured in the mold and allowed to expand. Expansion often occurred beyond mold volume and exhibited uncontrolled volumetric expansion. To avoid this phenomenon, another mold was put up side down. In practical consideration, during production batch size should be such that expansion would not go beyond the mold volume. Samples were taken out of the mold after 24 hours and cut to size. Cubes were then put inside water and allowed to cure under room temperature. Samples were tested after 28 days. Samples were taken out from water 2 days before testing and dried in oven at 110°C temperature for 24 hours. Figure 4.5 shows samples in 50 mm cube of test band FB-3. As seen form the figure, gradual improvement of expansion was evident from left to right.

4.8 Testing of Aircrete Blocks

ASTM C 495 (1999) provides the standard of testing lightweight insulating concrete less than 800 kg/m^3. ASTM C 495 guides to use cylindrical mold of size 3 in diameter and 6 in length. Density of aircrete produced in this study was not limited within this range of 800 kg/m^3 rather went even above 1300 kg/m^3.

ASTM C 39 (2001) designated 6 in diameter and 12 in long cylindrical specimen for compressive strength test for lightweight aggregate concrete. Cylindrical specimen

having higher width (diameter)-height ratio causes narrow passage that hinders volumetric expansion due to surface drag at matrix-mold interface. This phenomenon was evident and discussed later in light of volume surface ratio.

Figure 4.5: Samples of feasibility band FB-3 in 50 mm mold

BS 1881: 116 (1983) guided 150 mm X 150 mm cube samples for determination of compressive strength. However, due to availability and ease of molding 50 mm and 150 mm cube samples were used in this study. Figures 4.6 and Figure 4.7 show 50 mm and 150 mm samples for tests respectively.

Figure 4.6: 50 mm cube samples for test

Figure 4.7: 150 mm cube samples for test

ASTM C 567 (2000) provides procedures for determining oven-dry and equilibrium densities of structural lightweight concrete. This study dealt with cellular concrete, so did not covered by the recommended code of practice. Density was determined by weighing samples of controlled volume.

4.9 Aluminium Content Characterization

Primarily samples of feasibility band were tested for density and compressive strength. From practical and theoretical interpretation discussed in chapter 3, it was evident that indigenous materials identified as potential ingredients of lightweight concrete were not enough to produce required void inside concrete matrix. Thus a bubble intruder; aluminium powder was introduced. Aluminium powder was successfully able to initiate void in the mortar matrix. Details of mix proportion and aircrete properties are tabulated in Table 4.2. Expansion Index of respective mix for FB-1 as ratio of design density to expanded density is shown in the table. Increased aluminium content did reduce the density but subsequently reduced the strength of

hardened mortar as seen from Figure 4.8. Expansion trend was also plotted with density and strength in Figure 4.9. Expansion was associated with reduction of density thereby increment of expansion index. Mirror offset of density and expansion index was expected from theoretical background. Expansion trend suggested that expansion index remained almost plateau (1.61-1.87=16 percent) within cement-aluminum ratio 500-100. For cement-aluminium ratio less than 100, expansion started increasing from 1.87 to 2.83 (51 percent). This graphical trend suggested that void created by aluminium-water and aluminium-calcium oxide would be able to overcome gravitational weight of mixture causing effective expansion.

Table 4.2: Details of mix design and properties of aircrete for feasibility band FB-1

Mix Band	**S_1/C_1**	**C_1/L**	**W/C_1**	**Al (% of cement)**	**Design Density (kg/m^3)**	**Measured Density (kg/m^3)**	**Comp. Strength (MPa)**	**Expansion Index**
FB-1	-	-	0.60	0.20	1714	1066	4.98	1.61
				0.30	1714	1065	4.65	1.61
				0.40	1714	1041	4.36	1.65
				0.50	1714	1035	3.97	1.66
				0.80	1714	953	2.84	1.80
				1.00	1714	917	2.07	1.87
				1.50	1714	836	1.19	2.05
				2.00	1714	685	0.65	2.50
				3.125	1714	606	0.37	2.83

All ratios are by weight

4.10 Results

The bands were formed and tested one after another due to indication given by density trend against water-cement ratio. Results obtained from density measurement and compressive strength tests are summarized in Table 4.3 to 4.7. Design density for a particular mixture was calculated from related material contributions.

Corresponding expansion index was also incorporated for ease of understanding the expansion behavior. Expansion index less than one suggested contraction rather

expansion as in case of band FB-2 and was found in Table 4.3 for no aluminium inclusion.

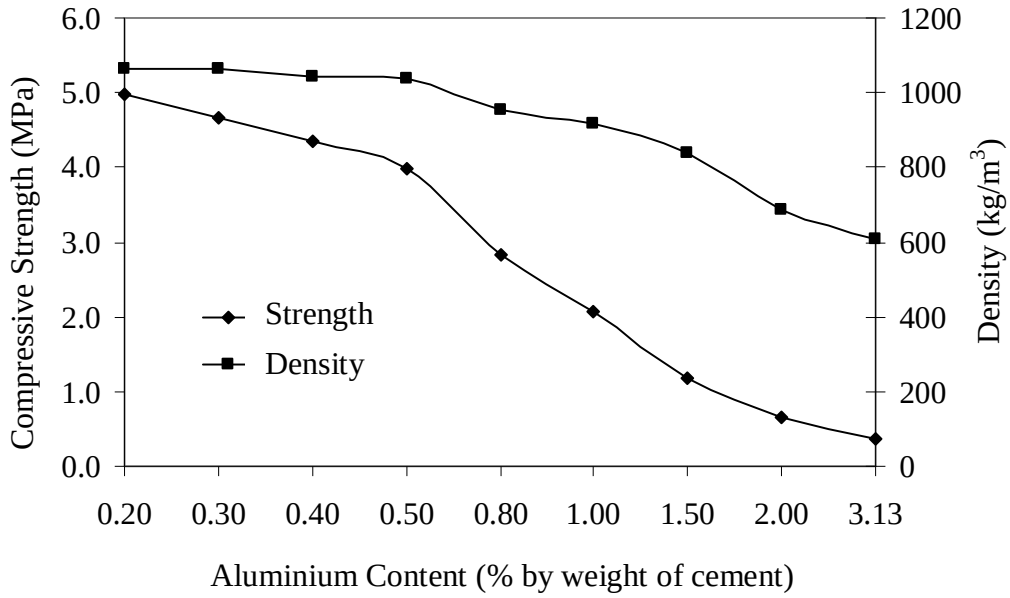

Figure 4.8: Effect of aluminium content on density and compressive strength of mortar

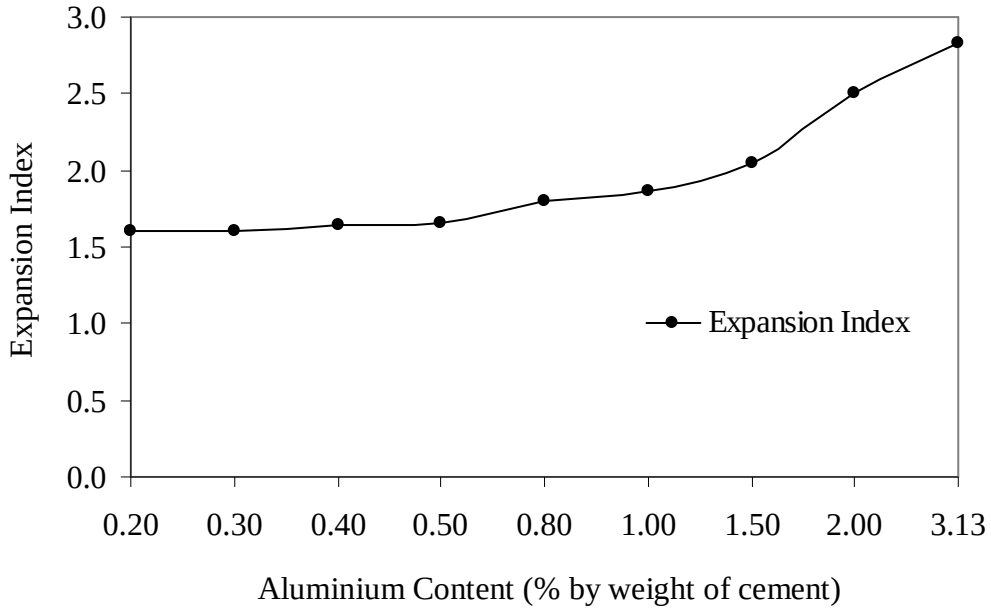

Figure 4.9: Effect of aluminium content on expansion index of mortar

Table 4.3: Details of mix design and properties of aircrete for feasibility band FB-2

Mix Band	S_1/C_1	C_1/L	W/C_1	A (% of cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	Expansion Index
FB-2	1.5	-	0.40	-	2106	1864	8.26	1.13
			0.45		2067	2192	15.44	0.94
			0.50		2031	2136	15.85	0.95
			0.55		1997	2216	15.06	0.90
			0.60		1966	2101	12.14	0.94
			0.65		1936	2091	11.98	0.93
			0.70		1908	2192	8.87	0.87
			0.75		1882	2160	7.96	0.87
			0.80		1857	2064	6.45	0.90
			0.85		1833	2013	4.93	0.91

Table 4.4: Details of mix design and properties of aircrete for feasibility band FB-3

Mix Band	S_1/C_1	C_1/L	W/C_1	A (% of cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	Expansion Index
FB-3	1.5	-	0.40	2.0	2106	1851	5.52	1.14
			0.45		2067	1744	7.99	1.19
			0.50		2031	1829	13.67	1.11
			0.55		1997	1747	10.68	1.14
			0.60		1966	1701	6.32	1.16
			0.65		1936	1627	6.01	1.19
			0.70		1908	1653	6.65	1.15
			0.75		1882	1635	5.00	1.15
			0.80		1857	1488	4.39	1.24
			0.85		1833	1635	4.10	1.12

Comparison of feasibility bands are illustrated in Figure 4.10 and Figure 4.11. With the progress of mix bands from FB-2 to FB-6, density could be reduced to as low as 700 to 1000 kg/m^3 and subsequently strength reduced to 0.50 to 2.0 MPa. Mix proportion FB-2 showed almost plateau density but sharply decreasing strength starting from water-cement ratio 0.50 indicating necessity of bubble intrusion to reduce density. No significant behavior could be characterized below water-cement ratio 0.50. This anomalous behavior might be due to zero compaction provided on the mixture thereby leaving large voids and escaping of generated gas.

Table 4.5: Details of mix design and properties of aircrete for feasibility band FB-4

Mix Band	S_1/C_1	C_1/L	W/C_1	A (% of cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	Expansion Index
FB-4	1.5	4.0	0.40	2.0	2127	1659	2.41	1.28
			0.45		2090	1885	6.21	1.11
			0.50		2055	1939	9.45	1.06
			0.55		2023	1816	8.51	1.11
			0.60		1993	1840	8.66	1.08
			0.65		1964	1725	6.50	1.14
			0.70		1937	1605	4.46	1.21
			0.75		1911	1549	3.49	1.23
			0.80		1887	1363	2.62	1.38
			0.85		1864	1317	2.07	1.42

Table 4.6: Details of mix design and properties of aircrete for feasibility band FB-5

Mix Band	S_1/C_1	C_1/L	W/C_1	A (% of cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	Expansion Index
FB-5	1.5	4.0	0.60	100	1993	1546	4.95	1.29
			0.65		1964	1574	4.62	1.25
			0.70		1937	1405	3.91	1.38
			0.75		1911	1383	3.02	1.38
			0.80		1887	1355	3.38	1.39
			0.85		1864	1263	2.79	1.48
			0.90		1842	1145	2.23	1.61
			0.95		1822	1215	2.78	1.50
			1.00		1802	1189	2.32	1.51
			1.05		1783	1084	2.02	1.65
			1.10		1765	1102	1.32	1.60
			1.15		1748	1093	0.54	1.60
			1.20		1731	1070	0.34	1.62

However, water content played vital role in void stabilization in the matrix. Decreasing trend of density shown by mix proportions FB-2, FB-3 and FB-4 suggested the water cement ratio to higher values to 1.20. Moreover, density below 1000 kg/m^3 was found for water-cement ratio more than 0.90 in mix FB-6. Density of mix band FB-3 containing cement and aluminium powder was within the range of 1600-1900 kg/m^3 whereas density of FB-4 was within 1300-1650 kg/m^3.

Table 4.7: Details of mix design and properties of aircrete for feasibility band FB-6

Mix Band	S_1/C_1	C_1/L	W/C_1	C_1/A	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	Expansion Index
FB-6	1.5	4.0	0.75	50	1911	1071	0.99	1.79
			0.80		1887	1010	1.05	1.87
			0.85		1864	1010	0.97	1.85
			0.90		1842	971	0.91	1.90
			0.95		1822	935	0.68	1.95
			1.00		1802	884	0.61	2.04
			1.05		1783	868	0.59	2.06
			1.10		1765	857	0.68	2.06
			1.15		1748	842	0.42	2.08
			1.20		1731	810	0.39	2.14

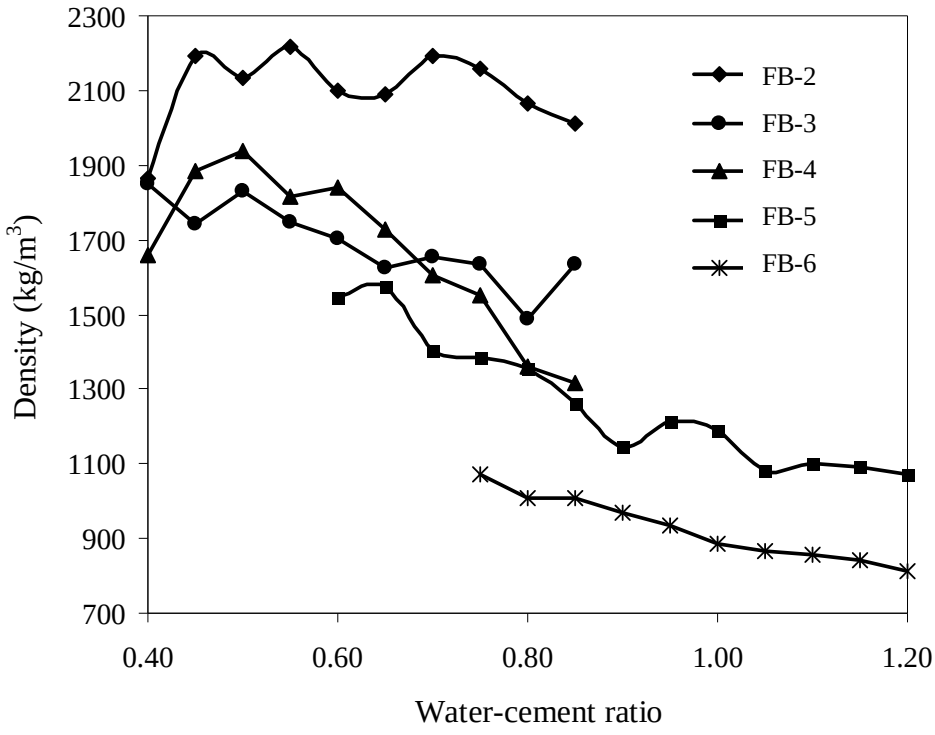

Figure 4.10: Relationship between density and water-cement ratio

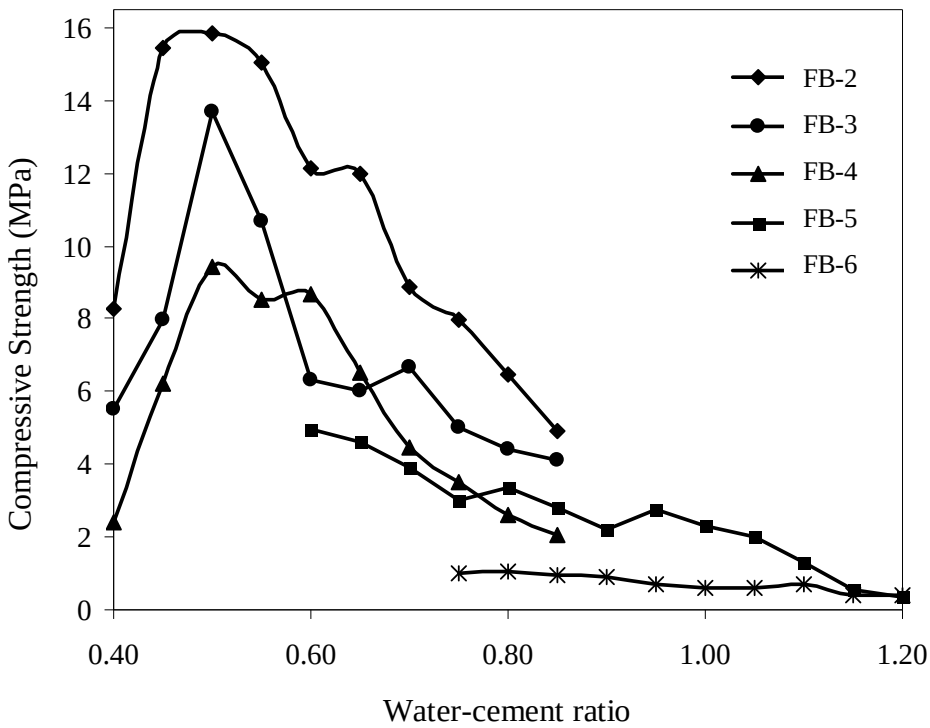

Figure 4.11: Relationship between compressive strength and water-cement ratio

Although having identical mix proportion and ingredients, FB-4 and FB-6 were showing varied volumetric expansion due to increase in volume-surface ratio at a ratio 1:3$\left(\frac{2\times2\times2\text{ inch cube mold}}{5\text{ faces}\times(2\times2)}:\frac{6\times6\times6\text{ inch cube mold}}{5\text{ faces}\times(6\times6)}\right)$.

Increased cement-aluminium ratio; 100 to 50 led to increased volumetric expansion thereby reduced density as seen from the comparison of FB-5 and FB-6. However, from comparison of feasibility bands, density trend was more pronounced to characterize than that of strength.

Voids were not of uniform shape all through the sample. Section of cube samples suggested formation of voids 2 to 15 mm in size forming honeycomb structure which is shown in Figure 4.12.

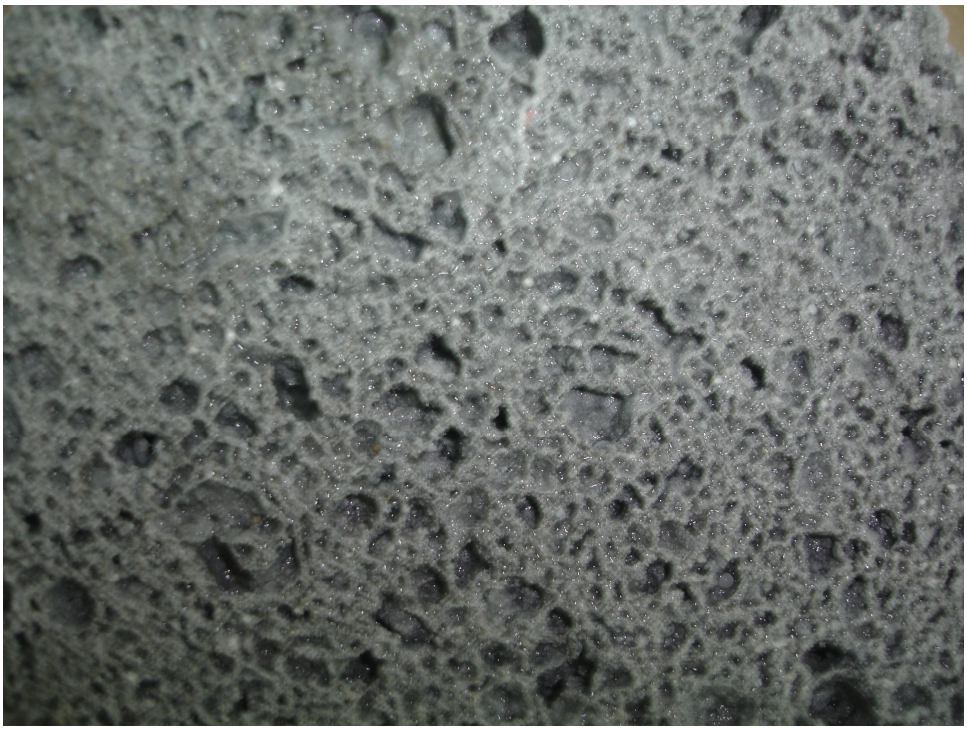

Figure 4.12: Void distribution inside aircrete sample

4.11 Lesson Learnt

A number of observations were noticed during feasibility study of aircrete. These observations are presented below in summarized form for convenience.

4.11.1 Size Effect of Mold

This study was started with 50 mm cube. 50 mm cube mold being smaller in size could be handled and tighten and remolded easily. Besides, material requirement was also less than that of 150 mm cube. Expansion of aircrete matrix naturally supposed to happen in three directions. Cube mold restricted the expansion and forced to swell the matrix in one direction. Drag force exerted by the side walls of mold hindered expansion of flow. It was clearly understood that the narrower the mold, the higher the relative drag. This problem was eliminated by using larger mold to confirm higher volume-surface ratio. However, industrial production of aircrete involves large tray as mold, which reduces surface friction to minimum. Figure 4.13 demonstrates swelling pattern caused by surface drag in mold.

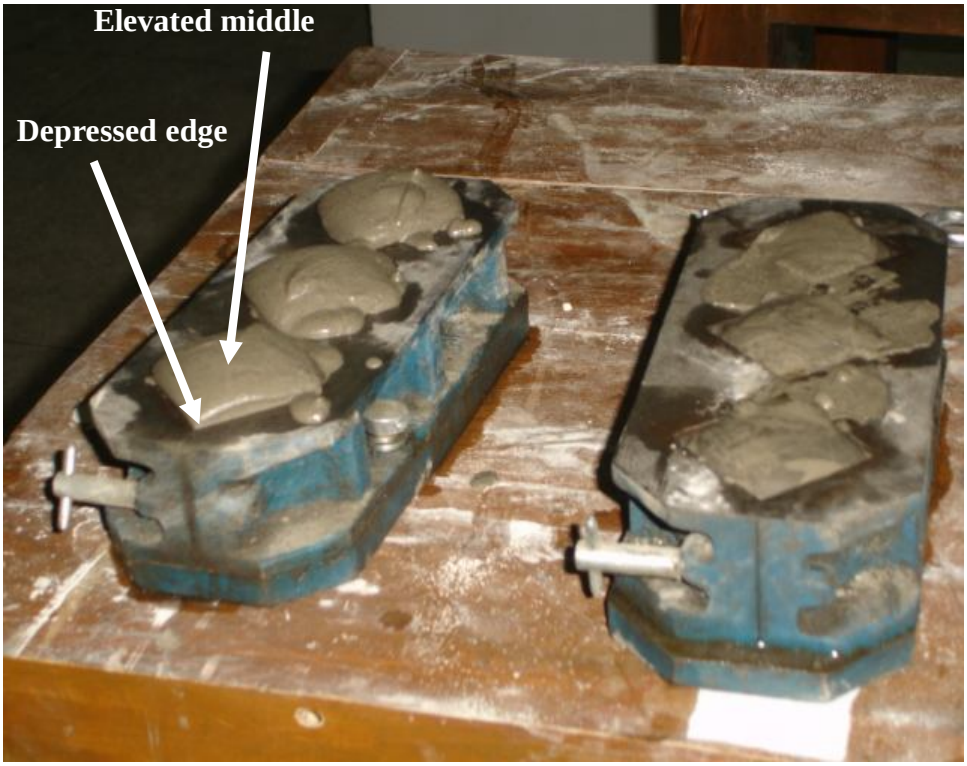

Figure 4.13: Curvature in expanded mortar due to surface drag

4.11.2 Mixing Sequence of Ingredients

First of all, water should be measured to make it available whenever required. Dry sand and cement being inert to each other should be weighed in second and third order where sand should be weighted before cement. Aluminium powder does not react with air and lies in the forth order of weighing. Often, very less amount (5-35 gm) of aluminium is required for samples. It may become complicated to measure such low quantity with usual balance in concrete laboratory. Electric balance may show initial fluctuation due to wind and container effect.

In this study, white, clean and small paper was taken and put on the balance. Small amount (50-100 gm) of cement form the measured sample was taken on the paper and aluminium powder was added very slowly by gently striking the container.

Desired aluminium was ensured by using back calculation before pouring powder on balance with cement [amount of aluminium = (weight of paper + cement + aluminium) – (weight of paper + cement)]. Unslaked lime reacts with moisture in air and advised to weigh last of all. All ingredients other than water should be mixed thoroughly to ensure uniform distribution of ingredients. Water then added and again mixed rigorously before pouring in the mold.

4.11.3 Water Leakage

Molds were tightened well to reduce water leakage during pouring and setting of aircrete as associated with high water-cement ratio. Commercially available grease was used to stop water seepage especially in 150 mm cubes. There are eight contact faces and four top surfaces (if covered by inverted mold) in a cube mold those should be sealed to reduce leakage. Figure 4.14 shows twelve locations where sealing to be done.

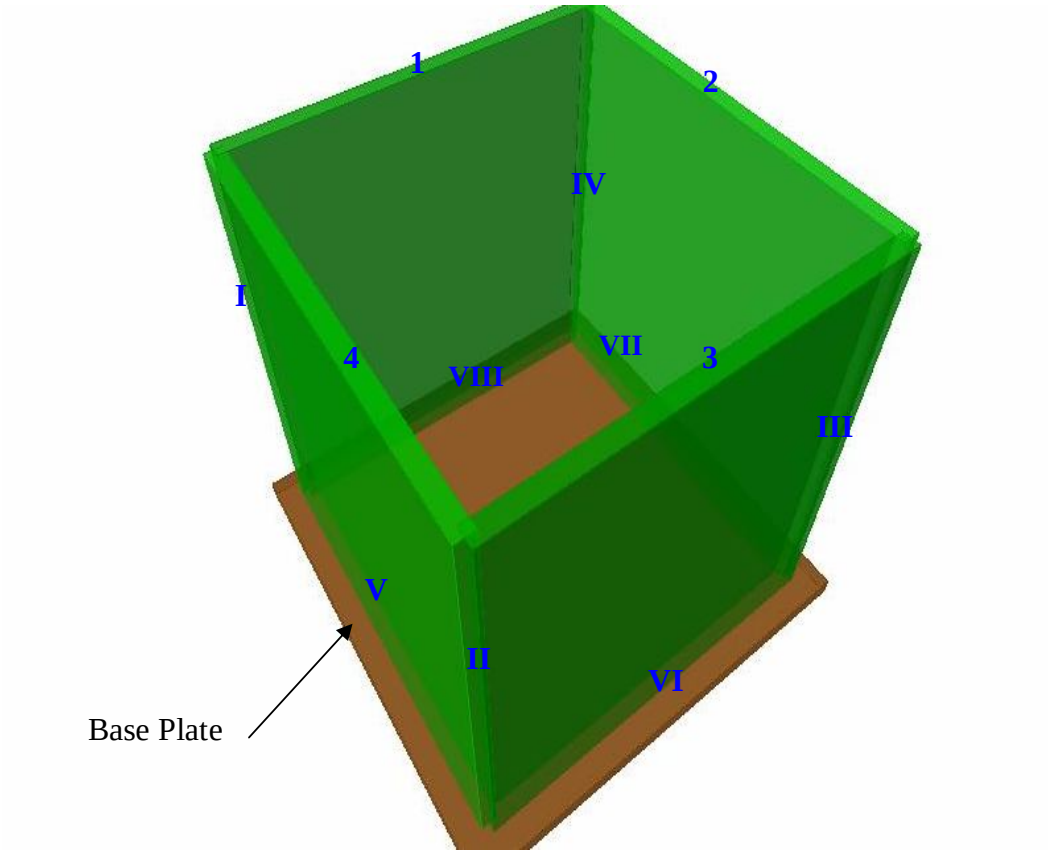

Figure 4.14: Four faces and eight joints of cube for sealing

Location 1, 2, 3, 4 were horizontal and open faced; the rest locations were joints. However, mass production of aircrete is expected to be free of this problem due to use of large mold to accommodate volumetric expansion and ease of removal of samples from the mold.

4.11.4 Accommodation of Expansion

Volumetric expansion often caused swelling and over flew the mold. It was desirable to have volumetric expansion but over flow created aesthetic and cleanliness hazards. Figure 4.15 shows uncontrolled expansion and related cleanliness hazard. To stop swelling outside the mold, another mold was introduced upside down as shown in Figure 4.16 and resulted controlled expansion is thus shown in Figure 4.17.

(a) Volumetric expansion of 50 mm cube samples with 2 percent aluminium

(b) Crack at top of sample due to uncontrolled volumetric expansion in 150 mm cube mold

Figure 4.15: Uncontrolled swelling in 50 mm and 150 mm cube

Figure 4.16: Covering mold to control volumetric expansion

Figure 4.17: Expanded sample after controlled expansion

4.11.5 Loss of Hydration Moisture

As associated with unslaked lime, when ingredients of aircrete mixed with water, rigorous hydration of lime occurs with swelling other than hydration of cement. Slaking of lime was exothermic reaction thus generated considerable amount of heat. Temperature was measured as high as 95^0C. Hydration of lime was observed to occur within first 45 minutes. The above-mentioned heat generated, due to slaking of lime, did aided expansion of aircrete but at cost of loss of water form the expanded matrix leaving brittle low strength cement paste yet to harden. Lack of moisture hindered hydration thus low strength aircrete and often cracked top surface. Figure 4.18 depicts cracked brittle top surface of aircrete. This phenomena lead to the indication that at early stage, concrete suffered dehydration and thereby hindrance in hardening. Resultant was brittle and low strength aircrete. Moisture restoration at this stage might have overcome the problem.

Figure 4.18: Crack on top surface of aircrete due to loss of moisture

4.11.6 Cutting of Aircrete

As associated with high water-cement ratio, segregation due to low viscous matrix was obvious. From visual observation, it was seen that top of the sample was weaker than bottom. Bubble formed in the semi liquid mortar matrix tried to heave up causing relatively dense deposition at the bottom and foamy lighter hardened slurry at the top. This fact was confirmed by cutting samples at 27 pieces of 50 mm samples from 150 mm cube. Section of sample was done by brick cutter machine as shown in Figure 4.19. The aim was to visualize the three dimensional expansion patterns that possibly acted behind low strength of aircrete. This phenomena suggested use of viscous admixture in the concrete.

Figure 4.19: Cutting of 150 mm cube sample into (3X3X3)-50 mm cubes

4.12 Feasibility Statement

After review of all material options and production technique, feasibility of aircrete production was studied. Potential local ingredients and a foaming agent; aluminium powder was chosen due to adoption of non-mechanized, non-prefoam and indigenous technology. Following conclusion can be drawn in light of the feasibility study:

i. Higher volume-surface ratio aided higher volumetric expansion during production of aircrete.

ii. Appropriate range of water-cement ratio to reduce density of concrete was 0.80-1.20. Water-cement ratio less than this range restricted volumetric expansion whereas more than this range reduced compressive strength below performance limit.

iii. After a series of trials comprising indigenous options, density of concrete was able to be reduced within range of 700-1000 kg/m^3. However, strength was very low (0.5-1.0 MPa).

iv. The reasons behind lower strength are high water-cement ratio, less cementation index and foamy honeycomb structure of hardened mortar matrix.

v. Finally, it can be concluded that lightweight concrete is feasible using indigenous materials and foaming agent (aluminium powder) through non-mechanized pre-foaming technique in Bangladesh.

Chapter 5
OPTIMIZATION OF AIRCRETE PERFORMANCE

5.1 General

Feasibility of aircrete had already been studied as discussed in chapter 5 and found to have optimistic possibility in Bangladesh. In the feasibility phase, density and compressive strength had been studied. This chapter addresses mix design characterization and an attempt to apply improved curing condition to aircrete samples for better product quality. Other than density and compressive strength, thermal conductivity and absorption capacity were also determined for the selected samples.

5.2 Optimization Bands without Autoclaving

Aircrete samples produced in feasibility phase contained constant aggregate-cement ratio and cement-lime ratio. Aggregate-cement ratio was taken as 1.5 and cement-lime ratio 4.0 for convenience. However, mix design required variable ingredient ratio for optimization of concrete properties and ease of product selection. Aggregate-cement ratio is more important as aggregate effectively contribute considerable amount of concrete volume. The basis of the mix proportioning was already discussed in earlier chapter. Sylhet sand, coarse aggregate and admixture were included in this phase whereas they were not been utilized in previous effort. A number of bands were formulated containing possible materials options. The bands were formulated to observe the tentative effect of ingredient content on physical properties without autoclaving. Figure 5.1 to Figure 5.4 illustrate four optimization bands that were formed to optimize the properties and to identify the possible zoning of ingredients without utilizing autoclaving. Three by three combinations of water content and cement contents were calculated for ease of plotting and interpretation. Due to inclusion of materials in the mixture, the contents varied. Necessarily, the sand-cement ratios were nearly constant diagonally in the constructed matrices.

Ordinary Portland cement gains strength earlier than that of Portland composite cement. Keeping this behavior of ordinary Portland cement in mind, bands OB-1 to OB-4 were formed using ordinary Portland cement. Local sand was used for band OB-1, OB-3 and OB-4 whereas band OB-2 was constructed using Sylhet sand. Band OB-1 and OB-2 were identical in respect of ingredients having cement-lime ratio of 8. They were constructed to observe the effect of inclusion of sand types available in Bangladesh. Next bands were associated with inclusion of water reducing admixture. Band OB-3 and OB-4 incorporated plasticizer at two different rates to observe its effect. Cement-lime ratio of band OB-3 and OB-4 were kept 4 as practiced in earlier feasibility phase. Water content and cement content were kept within the range of 430-540 kg/m^3. Other ratios of ingredients are shown in parenthesis. Sand-cement ratios were shown in circles. Here, S_1, S_2, C_1, C_2 and L are local sand, Sylhet sand, PCC, OPC, lime content in kg/m^3 respectively. Aluminium content is expressed as A in percentage of cement by weight. P_1 and $P_{0.5}$ denote plasticizer content of 1 and 0.5 ml per kg of cement respectively.

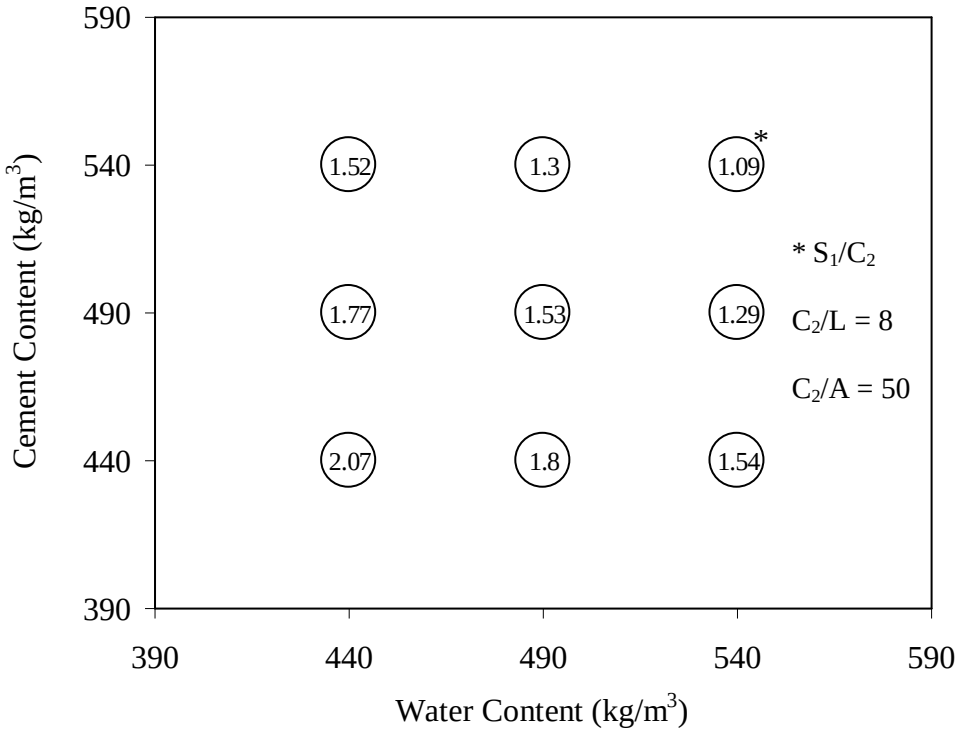

Figure 5.1: Distribution of ingredients in optimization band OB-1

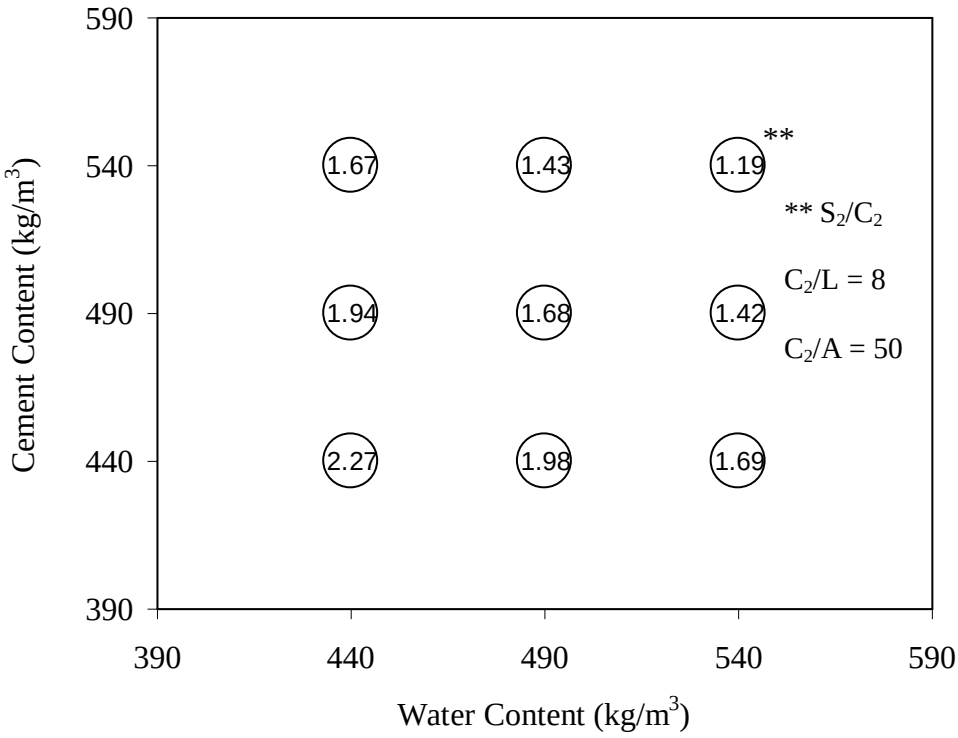

Figure 5.2: Distribution of ingredients in optimization band OB-2

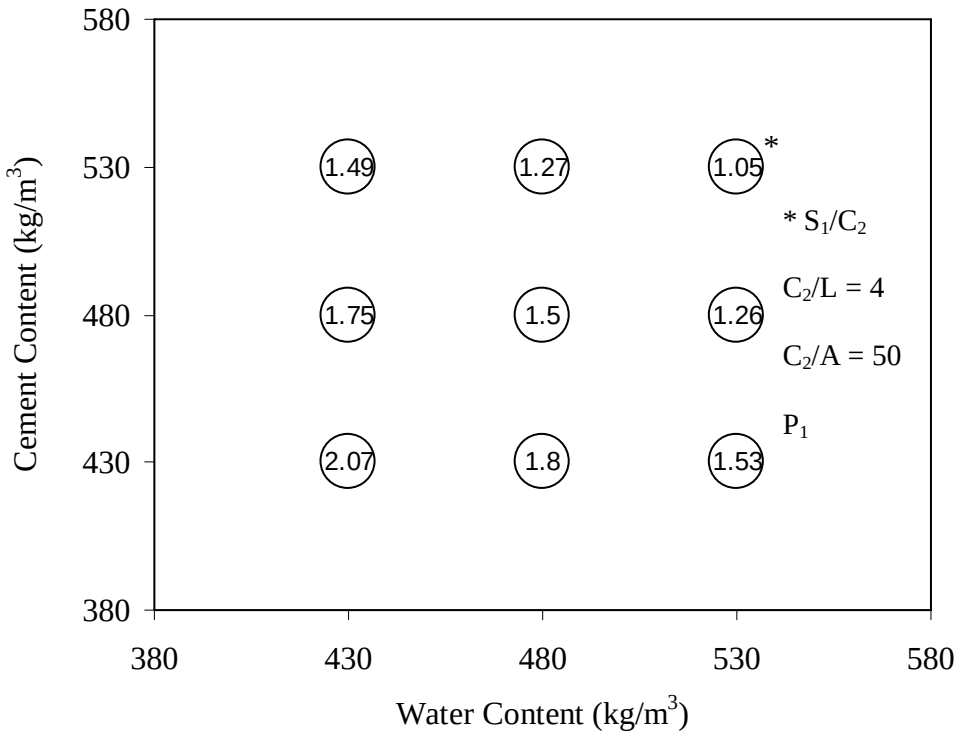

Figure 5.3: Distribution of ingredients in optimization band OB-3

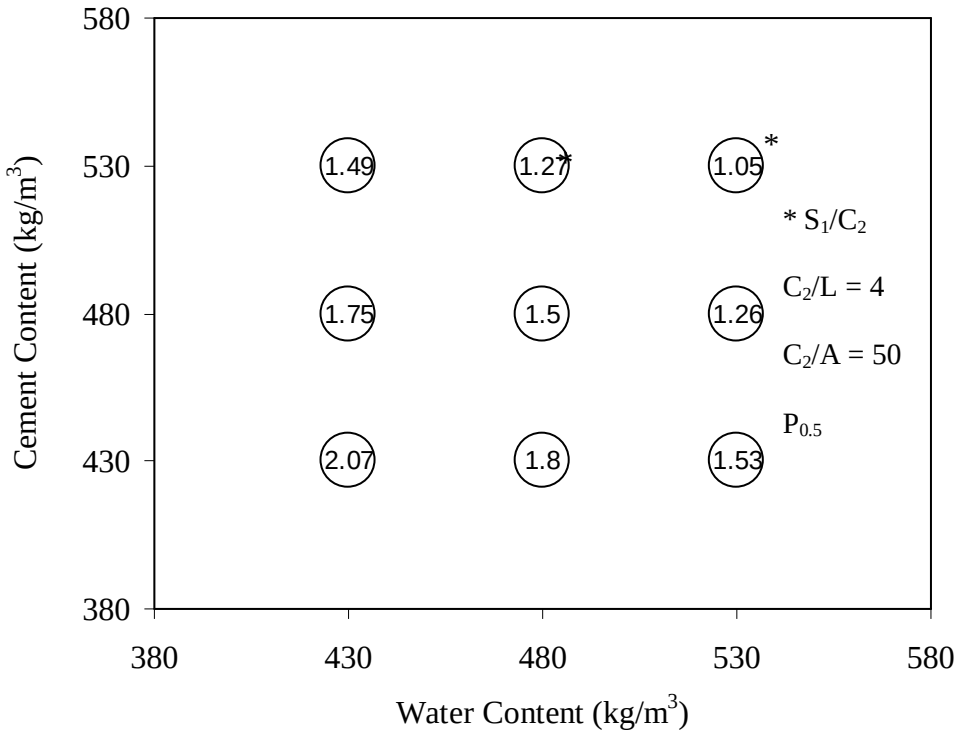

Figure 5.4: Distribution of ingredients in optimization band OB-4

5.3 Optimization Bands with Autoclaving

As discussed earlier, aircrete produced without autoclaving often suffered loss of moisture due to temperature rise associated with hydration of lime and cement. Elevated temperature was attainable in local scenario but controlled pressure curing was difficult to attain. Construction and procurement of such expensive unit of autoclaving chamber was beyond both financial scope and technical knowhow during the study. Therefore, alternative option of curing was adopted.

From literature review, it is seen that special improved curing techniques are often practiced to achieve high early strength. Various forms of steam curing are applied in numerous studies that are practiced in concrete industry (Cordon & Thorpe, 1965; Gebler, 1983; Kovler and Jensen, 2005; Dhir et al., 1994 & 1996; Jensen and Hansen, 2001 & 2002; Yazdani et al., 2008; Forlov et al., 2002; Higginson et al., 1961; Hanson, 1965; Dan et al., 1991; Ke-fang and Nichols, 2004; Cervera et al., 1999; Gesoğlu, 2010; chaini et al., 2005; Hermawan et al., 2001, 2002a & 2002b;

Bhutta, 2010). Curing was mostly applied at the early stage of hardening. However, delay in curing operation often practiced to attain optimum curing cycle (Neville, 2010; Hanson, 1965). Aircrete being susceptible to moisture loss at early age (30-45 minutes); the most required time of moisture restoration by curing was continuously from beginning of the hydration i.e. placing of semi-fluid cement matrix to mold. Local technique of heating and curing was applied for curing. Figure 5.5 to Figure 5.8 demonstrates four bands for autoclaving without application of pressure. Other than cement type (OPC), bands OB-5, OB-6 and OB-7 were identical to OB-1, OB-2 and OB-4 containing PCC. Inclusion of Portland composite cement containing fly ash or other mineral fillers was encouraged by previous works (Dan et al., 1991; Ke-fang and Nichols, 2004; Chaini et al., 2005). Researchers found that incorporation of silica fume, fly ash and slag could reduce the later strength reduction of concrete when cured by stream. Bands OB-5 to OB-8 were cured for 6 hours at a temperature of 85-95^{0}C which was denoted as VC. OB-8 contained viscosity modifying admixture (VMA) at a content of 10 ml per kg per cement and expressed in the term of VMA_{10}.

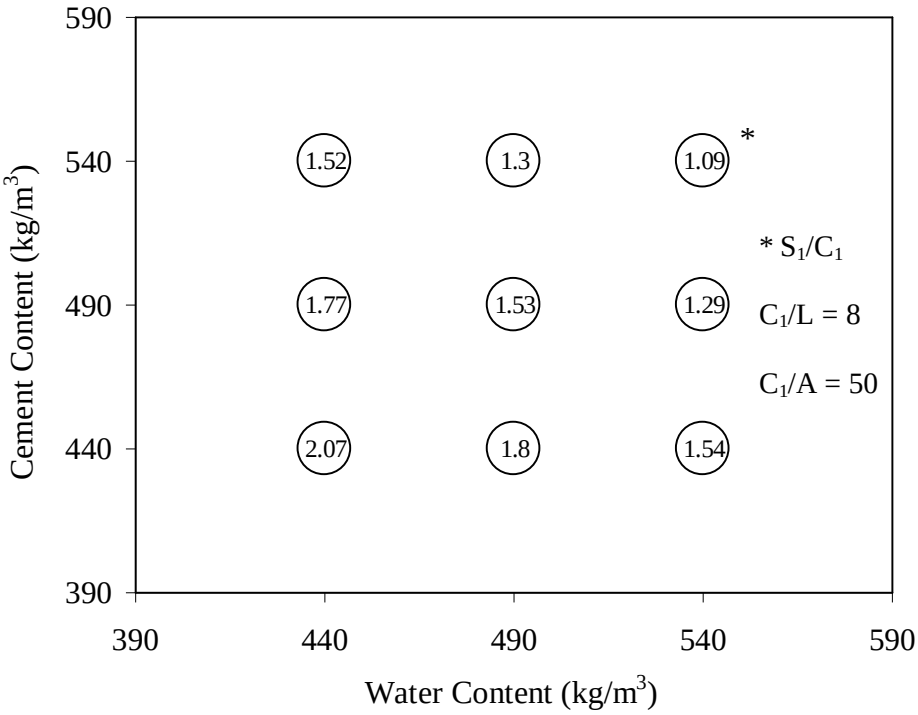

Figure 5.5: Distribution of ingredients in optimization band OB-5

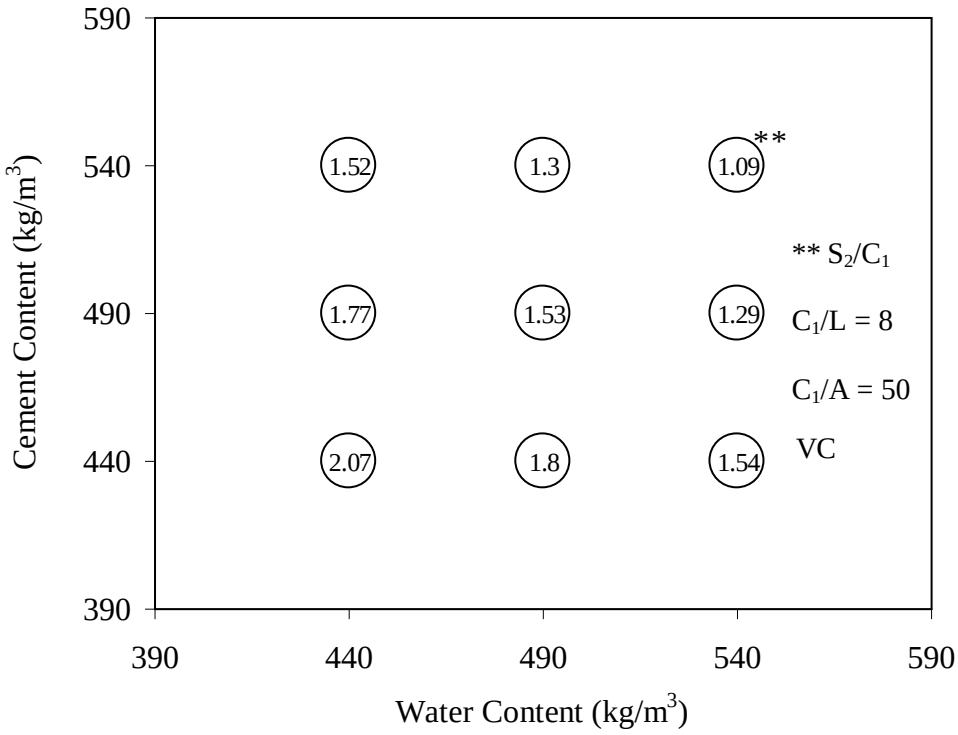

Figure 5.6: Distribution of ingredients in optimization band OB-6

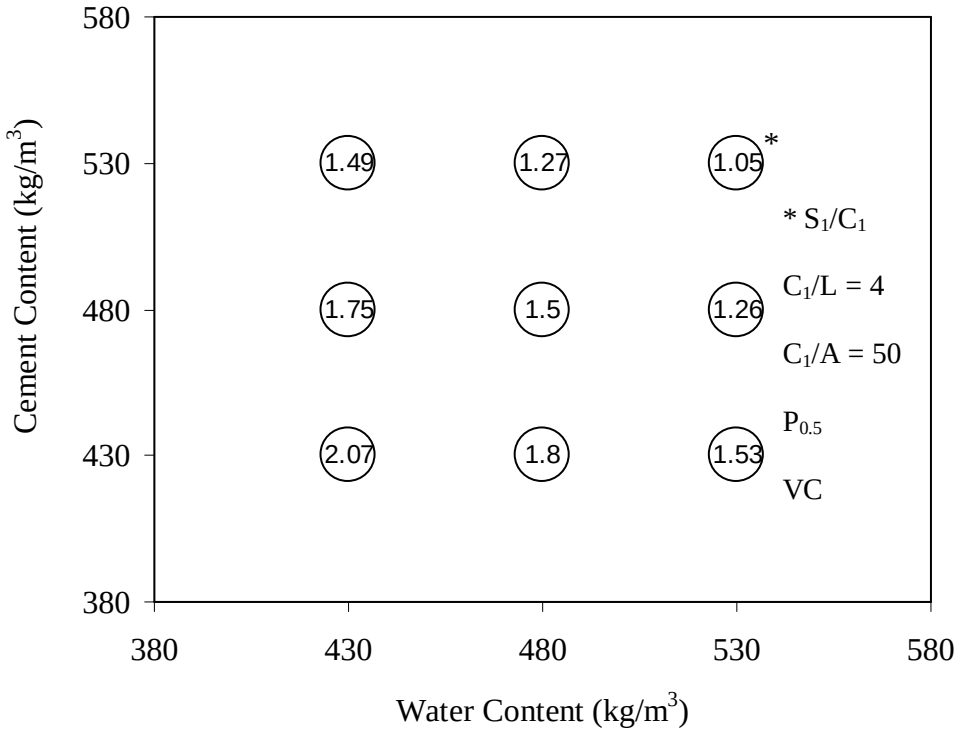

Figure 5.7: Distribution of ingredients in optimization band OB-7

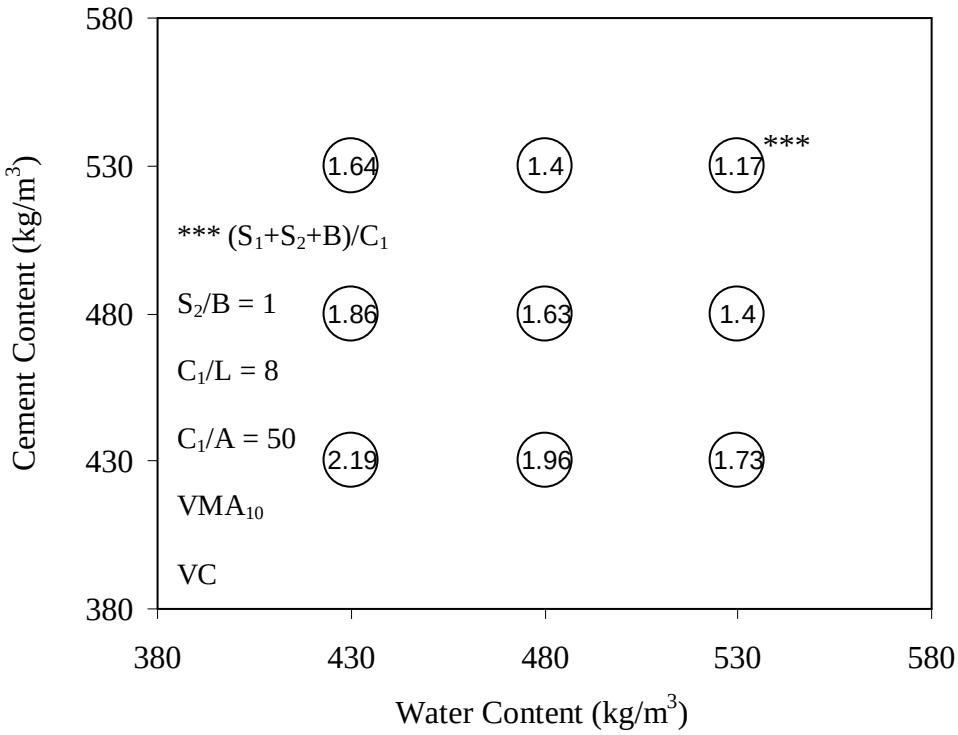

Figure 5.8: Distribution of ingredients in optimization band OB-8

A summary of the ingredients used is given in Table 5.1. All symbols carry their usual meaning as stated before.

Table 5.1: Summary of Optimization Bands

Ingredient	C_1	C_2	S_1	S_2	B	L	W	A	P	VMA	VC
OB-1		√	√			√	√	√			
OB-2		√		√		√	√	√			
OB-3		√	√			√	√	√	√		
OB-4		√	√			√	√	√	√		
OB-5	√		√			√	√	√			√
OB-6	√			√		√	√	√			√
OB-7	√		√			√	√	√	√		√
OB-8	√		√	√	√	√	√	√		√	√

5.4 Curing Arrangement

The mechanism of steam generation here used was very simple as often practiced in local rice processing farms in Bangladesh. Generalized steam generation and curing operation is shown in Figure 5.9.

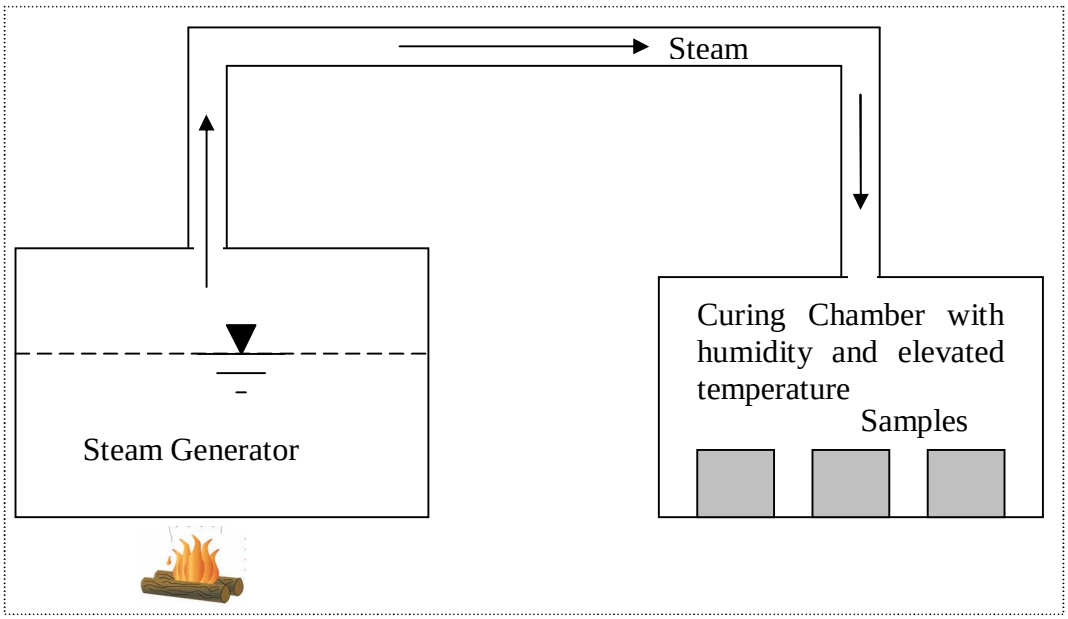

Figure 5.9: Curing process

Arrangement that had been utilized for vapor curing consists of following components shown in Figure 5.10 and Figure 5.11. Alphabetic sequences of the components are labeled in the figures from both directions.

A. Hearth Mouth: This opening was kept in the heating unit to insert wood or other fuel used for burning. It was an opening of size 10” X 6”.

B. Hearth: It was the heating unit of the curing system. It had a size of 4’ length; 3’ width; and 2’-6” height. Its top surface was curved as ‘U’ shape in two sides to accommodate a sit for the steam generator. Wood was feed into it to generate heat for the steam generator.

C. Ventilation openings: These opening were kept in three sides of the hearth to allow sufficient air ventilation aiding burning in the hearth. These opening were of size 10” X 6”. Hearth mouth also acted as opening.

D. Steam Generator: This was the steam-producing boiler. It was a cylindrical boiler with size 4’ length and 2’ diameter. It had two openings. First opening was inlet and the second one was outlet. The 1.5” diameter outlet was

connected to steam transmission pipe for carrying steam to the curing chamber.

E. Inlet: Steam generator had one inlet opening of 1.5” to pour water into it. Inlet opening could be sealed by wood or cork to stop leakage of vapor.

F. Steam Transmission Pipe: Steam generated in the boiler was transmitted to the curing unit using a 1.5” diameter pipe.

G. Steam Injection Hole: Roof of the curing chamber was punched to make two holes on it. Other than using one hole, two holes were used to ensure even distribution of steam in the curing chamber. The transmission pipe was divided it to two branches, which were connected to these two holes. Flexible polymer pipes were used at the junction of transmission pipe and injection hole.

H. Curing Chamber Roof: A 4” roof was precast and was kept with two holes to accommodate flexible polymer pipes for steam injection. It was put above the chamber and jointed with walls of chamber below using cement mortar.

I. Curing Chamber: It was the compartment accommodating molds for curing. Its size was 4’ by 4’ by 1’-6”. It was sized so to accommodate 9 molds at a time and their covers.

J. Chamber Opening: Three sides of the chamber were closed with walls. One side was kept open to insert samples in the chamber. During curing operation, this opening was sealed with double layer polythene sheet to prevent vapor escape.

Figure 5.10: Curing setup (South-North view)

Figure 5.11: Curing setup (North-South view)

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5.5 Curing Operation

Mixing and molding procedure were done following the same course of action described in earlier chapter 4. Water was poured in the steam generator and inlet was sealed. Wood, bamboo and dry leaves were used in the hearth to heat up water inside the steam generator. Molds were sealed and ingredients were measured to ensure quick mixing. Preparation of molds and samples are shown in Figure 12 (a). Heating up of water and generation of steam took 30-45 minutes from first initiation of fire. When the steam was visible with open eyes, samples were mixed and poured in the mold. Each sample was covered with another inverted empty 150 mm mold to accommodate expansion. Open side of curing chamber was sealed with two-layer polythene sheet to hinder escape of vapor and loss of humidity and temperature as shown in Figure 5.12 (b). Sealing was not necessarily fully leak proof as the curing operation was conducted under atmospheric pressure. This steam generation process was allowed for six hours. Samples were not removed from the curing chamber just after six hours of heating. Fire was stopped and samples were allowed to cool for twenty-four hours. Literature suggested gradual cooling was favorable for strength optimization. After twenty-four hours of cooling, samples were taken off the mold (Figure 5.13 referred) and cut to size and were moist cured for 14 days before testing.

(a) Preparation of samples before curing operation

(b) Polythene sheet covering during curing process

Figure 5.12: Curing preparation and sealing of curing chamber

(a) Samples inside curing chamber

(b) Samples after removal of top covering

Figure 5.13: Samples being taken out of the curing chamber after cooling

5.6 Experimental Investigation

Produced aircrete were tested for basic physical properties: absorption capacity, thermal conductivity, density and compressive strength. This study being a feasibility investigation, density and compressive strength are determined for all specimens whereas absorption capacity and thermal conductivity are determined for selected optimum samples.

5.6.1 Density and Compressive Strength

Density of samples was determined according to ASTM C 140 (1983) as it covered testing of masonry blocks. Compressive strength of 150 mm cube samples were carried out according to BS 1881:116 (1983) as specified earlier. Figure 5.14 shows typical samples for density, compressive strength and thermal conductivity tests.

For ease of interpretation, test results of density and compressive strength are plotted in a surface-mapping interface. Surface-mapping interface is relatively easier to

understand and optimization through zoning could be done by visual explanation. Having outstanding gridding and contouring capabilities surfer (surfer version 7.02, 2000) was used to plot the obtained data. Kriging method was used to plot the data in a smooth pattern. When computing the interpolation weights, the kriging algorithm considers both the inherent length scale of the data and the inherent trustworthiness of the data. If the data measurements are exceedingly precise and accurate, the interpolated surface goes through each and every observed value. If the data measurements are suspect, the interpolated surface may not go through an observed value, especially if a particular value is in stark disagreement with neighboring observed values. Contour maps are two-dimensional representations of three-dimensional data. Contours define lines of equal Z values across the map extents. The shape of the surface is shown by the contour lines. Contour maps can display the contour lines and colors or patterns between the contour lines. Surfer is a grid-based mapping program that interpolates irregularly spaced XYZ data into a regularly spaced grid. Grids may also be imported from other sources. The grid is used to produce different types of maps including contour, vector, image, shaded relief, 3D surface, and 3D wireframe maps. Maps can be displayed and enhanced in surfer, allow producing the map that best represents the data. An extensive suite of gridding methods is available in Surfer. The variety of available methods provides different interpretations of data and allows choosing the most appropriate method. In addition, data metrics allow gathering information about gridded data. Surface area, projected planar area, and volumetric calculations can be performed quickly in Surfer.

5.6.1.1 Aircrete without Autoclaving

Bands OB-1 to OB-4 were formed to optimize the properties without autoclaving. Compressive strength and density are tabulated along with their respective mix ingredients in Table 5.2 to Table 5.5. These results were plotted using surfer software. Plotted charts are shown in Figure 5.15 to 5.22. Expansion index of the samples was also calculated and presented in the tables. However, cement, sand,

lime and water contents of the ingredients are in kg/m^3. Aluminium content is shown in percentage of cement by weight and admixtures are measured ml per kg of cement.

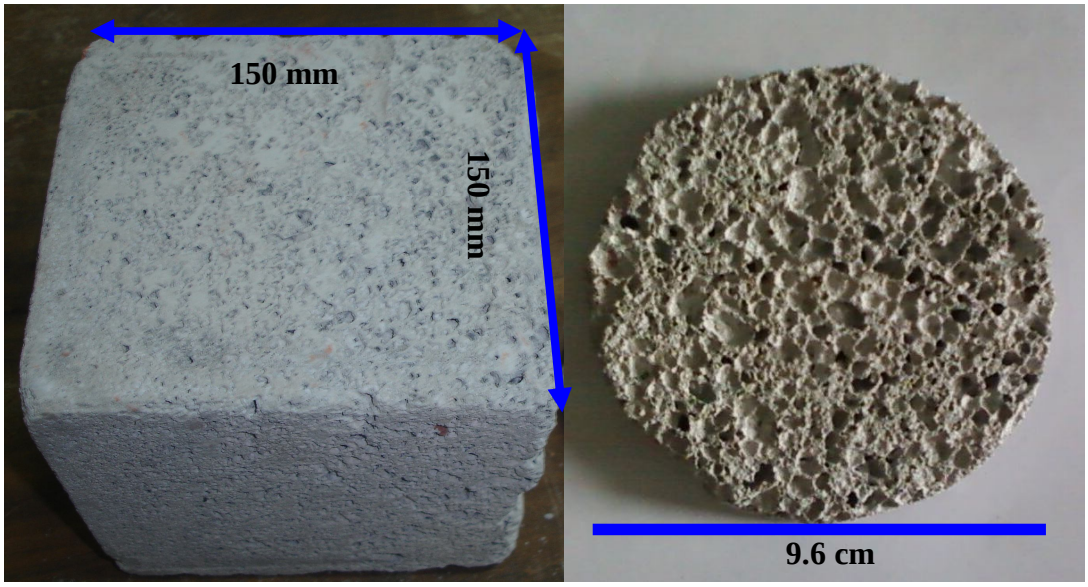


Figure 5.14: Typical Samples for density, compressive strength and thermal conductivity tests

Optimization Band OB-1

Table 5.2: Details of mix design and properties of aircrete for optimization band OB-1

Mix Band	C_2 (kg/m^3)	S_1 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	EI*
OB-1	540	587	68	540	2.0	1746	762	1.10	2.29
	540	703	68	490		1812	815	1.32	2.22
	540	820	68	440		1879	991	1.71	1.90
	490	632	61	540		1733	818	0.71	2.12
	490	748	61	490		1799	938	1.18	1.92
	490	865	61	440		1866	985	1.51	1.89
	440	677	55	540		1721	885	0.69	1.94
	440	793	55	490		1787	955	0.88	1.87
	440	910	55	440		1854	1008	1.36	1.84

*EI: Expansion Index

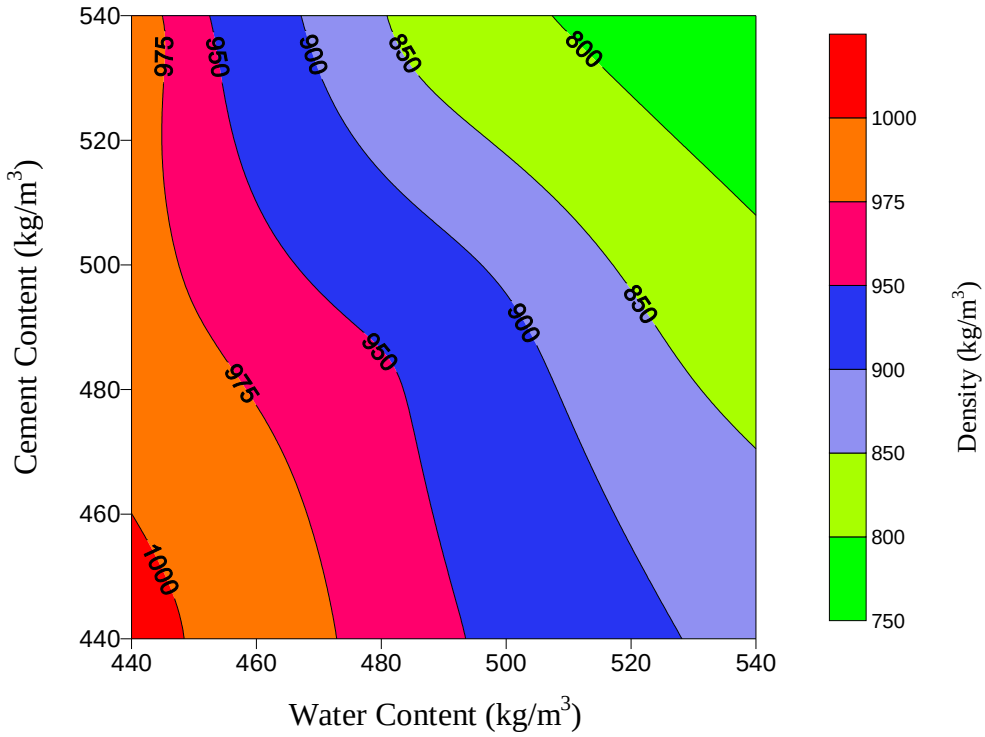


Figure 5.15: Relationship among density, cement content and water content for optimization band OB-1

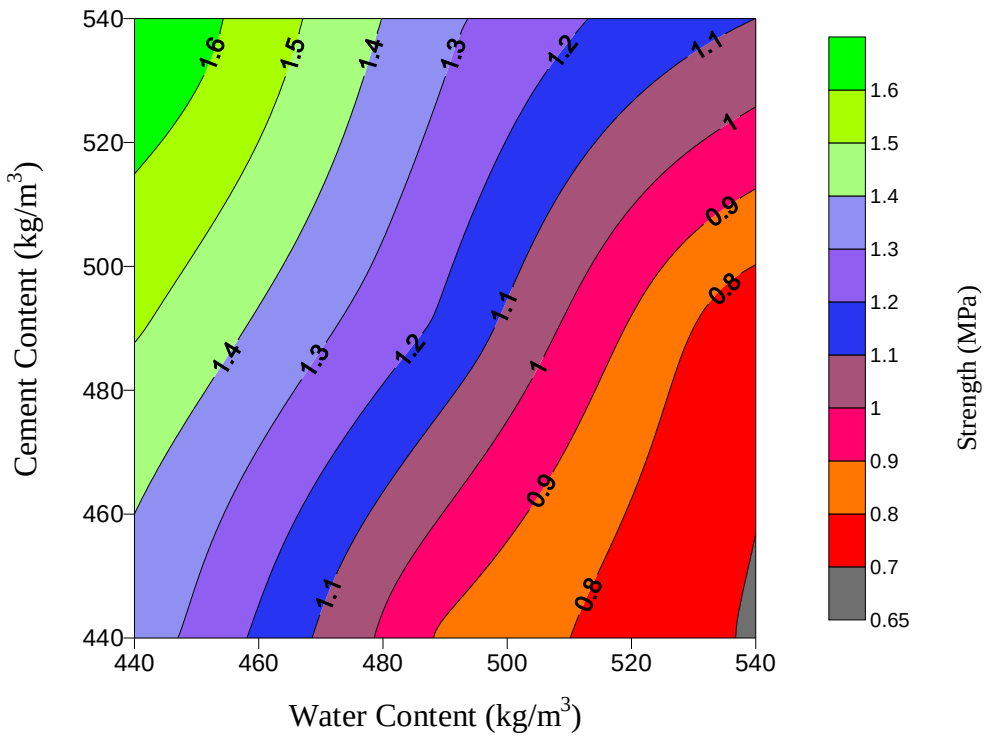


Figure 5.16: Relationship among compressive strength, cement content and water content for optimization band OB-1

Optimization Band OB-2

Table 5.3: Details of mix design and properties of aircrete for optimization band OB-2

Mix Band	C_2 (kg/m^3)	S_2 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	EI*
OB-2	540	645	68	540	2.0	1804	819	0.91	2.20
	540	773	68	490		1882	935	1.31	2.01
	540	901	68	440		1960	1093	1.62	1.79
	490	694	61	540		1795	896	0.78	2.00
	490	822	61	490		1873	1004	1.02	1.87
	490	950	61	440		1951	1139	1.44	1.71
	440	743	55	540		1787	921	0.73	1.94
	440	871	55	490		1865	1012	0.94	1.84
	440	999	55	440		1943	1183	1.08	1.64

*EI: Expansion Index;

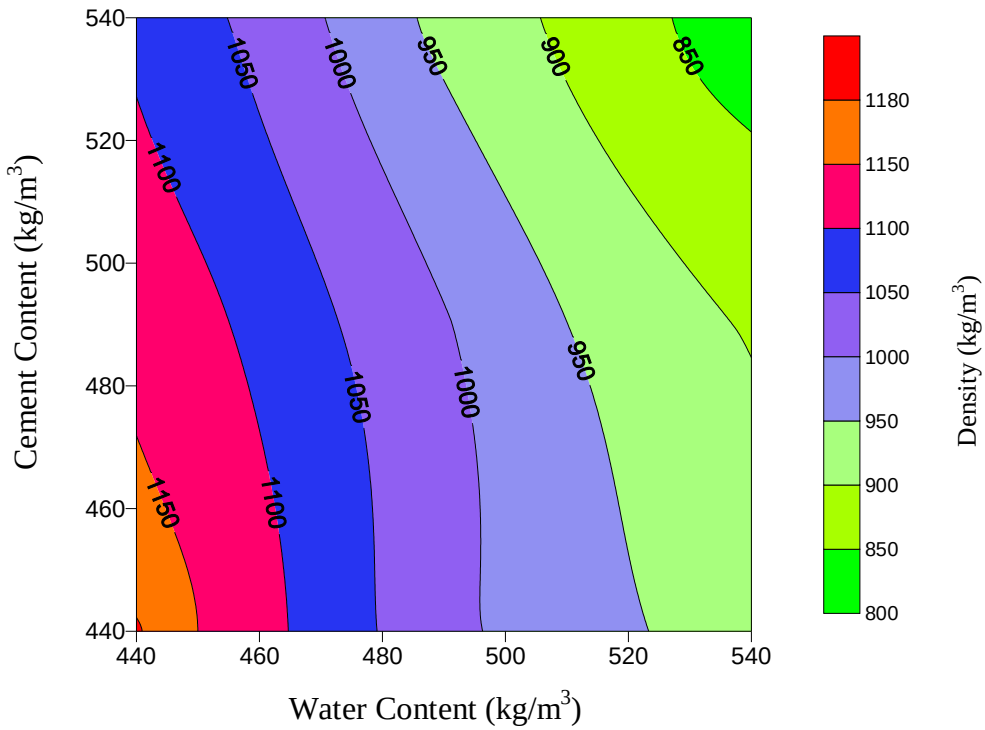


Figure 5.17: Relationship among density, cement content and water content for optimization band OB-2

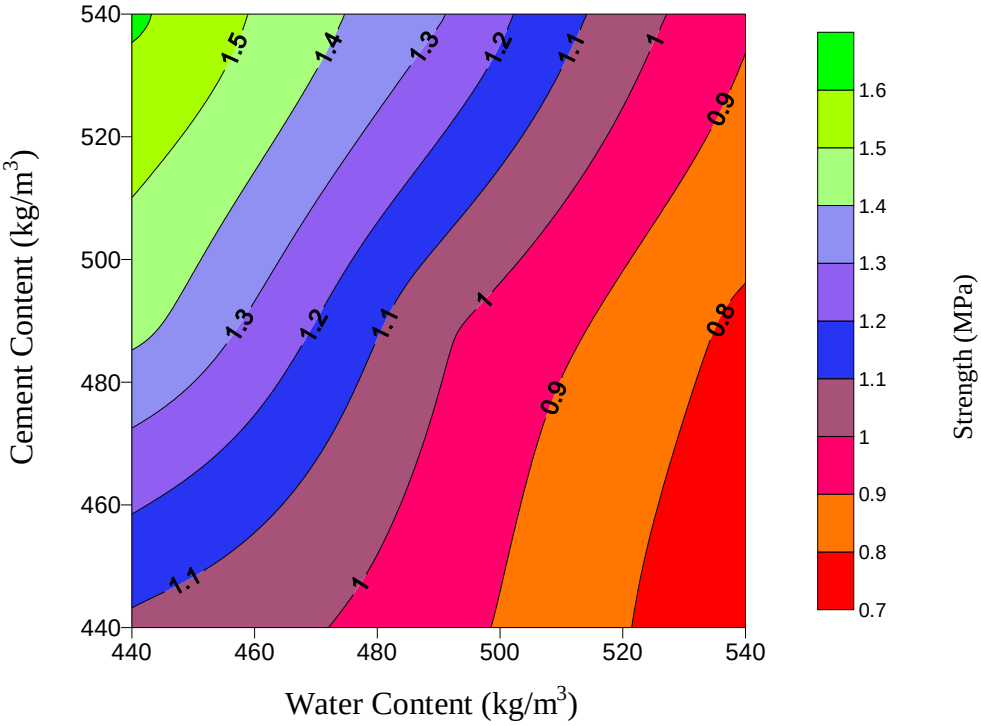


Figure 5.18: Relationship among compressive strength, cement content and water content for optimization band OB-2

Optimization Band OB-3

Table 5.4: Details of mix design and properties of aircrete for optimization band OB-3

Mix Band	C_2 (kg/m^3)	S_1 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	P#	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Str. (MPa)	EI*
OB-3	530	555	133	530	1.0	2.0	1759	776	0.82	2.27
	530	671	133	480			1825	845	1.04	2.16
	530	788	133	430			1892	1190	1.89	1.59
	480	606	120	530			1746	813	0.70	2.15
	480	722	120	480			1812	950	1.05	1.91
	480	839	120	430			1879	1201	1.29	1.56
	430	657	108	530			1734	898	0.68	1.93
	430	773	108	480			1800	1096	0.82	1.64
	430	890	108	430			1867	1286	1.12	1.45

*EI: Expansion Index; #ml per kg of cement

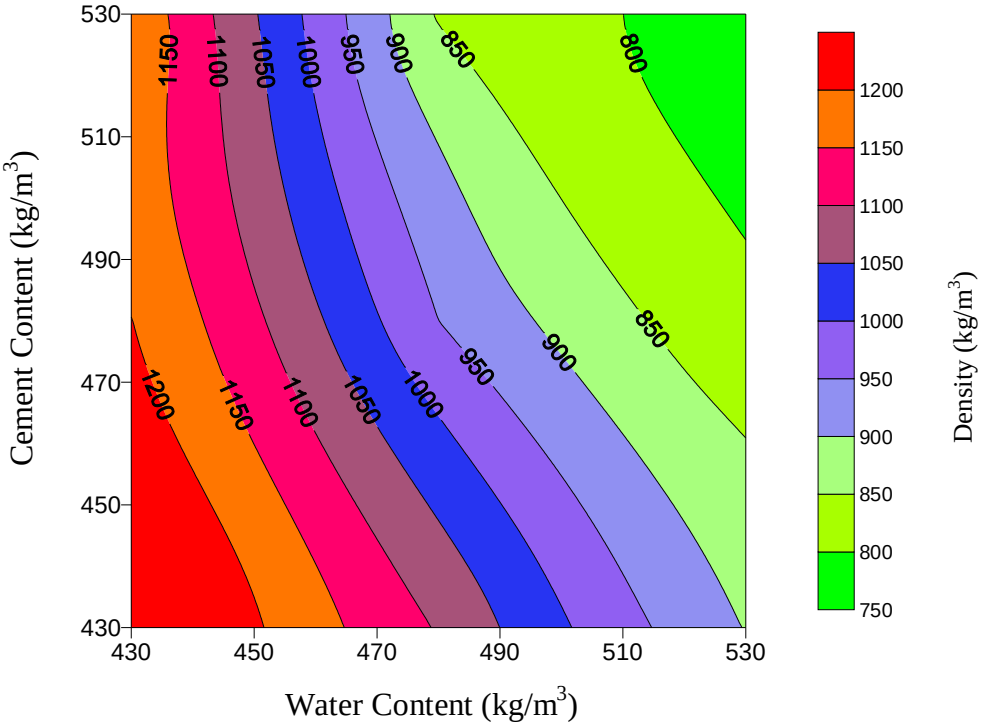


Figure 5.19: Relationship among density, cement content and water content for optimization band OB-3

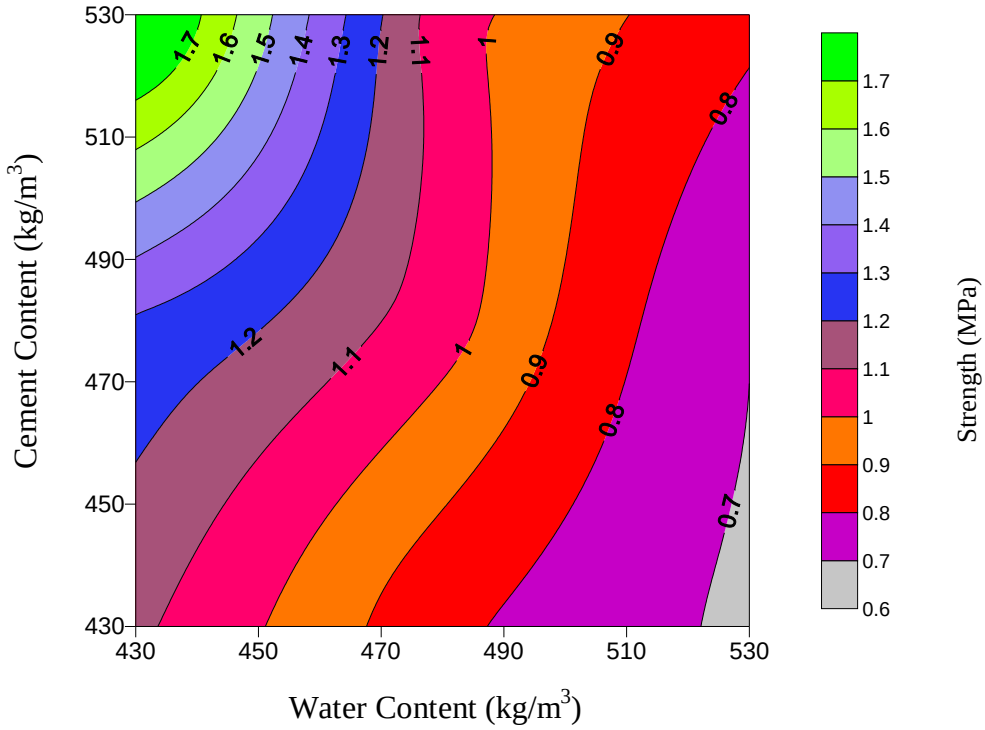


Figure 5.20: Relationship among compressive strength, cement content and water content for optimization band OB-3

Optimization Band OB-4

Table 5.5: Details of mix design and properties of aircrete for optimization band OB-4

Mix Band	C_2 (kg/m^3)	S_1 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	P#	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Str. (MPa)	EI*
OB-4	530	555	133	530	0.5	2.0	1759	750	0.69	2.34
	530	671	133	480			1825	840	1.15	2.17
	530	788	133	430			1892	1100	1.49	1.72
	480	606	120	530			1746	825	0.66	2.12
	480	722	120	480			1812	860	0.80	2.11
	480	839	120	430			1879	1158	1.21	1.62
	430	657	108	530			1734	855	0.56	2.03
	430	773	108	480			1800	1061	0.66	1.70
	430	890	108	430			1867	1201	0.85	1.55

*EI: Expansion Index; #ml per kg of cement

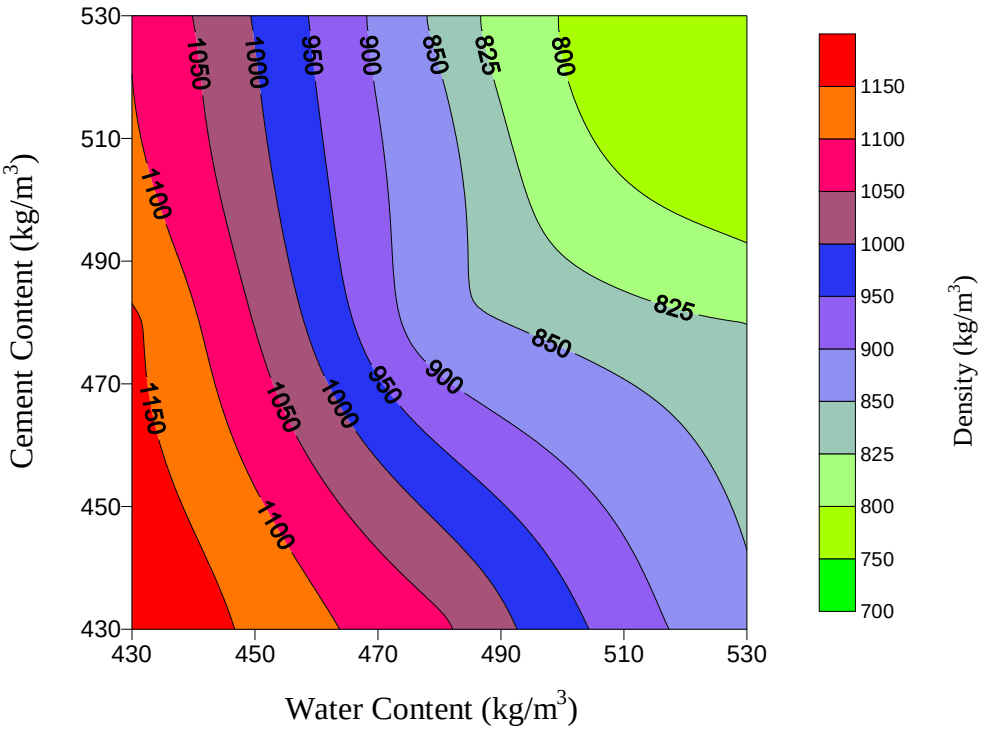


Figure 5.21: Relationship among density, cement content and water content for optimization band OB-4

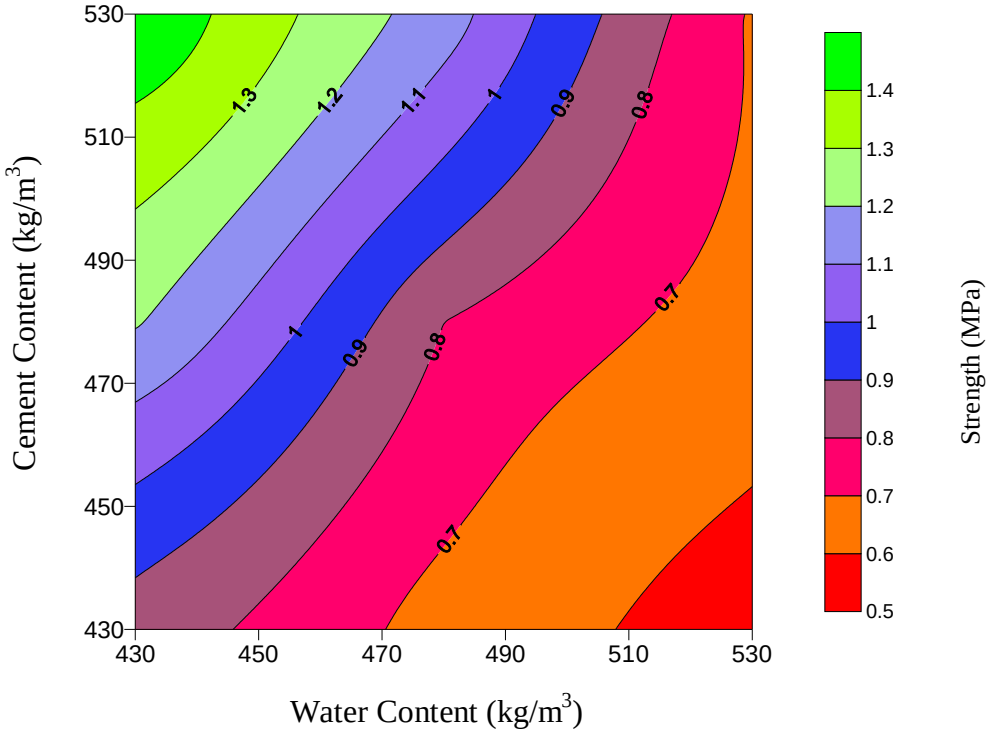


Figure 5.22: Relationship among compressive strength, cement content and water content for optimization band OB-4

5.6.1.2 Aircrete with Autoclaving

Result obtained form samples of optimization bands OB-5 to OB-8 are tabulated as shown in Table 5.6 to Table 5.9 and plots shown in Figure 5.23 to 5.30. Brick aggregate is introduced in Band OB-8 and denotes as B in kg/m^3. As mentioned earlier, elevated temperature was attainable in local scenario but controlled pressure curing was difficult to attain. Band OB-5 to OB-8 were subjected to vapor curing at atmospheric pressure. Construction and procurement of such expensive unit of autoclaving chamber was beyond both financial scope and technical knowhow during the study.

Optimization Band OB-5

Table 5.6: Details of mix design and properties of aircrete for optimization band OB-5

Mix Band	C_2 (kg/m^3)	S_1 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	EI*
OB-5	540	587	68	540	2.0	1746	770	1.84	2.27
	540	703	68	490		1812	812	2.04	2.23
	540	820	68	440		1879	830	2.21	2.26
	490	632	61	540		1733	791	1.78	2.19
	490	748	61	490		1799	821	1.93	2.19
	490	865	61	440		1866	859	2.16	2.17
	440	677	55	540		1721	792	1.70	2.17
	440	793	55	490		1787	892	1.79	2.00
	440	910	55	440		1854	921	1.94	2.01

*EI: Expansion Index

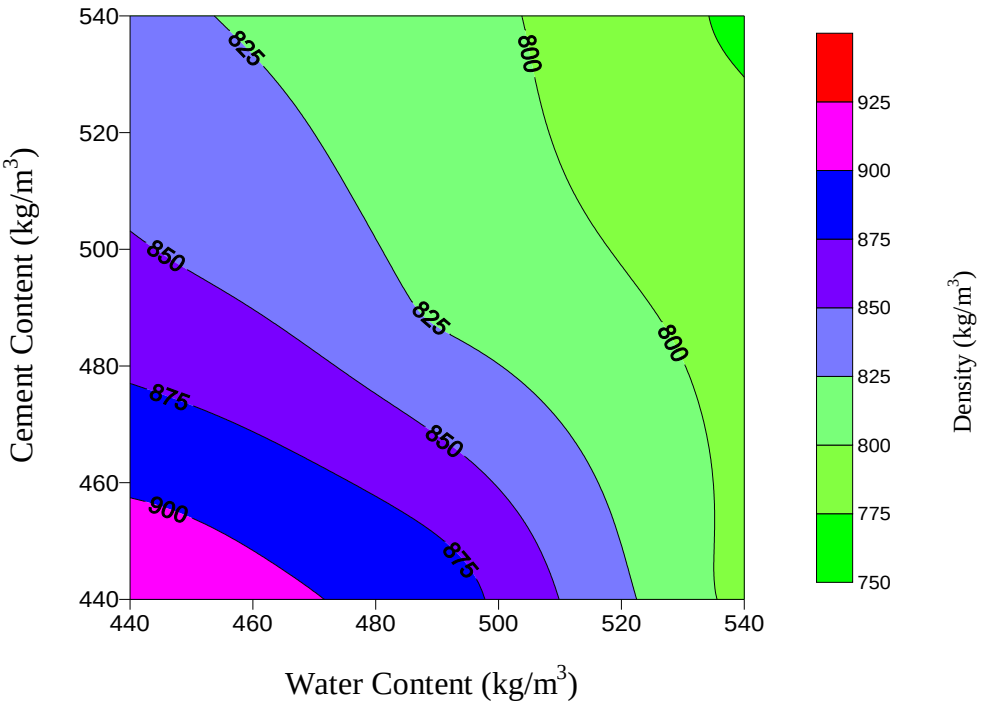


Figure 5.23: Relationship among density, cement content and water content for optimization band OB-5

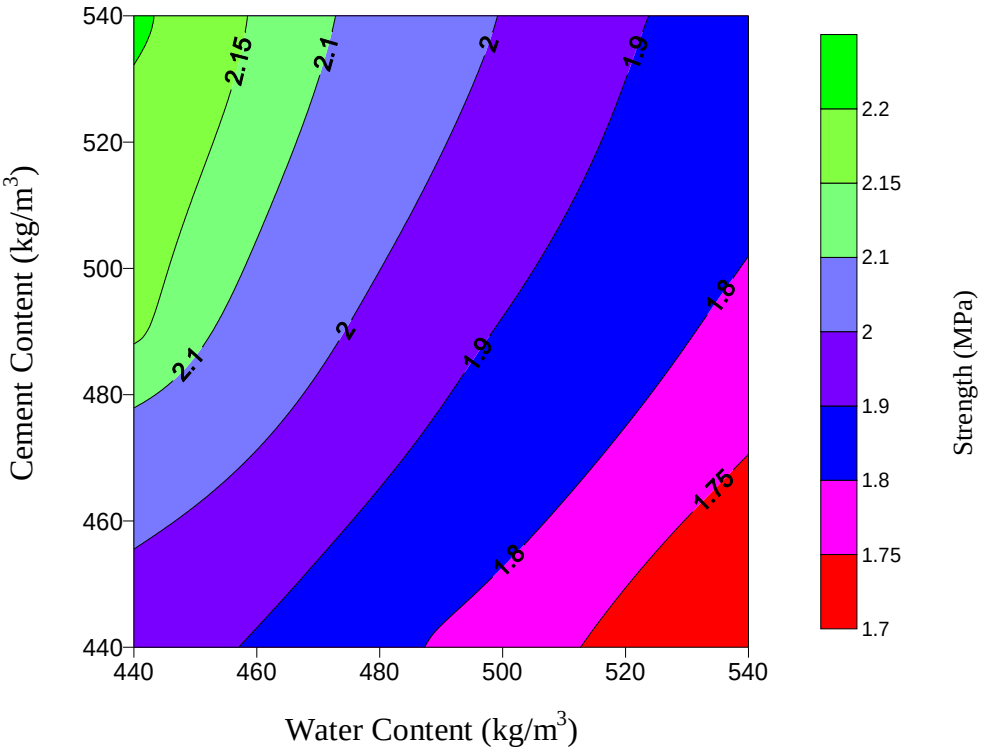


Figure 5.24: Relationship among compressive strength, cement content and water content for optimization band OB-5

Optimization Band OB-6

Table 5.7: Details of mix design and properties of aircrete for optimization band OB-6

Mix Band	C_1 (kg/m^3)	S_2 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Strength (MPa)	EI*
OB-6	540	645	68	540	2.0	1804	792	1.89	2.28
	540	773	68	490		1882	905	2.16	2.08
	540	901	68	440		1960	1010	2.32	1.94
	490	694	61	540		1795	879	1.66	2.04
	490	822	61	490		1873	980	2.13	1.91
	490	950	61	440		1951	1092	2.24	1.79
	440	743	55	540		1787	910	1.73	1.96
	440	871	55	490		1865	1080	1.79	1.73
	440	999	55	440		1943	1106	2.17	1.76

*EI: Expansion Index

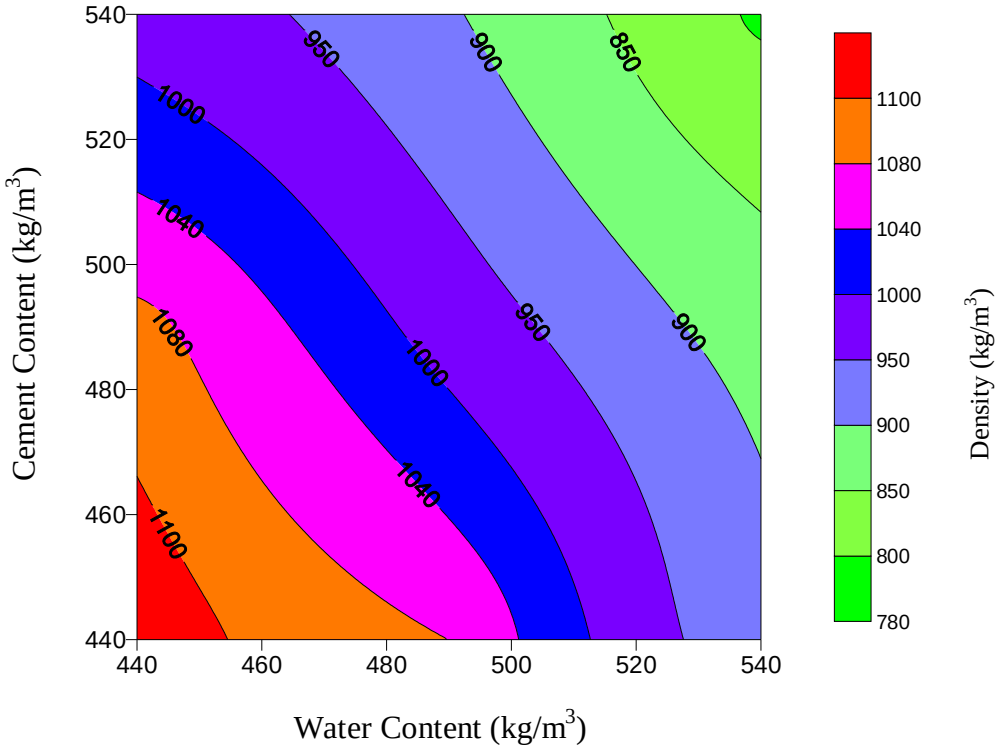


Figure 5.25: Relationship among density, cement content and water content for optimization band OB-6

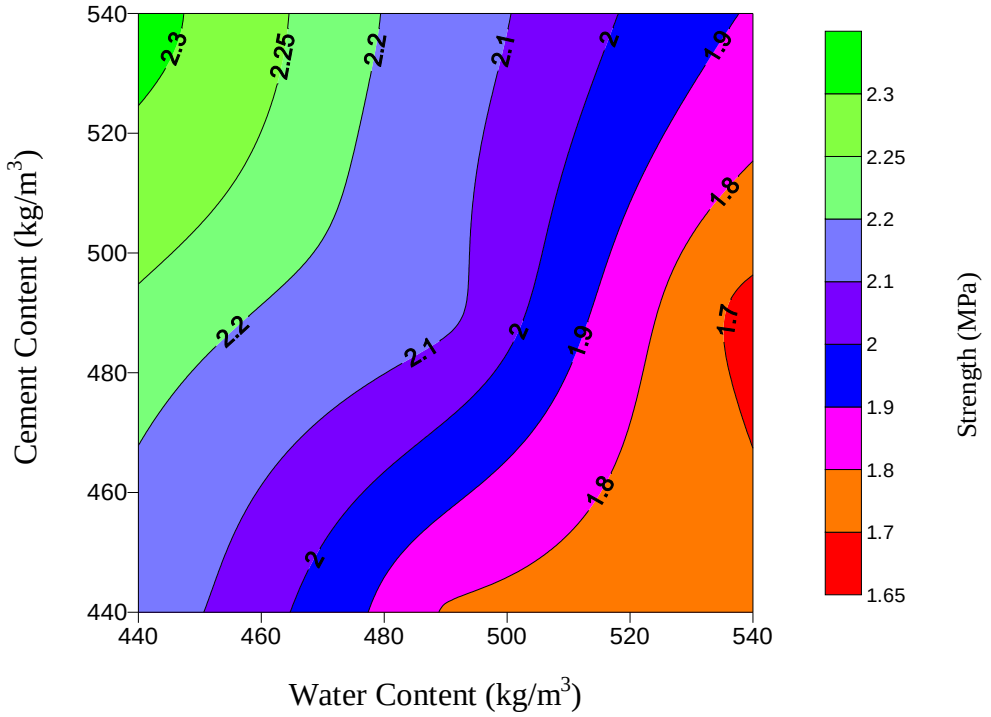


Figure 5.26: Relationship among compressive strength, cement content and water content for optimization band OB-6

Optimization Band OB-7

Table 5.8: Details of mix design and properties of aircrete for optimization band OB-7

Mix Band	C_1 (kg/m^3)	S_1 (kg/m^3)	L (kg/m^3)	W (kg/m^3)	P#	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Str. (MPa)	EI*
OB-7	530	555	133	530	0.5	2.0	1759	726	1.24	2.42
	530	671	133	480			1825	802	1.82	2.28
	530	788	133	430			1892	1003	2.05	1.89
	480	606	120	530			1746	803	1.16	2.17
	480	722	120	480			1812	870	1.70	2.08
	480	839	120	430			1879	1069	1.74	1.76
	430	657	108	530			1734	845	0.91	2.05
	430	773	108	480			1800	954	1.19	1.89
	430	890	108	430			1867	1140	1.48	1.64

#ml per kg of cement; *EI: Expansion Index

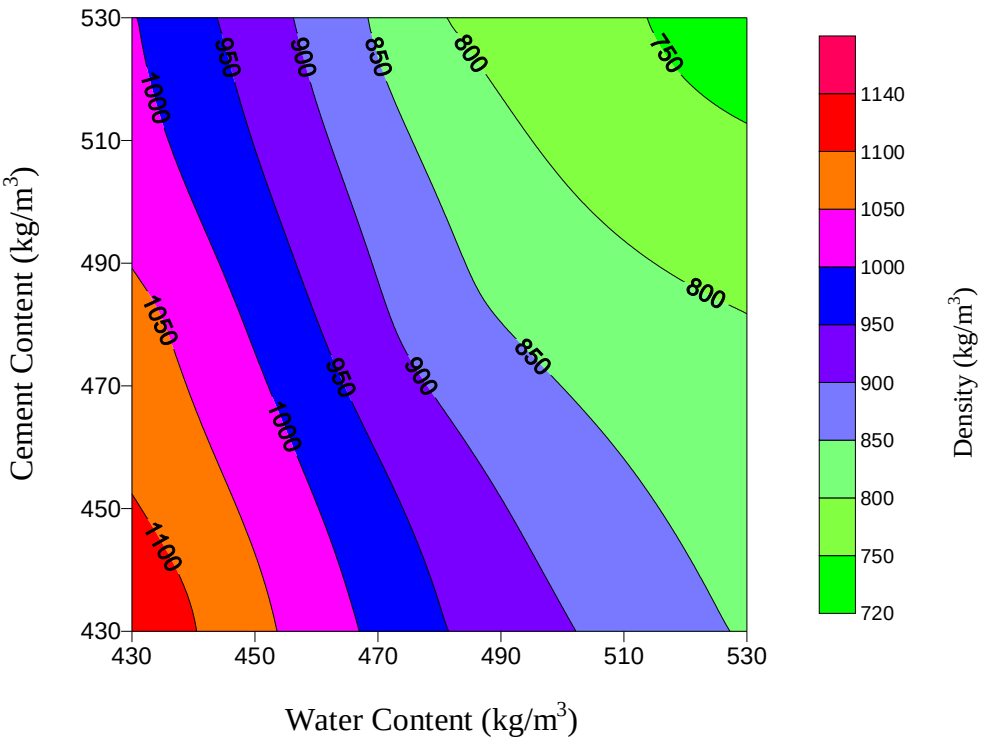


Figure 5.27: Relationship among density, cement content and water content for optimization band OB-7

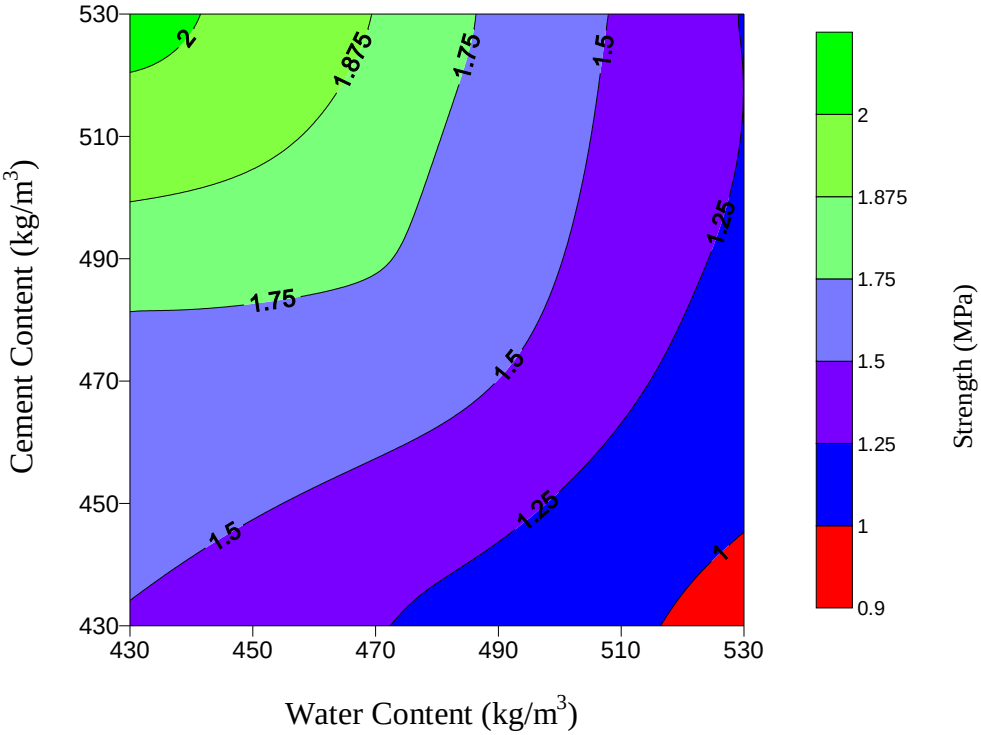


Figure 5.28: Relationship among compressive strength, cement content and water content for optimization band OB-7

Optimization Band OB-8

Table 5.9: Details of mix design and properties of aircrete for optimization band OB-8

Mix Band	C_1 (kg/m^3)	S_1 (kg/m^3)	S_2 (kg/m^3)	B (kg/m^3)	L (kg/m^3)	W (kg/m^3)	VMA#	A (% of Cement)	Design Density (kg/m^3)	Measured Density (kg/m^3)	Comp. Str. (MPa)	EI*
OB-8	530	220	200	200	66	530	10	2.0	1757	913	1.58	1.92
	530	344	200	200	66	480			1831	1082	1.92	1.69
	530	467	200	200	66	430			1904	1135	2.17	1.68
	480	270	200	200	60	530			1750	959	1.49	1.82
	480	382	200	200	60	480			1812	1086	1.77	1.67
	480	494	200	200	60	430			1874	1202	2.01	1.56
	430	343	200	200	54	530			1766	1124	1.32	1.57
	430	443	200	200	54	480			1816	1198	1.74	1.52
	430	543	200	200	54	430			1866	1275	1.84	1.46

*EI: Expansion Index; #ml per kg of cement;

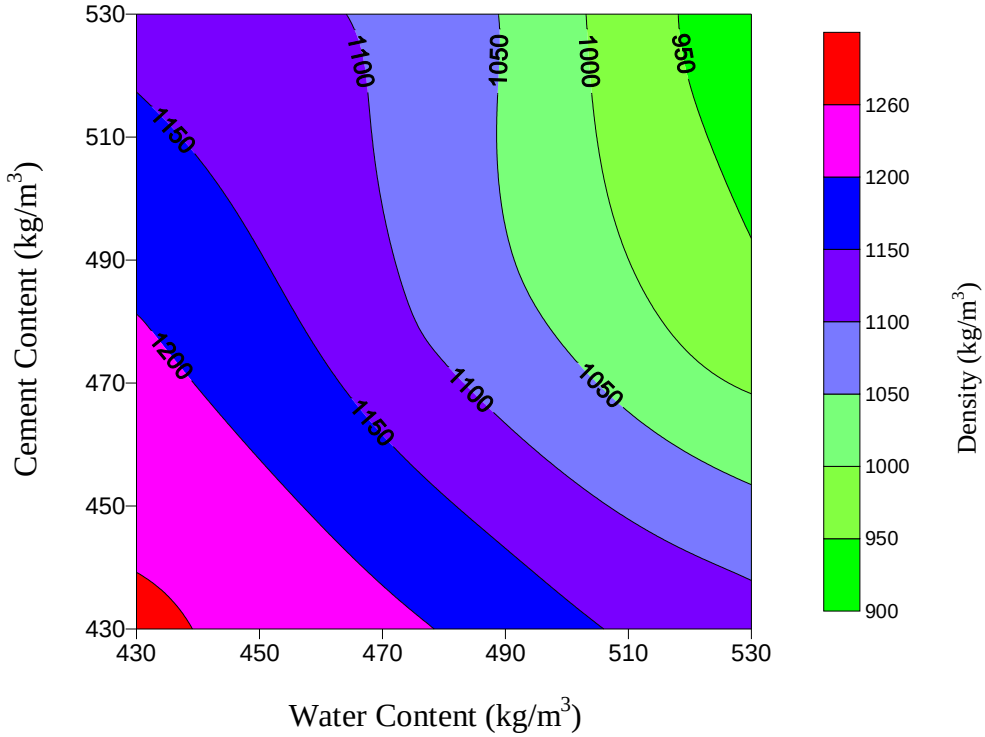


Figure 5.29: Relationship among density, cement content and water content for optimization band OB-8

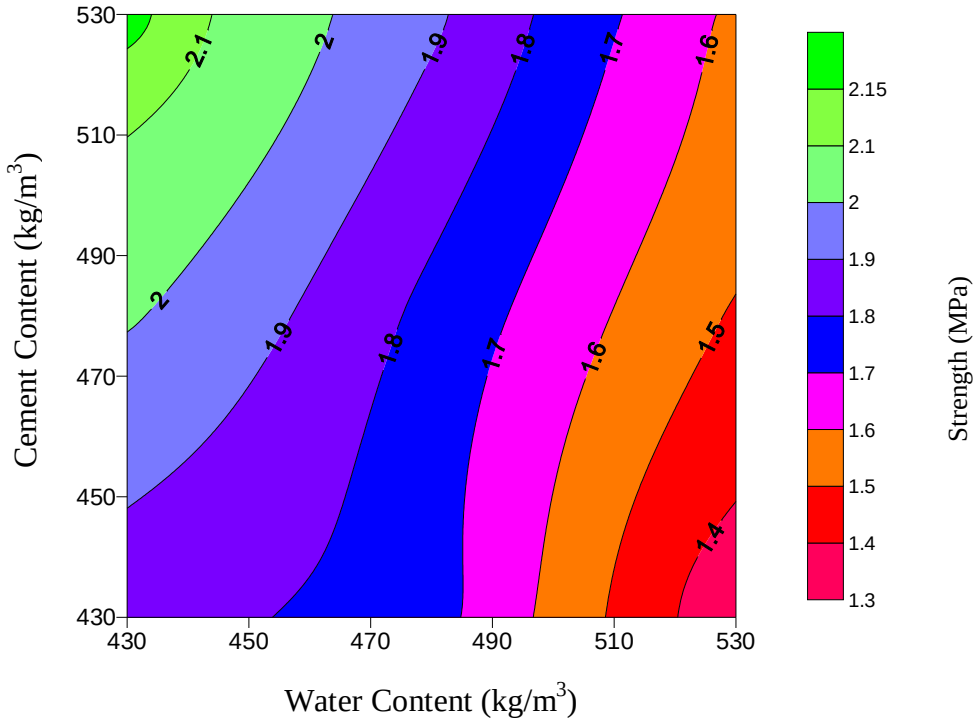


Figure 5.30: Relationship among compressive strength, cement content and water content for optimization band OB-8

5.6.2 Absorption Capacity

ASTM C 140 (1993) provides guideline for determining absorption capacity of masonry blocks. This practice is used for this study. Cut samples were soaked in water for twenty four hours. Samples were then taken out of water and surface moisture is removed using dry cotton rags. Saturated surface dry samples were weighed. Samples were then dried in oven for twenty four hours at a temperature of 105^0C. Samples are then weighed to obtain oven dry weight. Utilizing these weights, absorption capacities were calculated for samples. Results are shown along with thermal conductivity in the later part of this chapter.

5.6.3 Thermal Conductivity

ASTM C 177 (1999) specification covers the measurement of thermal insulating property of the resulting concrete by Means of the Guarded-Hot-Plate Apparatus. The apparatus required for measurement is not available. As concrete being bad conductor of heat, easier and available apparatus guided by Lees and Chorlton (Young, 2006 and Ahmed & Shahabuddin, 2000). This method is widely used in Bangladesh to measure coefficient of thermal conductivity. Samples are cut to size (96 mm diameter and thickness 10-17 mm) required for thermal conductivity test. Brief theoretical derivation and experimental measurement along with one sample calculation is described in Appendix 2.

5.7 Optimization

Data obtained from compressive strength and density test results, when plotted on surfer interface using Kriging method, formed smooth contours that could be interpreted with ease. Both series of optimization bands provided a general relationship among water content, cement content, density and compressive strength. Observing contour curvature, it could be deduced that density decreased with increased cement and water content, whereas compressive strength increased with increased cement content but decreased with increased water content, thereby

indicating a conflicting relation for all test bands. Expansion index varied inversely variable with density.

Range of density of band OB-1 varied from 750-1000 kg/m^3 but strength was as low as 0.70-1.50 MPa. Inclusion of Sylhet sand replacing finer Local sand led density and strength range towards higher value approximately 800-1200 kg/m^3 and 0.75-1.70 MPa. Next band OB-3, containing admixture and higher cement-lime ratio (lower lime content) than that of OB-1 and OB-2, provided density (800-1300 kg-m^3) and strength (0.70-1.90 MPa). The improvement expected after using plasticizer was not up to the satisfaction rather density increased compared to earlier bands. Another band OB-4 was tested comprising identical ingredients of OB-3 except that admixture content was reduced to half i.e. 0.5 ml per kg of cement. Results suggested improvement of density (750-1200 kg/m^3). However, no significant improvement of strength was observed. Research by Nasser and Chakrabarty (1985) suggested up to 71^{0}C temperature and under sealed condition, strength and elasticity of concrete with admixture (superplasticizer) are not affected considerably. But for unsealed concrete and for higher temperature strength is affected. Being suffered by high heat generated by hydration of lime, its action might have been hindered.

Band OB-5 and OB-6, being autoclaved form of OB-1 and OB-2 respectively, provided the most suitable range of density and strength than earlier bands. Properties of OB-5 were more favorable than that of OB-6. Density and compressive strength range of OB-5 is within the range of 775-925 kg/m^3 and 1.5-2.2 MPa respectively. Expansion index is found as high as 2.27 for OB-5. Band OB-7 containing plasticizer compromised both strength and density optimization as seen from Table 5.8. Similar behavior was found for OB-8 consisting viscosity modifying admixture. Addition of viscous admixture was not successful to improve strength as seen from Table 5.9. Aitkin, (1992) advised to restrict use of admixture within 10-30^{0}C. However, generation of heat caused by slaking of lime might have also affected the function of viscosity modifying admixture. Hence, admixture inclusion was found to be negligible in producing aircrete in Bangladesh for technique applied in this study.

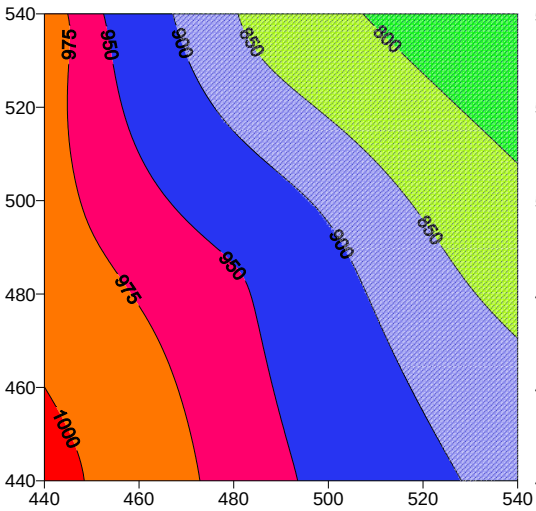
Coarse brick aggregate used in band OB-8 were not found uniformly dispersed in the mortar matrix. Crack generated under applied load could spread easily along weaker void interfaces. Use of coarse aggregate was not contributing to the failure resistance provided by the matrix. Weaker aggregate-matrix interface might not be performing as normal weight concrete. Nambiar and Ramamurthy (2008a) suggested strength model based on gel-space ratio. Gel strength provided by aircrete produced in the research was considerably low due to low cementation index and high water-cement ratio.

The comparisons discussed above were based on aircrete properties compared in a tabular manner. As the bands were not identical in respect to their ingredients, each band could be interpreted to identify optimum zone for given product performance. Optimum zoning for mix design could be done on charts formed by Surfer software as these charts are divided into sectors of gradual density and strength. Figure 5.15 to Figure 5.30 were used to characterize the property trend with cement content and water content. As an example, optimum zoning on OB-1 was shown in Figure 5. 31 for density less than 900 kg/m^3 and more than 1 MPa. Zoning operation could be practiced by visual observation or by using hatch line drawn by MS word-drawing toolbar. Here, zoning in Figure 5.31 was obtained by drawing hatch line using MS word. Similar operation could be performed on all bands for a given range of product performance. Shaded zone on Figure 5.31 (a) covers density less than 900 kg/m^3. Similarly, shaded zone on Figure 5.31 (b) was identified for strength more than 1 MPa. Figure 5.31 (c) was the overlap of shaded zones to obtain optimum zone for the given condition. Thus, zoning could be utilized to identify mix contents within a particular band.

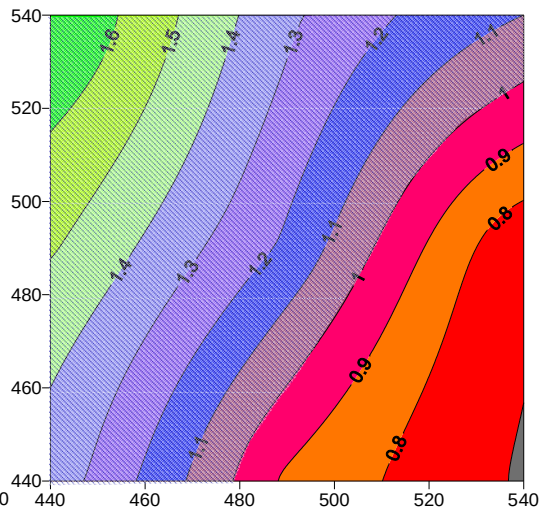
The zoning in the individual charts could also be used to compare the bands for ease of ingredients selection for range of properties covered within the domain of this research. Figure 5.31 (c) contains four dotted lines. Zone for a given strength and density was overlapped as shown in the figure for density less than 900 kg/m^3 and more than 1 MPa without autoclaving. Lower point of the overlapping zone was marked by line A. Dotted upward-facing small arrow indicates the mobility of line A

towards upper direction as this line A was lower boundary of the given criteria. Line B was the transition state of line A moving within the overlapping zone for desired performance. Line C and D are upper and lower boundary for water content for that particular performance. For example, for density less than 900 kg/m^3 and more than 1 MPa, the zone was identified on band OB-1. Lower boundary was found approximately 485 kg/m^3 of cement. Similarly water content could be found more than 480 kg/m^3. Comparing the bands OB-1 to OB-4, Table 5.10 was formed. Thus it could now be deduced that for the above given condition, band OB-1 was the best option if no autoclaving was applied. Similarly, best band was identified comparing all bands for strength greater than 2 MPa and density less than 900 kg/m^3. Comparison of all bands for the above-mentioned criteria was given in Table 5.11. The phrase "*Beyond range*" implied that either the concern band might not be able to achieve target strength and/or density within the ingredient domain. It was found that OB-5 was the optimum band in respect of density and strength if autoclaving was used.

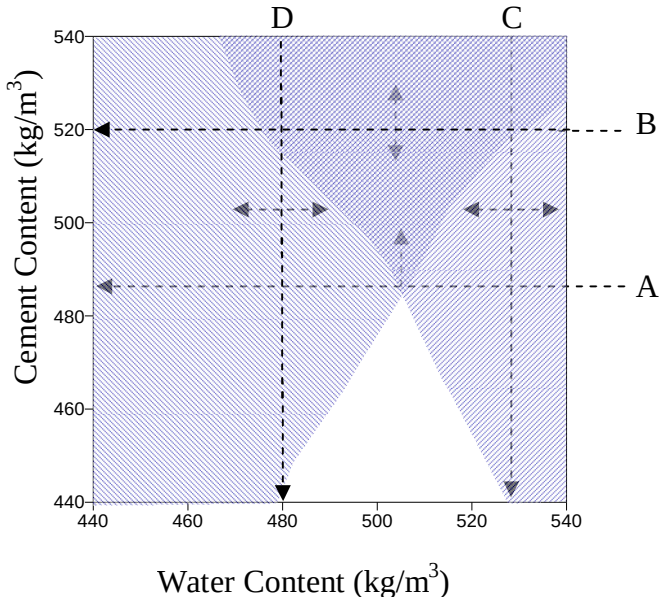
Being identified as the best, samples of band OB-5 were tested for absorption capacity and found within the range of 25-35 percent. Thermal conductivity measured by Lees and Chorlton's method indicated gradual reduction of thermal conductivity with density. The relation was not characterized as due to narrow density range and relative small no tests. The general trend was noticeable. Thermal conductivity increased with increased density whereas absorption capacity decreased. The relation did satisfy the usual theoretical background that lighter porous concrete absorbs more water and provided higher resistant against thermal conductivity. However, lowest and highest coefficient of thermal conductivity was recorded 0.18 and 0.36 W/m-k respectively. This range was within the usual value of coefficient of thermal conductivity practiced previously in a number of researches in the domain of lightweight concrete. Due to lack of resource constraint, internationally recognized method for thermal conductivity could not be practiced. Future researchers are advised to follow a recognized test method for rigorous study.



(a) Interpretation of density zone



(b) Interpretation of strength zone



(c) Zone overlap and identification of optimum mix contents

Figure 5.31: Typical zoning in OB-1 for density < 900 kg/m^3 and strength > 1 MPa

The optimization that is shown in this study is a typical procedure for a certain criteria. This set of procedure can be applied for other mix design charts and even optimization future study of this domain is also possible.

Table 5.10: Typical comparison of cement content and water content for identifying optimum mix band targeting density (<900 kg/m^3) and compressive strength (>1 MPa) without autoclaving

Mix Band	Density (kg/m^3)	Compressive Strength (MPa)	Water Content (kg/m^3)	Cement Content (kg/m^3)
OB-1	<900	>1.0	>470	>485
OB-2			510 - 530	>505
OB-3			>470 - 490	>490
OB-4			>470-495	>500

Table 5.11: Typical comparison of cement content and water content for identifying optimum mix band targeting density (<900 kg/m^3) and compressive strength (>2 MPa)

Mix Band	Density (kg/m^3)	Compressive Strength (MPa)	Water Content (kg/m^3)	Cement Content (kg/m^3)
OB-1	<900	>2.0	Beyond range	Beyond range
OB-2			Beyond range	Beyond range
OB-3			Beyond range	Beyond range
OB-4			Beyond range	Beyond range
OB-5			440 - 500	>460
OB-6			490 - 515	>510
OB-7			Beyond range	Beyond range
OB-8			Beyond range	Beyond range

5.8 Discussions

Research is a detailed study of a subject, especially in order to discover new information or reach a new understanding. This study was started with an aim to search for possible materials to produce aircrete and further optimization for physical properties. A number of approaches were applied by numerous researchers to produce lightweight concrete over the past decades. However, among many choices, a set of materials were chosen and applied with an approach formulated in light of previous practices. The materials and method used in this study are just one of many schemes through which aircrete concrete can be produced. Available materials were not enough to produce lightweight concrete below target level.

Necessity of a void intruder was noticed and a void intruder; foaming agent had to be introduced. Optimization phase of this research was initiated using four test bands with normal curing technique. Next set of bands were given steam-curing environment under atmospheric pressure. The first target of density reduction within the range (<1000 kg/m^3) was successful. The second goal was to improve compressive strength. The range of strength obtained is below the target level. The author was well aware and realized the obligations and shortcomings of the outcome product in respect of strength parameter. Nevertheless, not necessarily a research be always successful rather be successful in indicating the further future approaches with scope of minimum failure. As stated by Max Planck (1920), "I*ndispensable hypothesis, even though still far from being a guarantee of success, is however the pursuit of a specific aim, whose lighted beacon, even by initial failures, is not betrayed"*. The present popularity of aircrete is well recognized all over the world. The aircrete industry is grooming day by day. Although this research was a primary initiative using local materials with autoclaving in absence of pressure to make aircrete feasible in Bangladesh, its outcome and limitations was expected to provide positive direction to the next researchers.

Chapter 6
RECOMMENDATIONS FOR FUTURE STUDY

6.1 Conclusion

This study is aimed at investigating the feasibility of producing lightweight concrete in Bangladesh. Aircrete; a prominent branch of lightweight concrete is produced by reducing unit weight through introduction of void in the concrete matrix. The following findings were found noticeable during the study:

i. Cellular concrete produced from locally available materials through non-mechanized foaming and non-autoclaving treatment, resulted in lighter (<1000 kg/m^3) but lower strength (1.0 MPa) concrete product.

ii. General trend of variation of properties suggested that density decreased with increased cement and water content, whereas compressive strength increased with increased cement but decreased water content. Thus, density and compressive strength indicated a conflicting relation.

iii. Finer sands were more appropriate to contribute as filler than coarse aggregate in cellular concrete. The drag force exerted by foam generation was unable to disperse coarser aggregate uniformly in the matrix rather allowed settlement due to gravity.

iv. Thermal conductivity and absorption for selected samples were found within the range of 0.2-0.4 W/m-k and 25-35 percent respectively with well-established trend with corresponding density.

v. As per RILEM classification, lightweight concrete produced in this research can be grouped under class-III and Insulating type lightweight concrete.

vi. Moisture loss at the early stage of setting was observed emerging necessity of humidity restoration. Both density and compressive strength were reported to improve by application of steam curing environment.

6.2 Recommendations

Being a newer approach in Bangladesh, this study possesses a number of suggestions for future researchers attracted in this field. The following recommendations were suggested on light of the study:

i. Lime used in this research acted simultaneously as filler and expansive ingredient. Unslaked lime is one of the major causes of low compressive strength and through generation of heat affects hydration moisture and the action of admixtures. However, lime contributed the most in reducing strength of produced aircrete. Author suggests future study to be programmed without including lime as a potential ingredient of aircrete.

ii. Plasticizer and viscosity modifying admixture were unsuccessful in their performance to improve strength. Reason behind might be elevated temperature due to hydration of lime. Further study is suggested.

iii. Although not covered in this research, cork granules and polystyrene fiber are expected to be suitable as filler to reduce unit weight of concrete. However, cement-cork and cement-fiber compatibility should be studied rigorously.

iv. Mechanized mixing should be preferred in preparing aircrete otherwise ingredients may not disperse uniformly. Foaming agent can be used associated with mechanical mixing to achieve aircrete.

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APPENDIX-1

Table A1.1: Typical ingredients producing lightweight concrete

*Type of LW Concrete	Citation	Binder	Fine Aggregate	Coarse Aggregate	Admixture
LWAC	Tay & Yip (1989)	OPC	Natural sand	Solid sludge aggregate	-
LWACC	Tonyan & Gibson (1992)	Rapid hardening cement	Microsilica	-	Plasticizer, Foaming agent, Polystyrene
LWACC	Latona et al. (1997a, 1997b), Neufeld et al. (1994), Hu et al. (1997)	OPC, Fly ash	-	-	Lime, Aluminium powder
LWAC	Haug et al. (1996)	PCC	Natural quartz, lightweight sand	Crushed gravel (if used)	Plasticizer, Retarder, Air entraining
LWAC	Hunaiti et al. (1997)	OPC	Expanded perlite	-	Foaming agent
LWAC	Haque & Al (1999)	OPC/PCC	Lightweight	Lightweight Aggregate	Plasticizer
LWAC	Campione et al. (2001)	OPC	Natural sand	Expanded clay, Pumice	Polystyrene fiber
LWCC	Huang et al. (2001)	Alumina cement	-	-	Plasticizer, Foaming agent
LWWC	Stahl et al. (2002)	OPC	Natural sand	Wood aggregate	Plasticizer
LWAC	McBride et al. (2002)	OPC, Silica fume	Cenosphere, Silica fume	Natural aggregate	-
LWAC	Steinberg et al. (2003)	OPC	Microsillica slury	Expanded Clay Aggregate	Plasticizer

Table A1.1: Continued…

*Type of LW Concrete	Citation	Binder	Fine Aggregate	Coarse Aggregate	Admixture
LWAC	Lo et al. (2004)	OPC	Fly ash	Expanded Clay Aggregate	Plasticizer
LWAC	Cong-sheng et al. (2004)	OPC, Fly ash	Natural sand	Shale ceramsite	Plasticizer, Viscosity Modifying Admixture
LWAC	Lijiu et al. (2004)	OPC, Fly ash	Natural sand	Shale ceramsite	-
LWRPC	Sadrekarimi et al. (2004)	OPC, Silica fume	Quartz sand	-	Plasticizer
LWAC	Maltais et al. (2004)	OPC/PCC , Fly ash	Lightweight aggregate	Lightweight aggregate	-
LWGC	Glenn et al. (2004)	OPC	-	-	Aquagel
LWCC	Zhihua et al. (2005)	OPC, Fly ash, Fine blast furnace slag, silica fume	-	-	Foaming agent
LWACC	Qingjun et al. (2005)	OPC, Fly ash, Silica fume	Expanded shale, Expanded clay, Natural sand	Expanded shale, Expanded clay	Plasticizer
LWGAC	Nemes and Józsa (2006)	OPC	Natural quartz	Expanded Glass and Clay Aggregate	Plasticizer
LWWC	Teo et al. (2006)	OPC	Natural sand	Oil palm shell aggregate	Plasticizer
LWAC	Lo et al. (2006)	OPC	Lightweight expanded clay fine	Lightweight expanded clay	Plasticizer, Air entraining
LWWC	Karade et al. (2006)	Cement	Cork granules	Cork granules	-

Table A1.1: Continued…

*Type of LW Concrete	Citation	Binder	Fine Aggregate	Coarse Aggregate	Admixture
LWACC	Dunaeva et al. (2006)	High alumina Cement	-	-	-
LWCC	Doniec et al. (2008)	OPC, Fly ash	-	-	Foaming agent
LWAC	Mouli et al. (2008)	PCC	Natural sand	Natural pozzolana	-
LWAC	Mao & Ayuta (2008)	OPC	Natural sand, Perlite powder-	-	Foaming Agent
LWCC	Nambiar et al. (2008a, 2008b, 2009)	OPC, Fly ash	Pulverized sand	-	Foaming agent
LWHPC	Arisoy & Wu (2008)	OPC, Fly ash, Silica fume	Lightweight cenoshperes , Natural sand	-	Plasticizer, Air entraining
LWPC	Zhifeng et al. (2008)	OPC	-	Natural limestone	-
LWAC	Lachemi et al. (2009)	OPC, Fly ash	Blast furnace slag, Expanded shell	Blast furnace slag, Expanded shell	Plasticizer
LWAC	Hadi et al. (2009)	OPC, Fly ash	Tuff, Glass sand, Natural sand	-	Polystyrene fiber
LWAC	Al-Jabri et al. (2009)	OPC, Cement kiln dust	Natural sand, Vermiculite	Crushed lime stone	Foaming Agent
LWAC	Chen et al. (2010)	Cement	Natural sand	Sedimentary Lightweight aggregate	Plasticizer
LWAC	Hussain et al. (2010)	OPC, Volcanic ash	Natural sand, Volcanic pumice,	Gravel aggregate, Volcanic pumice aggregate	-

Table A1.1: Continued…

*Type of LW Concrete	Citation	Binder	Fine Aggregate	Coarse Aggregate	Admixture
LWAC	Chen et al. (2010)	OPC, Silica fume	Natural sand	Natural aggregate	Plasticizer, Polystyrene fiber
LWAC	Hussin et al. (2010)	OPC, Palm oil fuel ash	Natural fine sand	-	Plasticizer
LWAC	Liu & Song (2010)	OPC	Fluvial sand,	Lightweight aggregate	-
LWCC/LWWC	Rodrigues et al. (2010)	OPC, Rice husk ash	Bamboo pulp	-	-

*Type of Lightweight Concrete:

LWAC Lightweight Aggregate Concrete

LWACC Lightweight Autoclave Cellular Concrete

LWCC Lightweight Cellular Concrete

LWGAC Lightweight Glass Aggregate Concrete

LWGC Lightweight Gel Concrete

LWHPC Lightweight High Performance Concrete

LWPC Lightweight Pervious Concrete

LWRPC Lightweight Aggregate Reactive Powder Concrete

LWWC Lightweight Wood Concrete

APPENDIX-2

Theory of Lees and Chorlton

The thermal conductivity of a bad conductor like rubber, glass, leather, cardboard, ebonite, concrete etc. can be determined by Lees and Chorlton's method. In measuring, the conductivity of such a poor conductor one must remember that a thin layer of slab of the material must be used. The difficulty then arises in maintaining the face at uniform temperature and in measuring that temperature. Lees and Chorlton overcame this difficulty by placing a slab of a good conductor, such as brass or copper, of exactly the same diameter the experimental slab on each side of the layer of poor conductor. In Figure A2.1, let S be the disc of a poor conductor, such as concrete and A and B be the thick metallic discs, one on either side of S. C is a stream chamber form which heat passes to B, S and A.

When steam is passed through C, A is warmed up by the heat conducted by S. (Since the slab S is sufficiently thin, the loss of heat from the edge of the slab is small enough to be neglected that the flow of heat across S will be vertically down wards). After some time a steady state will be reached when the rate of flow of heat through S equals the heat lost frm A by radiation and convection.

If, θ_1 = temperature of B in the steady state, θ_2 = temperature of A in steady state, α = area of cross section of the slab S, K = thermal conductivity of the slab S, and d = thickness of the slab, then the quantity of heat conducted per second through the poorly conducting slab is:

$$Q = \frac{K\alpha(\theta_1 - \theta_2)}{d} \tag{5.1}$$

In the steady state, this heat Q is radiated per second from the lower disc A. If m and s be the mass and specific heat of A and $\frac{d\theta}{dt}$ be it state of cooling at its temperature θ_2, then the heat lost (radiated) per second from A is

$$Q = ms\frac{d\theta}{dt} \tag{5.2}$$

$\frac{d\theta}{dt}$ is determined by performing a subsidiary experiment.

From equation i and ii, we get

$$\frac{K\alpha(\theta_1 - \theta_2)}{d} = ms\frac{d\theta}{dt}$$

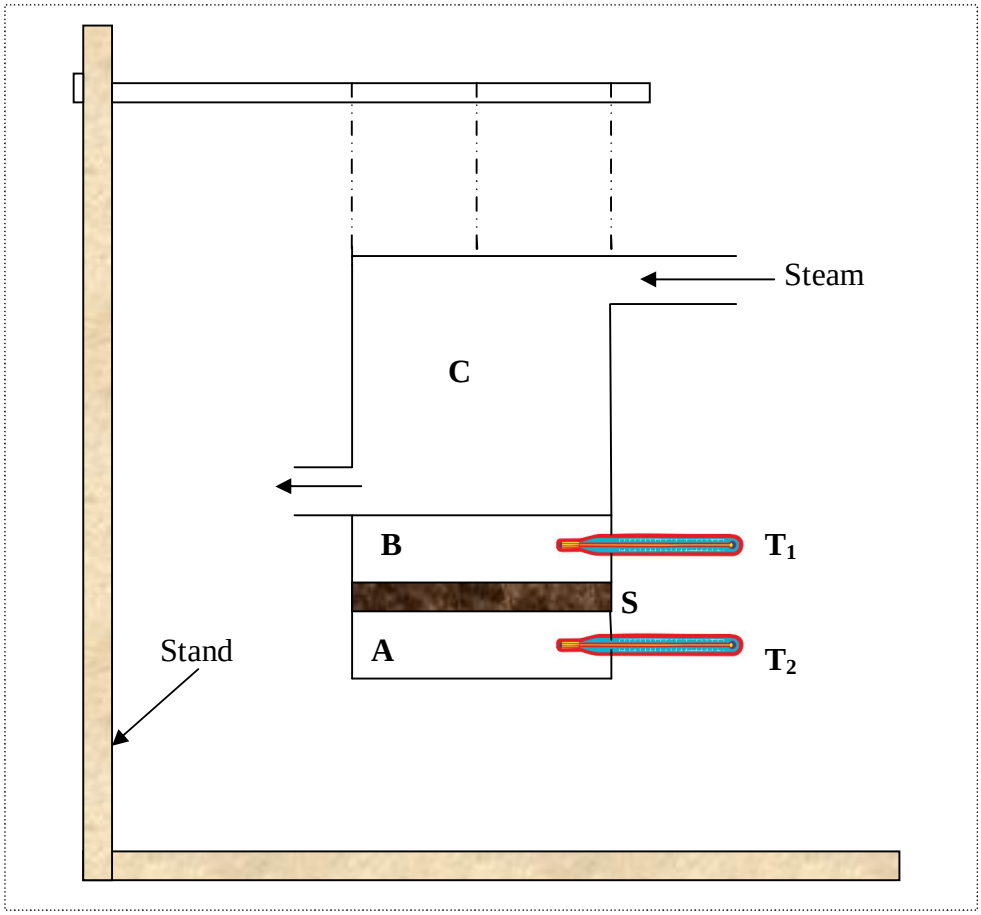
$$\text{Or, } K = \frac{ms\frac{d\theta}{dt}}{\alpha(\theta_1 - \theta_2)} \tag{5.3}$$

Description of Apparatus

The experimental arrangement of the Lees and Chorlton's apparatus is shown in Figure A2.1. A brass disc A of about 10 cm in diameter is supported by means of strings from a large ring on a retort stand. The experimental material in the form of a thin circular stab (S) of uniform thickness and having the same diameter as A, is placed on it (A). A steam chamber C is placed on the slab S. the steam chamber consists of two parts: the top part is a hollow brass cylinder C of the same diameter as S, having side tubes for entry and exit of steam while the bottom part B is a thick metal plate having the same surface area as that of A. The surfaces of A and B are nickel plated to obtain uniform and good emissivity. Two thermometers T_1 and T_2 are introduced into two holes drilled in the base B and A. The whole system is suspended horizontally from a stand by means of three threads attached to three small hooks provided symmetrically along the circumference of A.

Procedure

i. At first weight the disc A was determined as mass m. The diameter (D=2r) of the disc S with a scale (the disc is usually too big for a slide callipers was determined). The thickness d of the disc S was determined accurately with the help of a screw gauge. The apparatus arranged as shown in Figure A2.1. Improvement of the thermal contact of S with A and B was done by moistening it with glycerine.



(a): Configuration of Lees and Chorlton's apparatus

ii. Steam was allowed to pass from a distant boiler into C. The apparatus was screened off from the heat of the boiler. The temperatures θ_1 and θ_2 of B and A respectively were observed. When they were about to become

steady, record θ_1 and were taken at intervals of 5 minutes until they remain constant, for at least two consecutive intervals, i.e, for 10 minutes.

(b): Apparatus used for determining coefficient of thermal conductivity

Figure A2.1: Experimental setup of Lees and Chorlton's apparatus

iii. The supply of steam was stopped. B and C were removed. With the disc S still on top of it, the disc A was heated by moving a burner under it till its temperature rises about 10^0C above the steady temperature, θ_2. The burner was removed and A was allowed to cool. By keeping S on it, it was ensured that A now lost heat in the same surrounding as in the first art of the experiment when it gained heat. The temperature was noted (indicated by T_2) every half minute until the temperature falls by about 10^0C from θ_2.

iv. A graph was drawn with the time of cooling (t) as abscissa and the temperature (θ) of A as ordinate. A tangent was drawn at a point at which the value of the ordinate was θ_2. The slope of the tangent gave the rate of cooling $\frac{d\theta}{dt}$ at θ_2.

Calculation and Result

For convenience, one typical data interpretation and determination of thermal conductivity is shown in here.

Data

Mass of the brass disc A, m = 552 gm

Specific heat of the material of A (brass), s = 0.089 cal/gm ^{0}C

Diameter of the aircrete specimen disc, D = 9.6 cm

Thickness of the aircrete specimen disc, d = 1.6 cm

Area of cross section, $\alpha = \pi\left(\frac{D}{2}\right)^2$ sq. cm = 72.38 sq. cm

Temperature reading of B and A were taken using thermometer and tabulated as Table A2.1 and Table A2.2.

Table A2.1: Time temperature records of B and A

Time (minutes)	**θ_1 in ^{0}C**	**θ_2 in ^{0}C**
0	32	32
5	32	32
10	32	32
15	80	32
20	90	32
25	95	32
30	98	40
35	98	42
40	98	44
45	98	46
50	98	46
55	98	46
60	98	46

Table A2.2: Time temperature record of A during cooling

Time (minutes)	**θ_1 in ^{0}C**		**Time (minutes)**	**θ_1 in ^{0}C**
0	56		$4\frac{1}{2}$	49.5
$\frac{1}{2}$	55		5	49
1	54		$5\frac{1}{2}$	48.5
$1\frac{1}{2}$	53.5		6	48
2	53		$6\frac{1}{2}$	47.5
$2\frac{1}{2}$	52		7	47
3	51.5		$7\frac{1}{2}$	46.5
$3\frac{1}{2}$	51		8	46
4	50			

Calculation of temperature gradient

Using data of Table A2.2, value of $\frac{d\theta}{dt}$ was determined by drawing Figure A2.2.

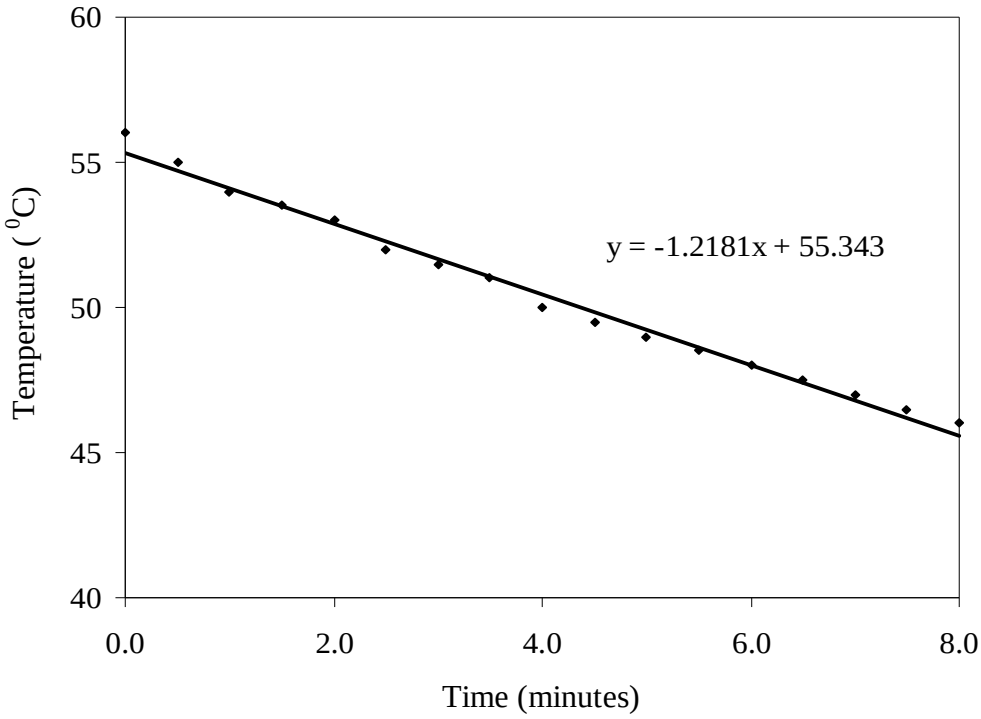


Figure A2.2: Relationship between temperature and time for material A

Calculation of Thermal Conductivity

From above data and value of tangent,

$$K = \frac{ms\frac{d\theta}{dt}d}{\alpha(\theta_1 - \theta_2)}$$

$$K = \frac{552 \times 0.089 \times 0.02 \times 1.6}{72.38 \times (98 - 46)}$$

$$K = 0.000417692\, cal/cm - \sec - {}^0C$$

$$K = 0.175\, W/m - k$$

Absorption Capacity and thermal conductivity test was conducted for the best suitable band in respect of density and compressive strength. However, optimization

band OB-5 and OB-6 were both superior than other bands. Samples of band OB-5 having lower density than that of OB-6 were tested for absorption capacity and thermal property. Table A2.3 provides coefficient of thermal conductivity for band OB-5. Variation of absorption capacity and thermal conductivity with respect to density is shown in Figure A2.3.

Table A2.3: Thermal conductivity of samples for optimization band OB-5

Mix Band	C_1	S_1	L	W	C_1/A	Density (kg/m^3)	Absorption Capacity	Coefficient of Thermal Conductivity (W/m-k)
OB-5	540	587	68	540	50	770	38	0.18
	540	703	68	490		812	32	0.21
	540	820	68	440		830	28	0.23
	490	632	61	540		791	35	0.22
	490	748	61	490		821	32	0.25
	490	865	61	440		859	26	0.29
	440	677	55	540		792	33	0.21
	440	793	55	490		892	26	0.32
	440	910	55	440		921	26	0.36

Content in kg/m^3

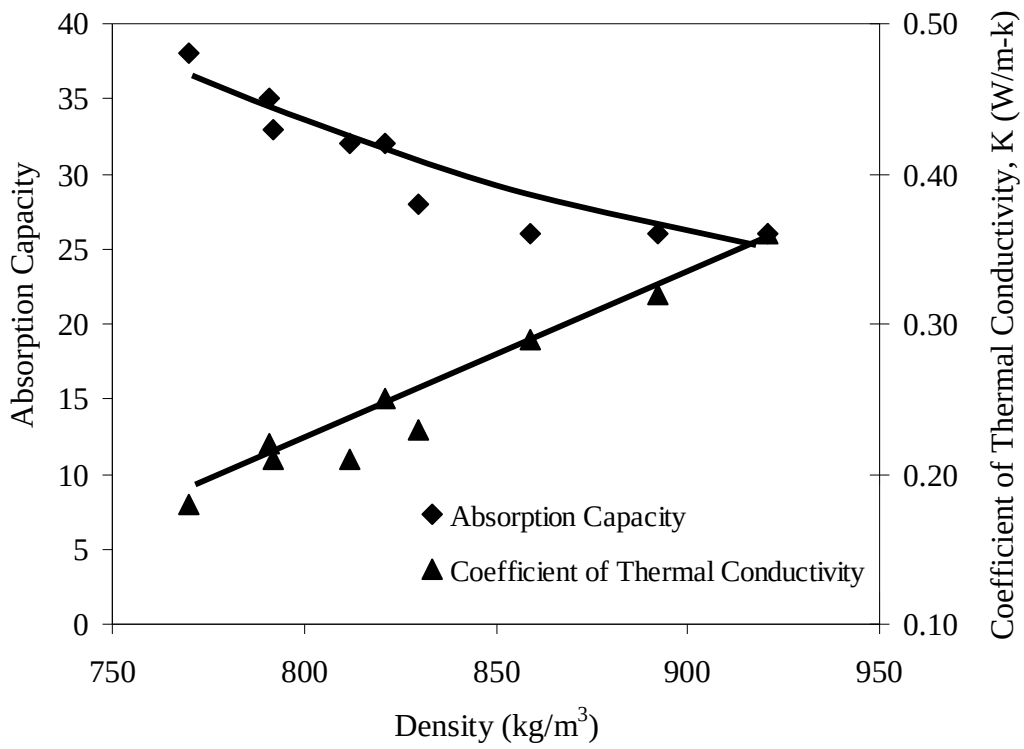


Figure A2.3: Relationship among coefficient of thermal conductivity, absorption capacity and density

Precautions

i. Temperature θ_1 and θ_2 of B and A should be noted when they remain steady for at least 10-15 minutes.

ii. The surfaces of A and B should be nickel plated to ensure uniform and good emissivity.

iii. The discs B, S and A should be lightly pressed together so that there was no air films between B and S and between S and A. Some glycerine might also be applied to the faces in contact to obtain good thermal contacts.

iv. The thermometers should be place close to the faces of S, one on either side.

v. A non-luminous flame should be used while heating A so that the emissivity or the surface did not change by the deposition of soot on it.

vi. The thickness of the disc S should be measured at a number of points on its surface.

vii. During cooling, the temperature of the lower disc A should be noted every half minute or more frequently, in the rate of cooling be very rapid.

viii. The samples should be plane on both faces. If required, they should be treated by rough surface for any uneven hump on the surface.