STRUCTURAL LIGHTWEIGHT CONCRETE WITH NATURAL PERLITE AGGREGATE AND PERLITE POWDER

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MESUT AŞIK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

SEPTEMBER 2006

Approval of the Graduate School of Natural and Applied Sciences.

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Erdal Çokca
Head of the Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Lutfullah Turanlı
Supervisor

Examining Committee Members

Prof. Dr. Mustafa Tokyay (METU,CE)

Assoc. Prof. Lutfullah Turanlı (METU,CE)

Prof. Asım Yeğinobalı (TÇMB)

Assoc. Prof. Ali İhsan Ünay (METU,ARCH)

MSc. Mehmet Fatih Kocabeyler (DSİ)

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Mesut Aşık

Signature :

ABSTRACT

STRUCTURAL LIGHTWEIGHT CONCRETE WITH NATURAL PERLITE AGGREGATE AND PERLITE POWDER

AŞIK, Mesut
M.S., Department of Civil Engineering
Supervisor: Assoc.Prof. Lutfullah TURANLI

September 2006, 80 pages

Structural lightweight aggregate concrete is an important and versatile material, which offers a range of technical, economic and environmental-enhancing and preserving advantages and is designed to become a dominant material in the new millennium. For structural application of lightweight concrete, the density is often more important than the strength. A decreased density for the same strength level reduces the self-weight, foundation size and construction costs. Structural lightweight aggregate concrete generally used to reduce dead weight of structure as well as to reduce the risk of earthquake damages to a structure because the earthquake forces that will influence the civil engineering structures are proportional to the mass of those structures.

In this study, structural lightweight aggregate concrete was designed with the use of natural perlite aggregate that will provide an advantage of reducing dead weight of structure and to obtain a more economical structural lightweight concrete by the use of perlite powder as a replacement of the cement. Six mixes were produced with different cement content and with or without perlite powder. Six mixes divided into two groups according to their cement content. First group had a cement content of 300 kg/m^3 and second group had cement content of 500 kg/m^3; also the water/cement ratios of groups were 0.49 and 0.35 respectively. Moreover, each group had three sub-mixes with 0%, 20% and 35% of perlite powder as cement replacement.

According to results of experimental study, it was concluded that natural perlite aggregate can be used in the production of structural lightweight aggregate concrete. Based on the strength and density results of experimental work, it is possible to produce lightweight concrete with 20 MPa-40 MPa cylindrical compressive strength by using natural perlite aggregate. Also, the use of perlite powder, which will provide economy, can reduce dead weight further and increase performance.

Key words: Perlite Aggregate, Perlite Powder, Structural Lightweight Concrete.

ÖZ

DOĞAL PERLİT AGREGALI VE ÖĞÜTÜLMÜŞ PERLİT KATKILI TAŞIYICI HAFİF BETON

AŞIK, Mesut
Yüksek Lisans, İnşaat Müh. Bölümü
Tez Yöneticisi: Doç. Dr. Lutfullah TURANLI

Eylül 2006, 80 Sayfa

Taşıyıcı hafif beton teknik, ekonomik ve çevreyi koruyucu bir alan sunan önemli ve çok yönlü bir malzemedir. Ayrıca taşıyıcı hafif beton sağladığı avantajlar ile yeni çağın en önemli yapı malzemelerinden biri olacaktır. Taşıyıcı hafif betonda çoğunlukla kütle, dayanımdan daha önemlidir. Aynı dayanım için azalan kütle, yapının öz ağırlığını, temel ebatlarını ve yapım maliyetlerini düşürmektedir. Taşıyıcı hafif betonlar genellikle yapının öz ağırlığını azaltmak için kullanılır ve dolayısıyla yapıya gelen deprem etkisi de azalmış olur; çünkü yapıya etkiyen deprem yükü yapının kütlesiyle doğru orantılıdır.

Bu çalışmada, doğal perlit agregası ile yapının öz ağırlığının azalmasını sağlayacak taşıyıcı hafif beton dizaynı yapılmıştır. Ayrıca betonda ekonomiyi sağlamak için de betonda mineral katkı olarak belirli bir oran dahilinde çimentonun yerine perlit tozu kullanılmıştır. Çimento ve perlit tozu miktarı farklı olan altı karışım hazırlanmıştır. Bu altı karışım çimento miktarlarına göre ikiye ayrılmıştır. İlk grup 300 kg/m^3 çimento içermektedir ve su/çimento oranı 0.49'dur. İkinci grubun ise çimento miktarı

500 kg/m^3 ve su/çimento oranı 0.35'dir. Her iki grupta %0, %20, %35 perlit tozu içeren üç alt gruba ayrılmıştır.

Yapılan araştırma ve deneyler sonucunda doğal perlit agregasının taşıyıcı hafif beton üretiminde kullanılabileceği görülmüştür. Çalışmada elde edilen kütle ve dayanım sonuçlarına bakılırsa, doğal perlit agregası ile 20 MPa-40 MPa silindir basınç dayanımı olan hafif beton üretmek mümkündür. Ayrıca ekonomik beton elde edilmesini sağlayan perlit tozu kullanılarak da taşıyıcı hafif betonun performansının arttırılabileceği ve kütlesinin daha da düşürülebileceği görülmüştür.

Anahtar Kelimeler: Doğal Perlit Agregası, Perlit Tozu, Taşıyıcı hafif beton.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Assoc.Prof. Lutfullah Turanlı for his perfect assistance guidance, recommendations and support throughout this research and preparation of this thesis. Also I would like to acknowledge Asist. Burak Uzal for his important support and assistance.

I am thankful to my wife, Emine Nur, for her valuable help and especially spiritual supports.

Sincere thanks are due to my friend Özlem Aslan for her support. Thanks are also extended to the staff of the laboratory, Ali Yıldırım and Harun Koralay for their help during the experimental study.

I wish to thank Denge Mimarlık Mühendislik, the firm where I have been working, for their support at preparation of this thesis.

Finally, I am grateful to my family for their endless encouragement and support throughout my life.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

TABLE

LIST OF FIGURES

FIGURE

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
SLWAC	Structural Lightweight Aggregate Concrete
LWA	Lightweight Aggregate
PP	Perlite Powder
NPA	Natural Perlite Aggregate
SP	Superplasticizer
TS	Turkish Standard
NWC	Normal Weight Concrete
LWAC	Lightweight Aggregate Concrete

CHAPTER 1

INTRODUCTION

1.1. General

Structural lightweight aggregate concrete is an important and versatile material, which offers a range of technical, economic and environmental-enhancing and preserving advantages and is designed to become a dominant material in the new millennium. It has many and varied applications: multistory building frames and floors, curtain walls, shell roofs, folded plates, bridges, prestressed and pre-cast elements of all types and others.

Structural lightweight aggregate concrete generally used to reduce dead weight of structure as well as to reduce the risk of earthquake damages to a structure because the earthquake forces that will influence the civil engineering structures and buildings are proportional to the mass of those structures and buildings. Thus, reducing to the mass of structure or building is utmost important to reduce their risk due to earthquake acceleration. Also, reduction in the dead weight of a construction could result in a decrease in the cross-section of columns, beams, plates and foundations.

Higher strength/weight ratio, better tensile strain capacity, lower coefficient of thermal expansion and superior heat and sound isolation characteristics due to air voids of the lightweight aggregates are advantages of structural lightweight aggregate concrete.

Natural pozzolans are the naturally occurring siliceous or siliceous and aluminous materials which in themselves posses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. The use of finely divided natural pozzolans as concrete admixtures has significant effect on the properties of fresh and hardened concrete. Water requirement, workability, time of setting, heat of hydration, bleeding and finishability are some of the properties of fresh concrete affected by the use of finely divided mineral admixtures. Strength, permeability, sulfate resistance, alkali silica reactivity and economy are major properties of hardened concrete influenced by the use of finely divided natural pozzolans.

In this study, the major reason of using natural pozzolan is to provide economy and also the reason of selecting perlite powder as a natural pozzolan is to decrease the cost of pozzolan by using powder of natural perlite aggregate which is the main part of structural lightweight aggregate concrete of this study.

Although there are many studies on structural lightweight aggregate concrete, there are few published studies on the use of natural perlite aggregate in structural lightweight aggregate concrete and there are few published materials on structural lightweight aggregate concrete with perlite powder.

1.2. Object and Scope

The object of the study is to investigate the performance of structural lightweight aggregate concrete with the use of natural perlite aggregate and to obtain a more economical structural lightweight aggregate concrete mixture with the use of perlite powder as a cement replacement.

Two groups of concrete mixtures were produced with different cement contents and water/cementitious-materials ratio (w/cm). Each group has three sub-mixes with different percentages of perlite powder as cement replacement. One of the sub-mixes was without perlite powder and the other two were produced by using 20% and 35%

of perlite powder as cement replacement. Superplasticizer was used in all mixtures to obtain the required slump and workability.

For the mixtures produced, properties of fresh concrete such as: slump, density, air-content and setting time were determined. Also, compressive strength, tensile strength and modulus of elasticity of hardened concrete and as a durability performance, drying shrinkage and chloride penetration of hardened concrete were determined.

Moreover, the effect of perlite powder on the properties of fresh and hardened concrete was investigated. The optimum percentage of perlite powder to be used as cement replacement was also searched.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1. Concrete

Concrete is a composite material that consists of a cement paste within which various sizes of fine and course aggregates are embedded. It contains some amount of entrapped air and may contain purposely-entrained air by the use of air-entraining admixtures. Various types of chemical admixtures and/or finely divided mineral admixtures are frequently used in the production of concrete to improve or alter its properties or to obtain a more economical concrete.

Since the cement paste is a plastic material when the cement and water are first mixed, the mixture of the concrete making materials is also plastic when first mixed. Since cement paste gains the rigidity and hardness (due to chemical reactions taking between the cement and the water) as time passes, the plastic concrete mixture also gains rigidity and hardness in time. Therefore, by placing the plastic concrete mixture into a mold having the desired shape and dimensions, a rock like material having the desired shape and dimensions is obtained when the concrete hardness.

The plastic state of the concrete starting from the time that the concrete making materials are mixed until the concrete gains rigidity is called “fresh concrete”; the state of the concrete starting from the time it gains rigidity is called “hardened concrete” [1].

Concrete is a material that literally forms the basis of our modern society. Scarcely any aspect of our daily lives does not depend directly or indirectly on concrete.

The popularity and wide use of concrete as a construction material derives from its advantages over other construction materials. Some of these advantages can be listed as follows:

- Concrete has the ability to be cast to any desired shape since it is in a plastic condition when the materials are mixed and hardens as time passes.
- Concrete is durable because it does not easily lose its quality as does steel, which corrodes, and as does timber, which decays with time.
- Concrete is economical: a) because of the abundance and relatively low price of the aggregates which constitute about three fourths of its volume, b)because semi-skilled workers can largely be employed and relatively unsophisticated equipment used in concrete work, c)because of the low maintenance cost.
- Concrete is an efficient material as compared to metals and other construction materials. Aggregates, which constitute the greatest part of concrete volume, are abundant and cheap as mentioned.
- Concrete has satisfactorily high compressive strength.
- Concrete has fairly high fire resistance as compared to that of metals and timbers.
- Concrete has aesthetic properties since concrete elements of any shape and color can be produced easily by the use of admixtures [1].

2.1.1. Concrete Making Materials

2.1.1.1. Cement

Cement is a generic term that can apply to all binders. There is a wide variety of cements that are used to some extent in the construction and building industries, or to solve special problems. The chemical composition of these cements can be quite diverse, but by far the greatest amount of concrete used today is made with portland cements [2].

Portland cement is a hydraulic binder produced by pulverizing a small amount of gypsum along with the portland cement clinker that is obtained by burning an appropriate combination of calcareous and clayey materials.

The mixture of cement and water is called “cement paste”. The function of the cement paste in a concrete is to cover the surfaces of the aggregate particles, to fill the spaces between the particles and produce a compact mass by binding the aggregates particles [1].

2.1.1.2. Aggregates

Aggregates generally occupy 70 to 80 percent of the volume of concrete and can therefore be expected to have an important influence on its properties. They are granular materials, derived for the most part from natural rock (crushed stone or natural gravels) and sands, although synthetic materials such as slag and expanded clay or shale are used to some extent, mostly in lightweight concretes. In addition to their use as economical filler, aggregates generally provide concrete with better dimensional stability and wear resistance [2].

Aggregate classifications are made principally for the purpose of easier identification of particular aggregate lots, or to become familiar with the different types of aggregates. There are numerous ways of classifying aggregates. These classifications are made according to source of aggregate, specific gravity or unit weight of aggregate, size of aggregate particles, shape of aggregates, surface texture of aggregates, mode of preparation of aggregates, geological origin of aggregates, mineral composition of aggregates and reactivity of aggregates [1].

Aggregates are not generally classified by mineralogy; the simplest and most useful classifications are on the basis of source and specific gravity.

Aggregates are classified as natural or artificial aggregates according to their source:

1. *Natural Aggregates*: Natural aggregates are those taken from native deposits with no change in their natural state during production other than crushing,

grading or washing. Sand, gravel, crushed stone, pumice are examples of natural aggregates.

2. *Artificial Aggregates*: Artificial aggregates are those materials or particles which are obtained either as a by-product of an unrelated industrial process or by a special manufacturing process like heat treatment. Blast-furnace slag is typical example of a by-product aggregate; expanded perlite, expanded vermiculite, burned clay and fly ash aggregate are example of aggregates produced by heat treatment.

With regard to their specific gravity or unit weight, concrete aggregates are classified as:

1. *Normal Weight Aggregates*: Normal weight aggregates have specific gravities of between 2.4 and 2.8.
2. *Lightweight Aggregates*: Aggregates with a specific gravity of less than 2.4 are called lightweight aggregates.
3. *Heavyweight Aggregates*: Aggregates with a specific gravity more than 2.8 are called heavyweight aggregates [1].

There are three main reasons for mixing aggregate with cement paste to form concrete rather than using cement paste alone. The first and oldest reason is that aggregate is cheaper than cement, so its use extends the mix and reduces costs. Second, aggregate reduces shrinkage and creep, giving better volume stability. Third, aggregate gives greater durability to concrete. Many deterioration processes principally affect the cement paste. There are clear economic and technical reasons for using as much aggregate and as little cement as possible in a concrete mix.

Aggregate is the main constituent of concrete and the properties of aggregate influence the properties of concrete. Consistency of particle size distribution is important to the properties of fresh concrete. There is a more minor influence on the hardened concrete properties. Larger maximum size benefits lean concrete but optimum size is around 20mm for normal concrete. Equidimensional particle shapes are best. Shape and texture affect water demand and aggregate-cement paste bond.

Aggregate must be strong enough to withstand mixing, handling and compaction without degradation. Most aggregates restrain concrete shrinkage. A few aggregates undergo large volume changes on wetting and drying, and may produce concrete with poor volume stability. Some aggregates are less able to cope than others with stress induced by environmental conditions. Susceptible aggregates may disintegrate after cycles of freezing and thawing. The thermal coefficient of expansion of concrete is largely determined by the aggregate. All aggregates produce fire resistant concrete though lightweight aggregates are usually best.

Moderate fines contents are useful for cohesion of concrete and finish ability of concrete. Excessive fines contents increase water demand and may interfere with the aggregate-cement paste bond. Occasionally, impurities are associated with aggregates. At best, impurities impart no benefit to concrete if present in sufficient quantities, their effects can be detrimental. Aggregate is essential to the economy, stability and durability of concrete [3].

2.1.1.3. Water

Water is a key ingredient in the manufacture of concrete. It is also material on its own right. Understanding its properties is helpful in gaining and understanding of its effects on concrete and other building materials.

Although water is an important ingredient of concrete little needs to be written about water quality, since it has little to do with the quality of the concrete. However mixing water can cause problems by introducing impurities that have detrimental effects on concrete quality. Although satisfactory strength development is of primary concern, impurities contained in the mix water may also affect setting times, drying shrinkage, or durability, or they may cause efflorescence. Water should be avoided if it contains large quantities of suspended solids, excessive amounts of dissolved solids, or appreciable amounts of organic materials [2].

2.1.1.4. Mineral Admixtures

Mineral admixtures refer to the finely divided materials which are added to obtain specific engineering properties of cement mortar and concrete. The other, equally important, objectives for using mineral admixtures in cement concrete include economic benefits and environmentally safe recycling of industrial and other waste by-products. Unlike chemical admixtures, they are used in relatively large amounts as replacement of cement and/or of fine aggregate in concrete [5].

Mineral admixtures are classified into three general types:

1. Those which are pozzolanic or mainly pozzolanic with some additional cementitious properties.
2. Those which are cementitious
3. Others

Pozzolans are siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [5].

The name “pozzolan” is a corruption of Pozzuoli, a town in the Bay of Naples that was the source of a highly prized deposit of weathered ash from Mount Vesuvius. The name is now applied to any reactive aluminosilicate material, of either natural or industrial origin [2].

Volcanic ashes, volcanic tuffs (trusses), volcanic glasses, pumicites, calcined clays or shales, diatomaceous earths, fly ashes (the fine ashes obtained from the burning of pulverized coal in power plants for generating electricity), condensed silica fumes (the finely divided materials obtained as a by-product material in the manufacture of silicon metal or silicon alloys), and rice husk ashes are the commonly known materials that exhibits pozzolanic characteristics [4].

When pozzolans are used in combination with portland cement, calcium hydroxide liberated from the hydration of portland cement reacts with the alumino silicates present in the pozzolans to form cementitious compounds possessing cohesive and adhesive properties [5].

The amorphous or glassy silica, which is the major component of pozzolan, reacts with calcium hydroxide formed from the hydration of the calcium silicates. The principal reaction is;

$$\underset{\substack{\text{Calcium}\\ \text{Hydroxide}}}{\mathrm{CH}} \quad + \quad \underset{\text{Silica}}{\mathrm{S}} \quad + \quad \underset{\text{Water}}{\mathrm{H}} \longrightarrow \underset{\substack{\text{Calcium Silicate}\\ \text{Hydrate}}}{\mathrm{C-S-H}} \tag{2.1}$$

The activity of a pozzolanic material with hydrated lime, that is, how well a pozzolan will behave in a mortar or in a concrete, is expressed as its “pozzolanic activity”. In other words, “pozzolanic activity” refers the reaction of alumino-silicates with calcium hydroxides to form cementitious products. Pozzolanic activity of natural pozzolans and fly ashes is determined by conducting tests to find out their “strength activity index” according to ASTM C311 [6]. The test for strength activity index is used to determine whether a mineral admixture results in an acceptable level of strength development when used with hydraulic cement concrete [4].

A pozzolan in finely divided form may be used in three ways for producing a binding effect:

1. *directly*: by mixing it with calcium hydroxide or
2. *as an addition in the production of blended cements*: the pozzolan is interground with portland cement clinker at the cement factor or,
3. *as concrete admixture*: by adding pozzolan to the mixture during or before the batching operation.

Pozzolans generally grouped as:

1. *Natural Pozzolans*: These are naturally occurring materials such as volcanic ashes, volcanic glasses, volcanic tuffs.

2. *Artificial Pozzolans*: These are industrial by-products such as fly ashes, silica fumes, and granulated blast furnace slag

Natural pozzolans are mostly materials of volcanic origin. Naturally occurring materials such as clays, shales and diatomaceous rocks are also regarded as natural pozzolans after being thermally treated [4].

Natural pozzolans of volcanic origin are formed during explosive volcanic eruptions when the quick cooling of magma, composed mainly of alumino silicates, results in the formation of amorphous (glass) or vitreous phases with disordered structure. Due to simultaneous dissolved gases, the solidified matter frequently acquires a porous structure with high surface area. Because of the large surface area and disordered structure, the alumino silicates present in pozzolans undergo chemical reaction with Ca^+ ions in the presence of water. This forms the basis of pozzolanic reaction with lime, and the resultant pozzolanic activity.

Natural pozzolans and industrial by-products are generally available at substantially lower costs than portland cement. They are generally finer than cement and process pozzolanic and sometimes cementitious properties. Thus their use as partial replacement for cement can lead to considerable cost savings in addition to the possible benefits such as improved workability, reduced bleeding, and heat of hydration, enhanced ultimate strength, impermeability and chemical durability, and improved resistance to thermal cracking [5].

2.1.1.5. Chemical Admixtures

Although concrete admixtures are chemicals in a literal sense, by convention in concrete technology, the term “chemical admixture” is restricted to water soluble compounds other than air-entraining agents. They are adding primarily to control setting and early hardening of fresh concrete or to reduce its water requirements [4].

Chemical admixtures grouped as:

a) Water reducing admixtures,

b) Retarding admixtures,
c) Accelerating admixtures,
d) Water-reducing and retarding admixtures,
e) Water-reducing and accelerating admixtures,
f) High-range water reducing admixtures (plasticizers),
g) High-range water-reducing and retarding admixtures (superplasticizers),

A water reducing admixture lowers the water required to attain a given slump; that is, it reduces the water demand of the concrete. This property can be used to advantage in several ways. Achieving the desired slump with less water at constant cement content means an effective lowering of the w/c ratio, with a consequent general improvement in strength, impermeability and durability. Alternatively, the desired slump may be achieved without changing the w/c ratio by lowering the cement content. This may be done for economic reasons or for technical reasons. Finally, a water-reducing admixture may be used to increase slump without increasing cement and water contents, to facilitate difficult placements [2].

Water reducers consist of Ca, Na or NH_4 salts of lignosulfonic acid, Na, NH_4 or triethanolamine salts hydroxycarboxylic acid, and carbohydrates. Lignosulfonates containing (OH), (COOH) and (SO_3H) groups are more widely used than others.

Normal water reducers decrease the water requirements of concrete by about 10 to15 percent, whereas superplasticizers are capable of reducing the water requirements by about 30%. Most superplasticizers are based on sulfonated melamine formaldehyde, sulfonated naphthalene formaldehyde and modified lignosulfonates [5].

The compounds of both the normal range and high range water reducing admixtures are adsorbed at the solid-water interface and they function by dispersing the cement particles. The significance difference between the normal-range and high-range water reducing admixtures is that the latter can be added at high dosage rates without having an unacceptable effect on the time of setting or amount of air content. The molecules of formaldehyde condensates of naphthalene and melamine contain no hydroxyl groups which are responsible for retardation [4].

Retarders can be used whenever it is desirable to offset the effects of high temperatures that decrease setting times or to avoid complications when unavoidable delays may occur between mixing and placing. Prolonging the plasticity of fresh concrete can be used to advantage in placing mass concrete. Retarders can also be used to resist cracking due to form defection can occur when horizontal slabs are placed in sections. If the plastic period is prolonged, the concrete can adjust to form deflections without cracking [2].

Many organic and inorganic compounds have been used as retarders. The organic compounds include unrefined Ca, Na or NH_4 salts of lignosulfonic acid, Na, NH_4 or triethanolamine salts hydroxycarboxylic acid, and carbohydrates. Inorganic compounds such as oxides of Pb and Zn, phosphates, Mg salts, fluorates and borates also act as retarders. Chemicals falling in to first three categories also posses water reducing capabilities and can be classified as water-reducing and set-retarding admixtures [5].

Accelerators are used to reduce the setting times and accelerate the hardening of concrete. Many inorganic compounds play this role, including chlorides, fluorides, carbonates, silicates, aluminates, borates, nitrites, thiosulfates etc. organic compounds such as triethanolamine, diethanolamine, propionate, urea, glyoxal and formate have also been advocated for use as accelerators. Calcium chloride is the most efficient and economical accelerator for use in concrete [5].

When considering accelerating admixtures, it is important to distinguish between admixtures that accelerate the normal processes of setting and strength development and those that provide very rapid setting characteristics not normally associated with ordinary portland cements. Regular accelerators are used to speed construction by permitting earlier finishing of flatwork and earlier attainment of sufficient strength to allow removal of formwork and to carry construction loads [2].

2.2. Structural Lightweight Concrete

Concretes are grouped in to three according to their unit weights:

1. *Heavy concrete*: Unit weight is in the range of 3200 kg/m^3-4000 kg/m^3 and this kind of concrete mainly used in nuclear reactors.
2. *Normal concrete*: Unit weight is in the range of 2400 kg/m^3-2600 kg/m^3.
3. *Lightweight concrete*: Unit weight is less than 2000 kg/m^3.

Lightweight concretes can be divided into structural lightweight concretes and ultra-lightweight concretes for non-structural purposes. ACI Committee 213 [7] makes three divisions (Figure 2.1.) on the basis of strength and unit weight:

- Low-density, low-strength concrete used for isolation,
- Moderate-strength lightweight concrete used for concrete block and other applications where some useful strength is desirable,
- Structural lightweight concretes,

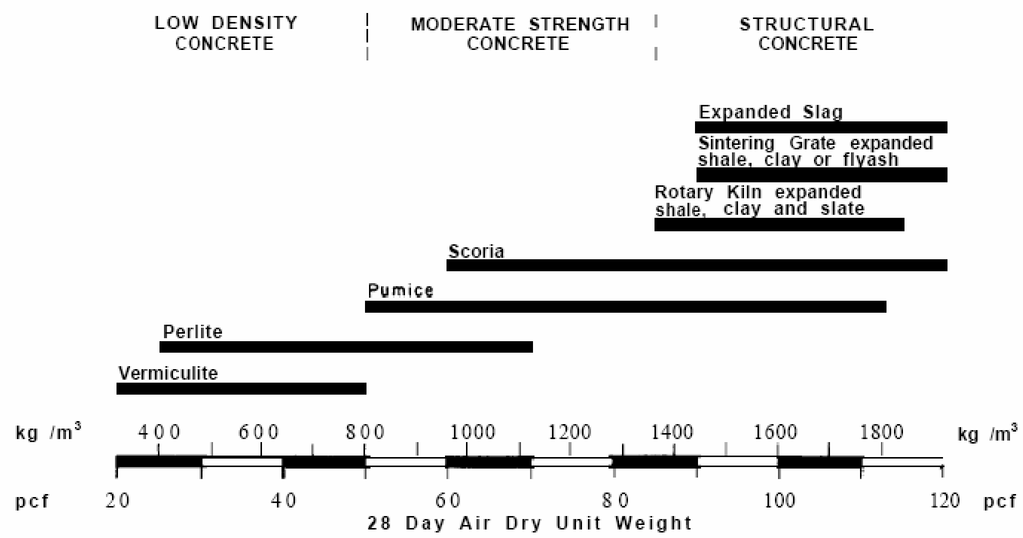


Figure 2.1. Approximate Unit Weight and Use Classification of Lightweight Aggregate Concretes [7].

Low density concretes, these very light nonstructural concretes, are employed chiefly for insulation purposes. With low unit weights, seldom exceeding 800 kg/m^3, thermal conductivity is low. Compressive strengths ranging from about 1.0 MPa to 7.0 MPa are characteristics.

Moderate strength concretes, require a fair degree of compressive strength, and thus they fall about midway between the structural and low-density concretes. These are sometimes designed as "fill" concretes. Compressive strengths are approximately 7.0 MPa to 17.0 MPa and insulation characteristics are intermediate.

Structural concretes, contain aggregates that fall on the other end of the scale and that are generally made with expanded shales, clays, slates, slags, pumice and scoria. Minimum compressive strength, by definition, is 17.0 MPa. Most structural lightweight aggregates are capable of producing concretes with compressive strengths in excess of 35.0 MPa and, with many of these; concretes can be made with strengths considerably greater than 40.0 MPa. Since the unit weights of structural lightweight aggregate concretes are considerably greater than those of low density concretes, insulation efficiency is lower. However, thermal conductivity values for structural lightweight concrete are substantially better than for normal weight concrete [7].

According to ACI 213 [7], *structural lightweight aggregate concrete* is structural concrete made with lightweight aggregate; the air-dried unit weight at 28 days is usually in the range of 1440 kg/m^3 to1850 kg/m^3 and the compressive strength is more than 17.2 MPa. However, ACI 213 [7] definition continues like that this definition is not a specification. Job specifications may, at times, allow unit weights up to 1900 kg/m^3.

2.2.1. History

Lightweight aggregate concrete is not a new invention in concrete technology. It has been known since ancient times, so it is possible to find a good number of references in connection with the use of LWAC. It was made using natural aggregates of volcanic origin such as pumice, scoria etc. Sumerians used this in building Babylon in the 3rd millennium B.C. The Greeks and the Romans used pumice in building constructions. Some of these magnificent ancient structures still exists, like St. Sofia Cathedral or Hagia Sofia, in Istanbul, in Turkey, built by two engineers, Isidore of Miletus and Anthemius of Tralles, commissioned by the Emperior Justinian in the 4th century A.D.; the Roman temple, Pantheon, which was erected in the years A.D. 118 to 128; the prestigious aqueduct, Pont du Gard, built ca. A.D. 14; and the great Roman amphitheatre, Colosseum, built between A.D. 70 and 82. With the increase in the demand for LWAC and unavailability of aggregates, technology for producing lightweight aggregates has been developed [9].

The use of lightweight concrete in the United Sates dates back to 1900s. Expanded clays and shales were developed commercially by S.H. Hayde and were used for shipbuilding during World War I. The Park Plaza Hotel in St. Louis was a early example of lightweight concrete construction in the 1920s. Since 1950s, lightweight concrete has been used regularly in multistory buildings and other large structures. Some of the more notable structures are the Bank of America Corporate Center, Cahrlotte; the Watergate Apartments, Washington D.C.; and the Lake Point Towers, Chicago. Lightweight concretes are also used for applications as diverse as highway bridges and offshore drilling platforms [2].

Concrete is most known as a grey material with good mechanical strength, but heavy and cold. It is generally understood that concrete is not necessarily just heavy, sharp-edged grey blocks. It can acquire any shape, color, density and strength [9].

2.2.2. Structural Lightweight Aggregates

According to ACI 213 [7], structural lightweight aggregates are grouped into two:

1. Naturally occurred and unprocessed aggregates
2. Processed aggregates

Natural lightweight aggregates are mostly of volcanic origin and, thus, found only in a certain parts of the world. Pumice and scoria are the oldest known LWA; they were used extensively in Roman time. These are light and strong enough to be used in their natural state, but their properties are variable [9].

Perlite, a hydrated volcanic glass, commonly has a pearly, vitreous luster characterized y concentrating onionskin fractures. A relatively high water content of 2 to 5 percent distinguishes perlite from other hydrous volcanic glasses, such as obsidian, hydrated volcanic ash and pumicites. Upon rapid heating, perlite transforms into a cellular material of low bulk density. As the chemical water held within the perlite boils, generally at temperatures in the range of 900 °C-1000 °C, the resultant steam forms bubbles within the softened rock to produce a frothy-like structure. The formation of these bubbles allows perlite to expand up to 15-20 times of its original volume. This new material is referred to as "expanded perlite". Because of its favorable physical and chemical characteristics, expanded perlite finds diverse utilization in various applications: for use as a lightweight aggregate in the construction industry; as a rooting medium and soil conditioner in horticulture; as a bleaching agent in the textile industry; as an absorbent in the chemical industry; and as a filter aid and as filler in miscellaneous processes [9].

In all cases the lightweight aggregates used in structural concrete are light in weight due to cellular structure of the individual aggregate particles. This cellular structure within the particle size is foamed at high temperatures, generally 1000 °C or higher, one or more of the following process:

- Formation of gases, due to reaction of heat in certain constituents in the raw materials, coincidental with incipient fusion of the mineral, so that the gases are entrapped in a viscous, pyroplastic mass causing bloating or expansion.
- After heating, subjecting a softened of molten mass to intermixing with controlled amount of water or steam so that a cellular structure is produced by entrapped steam and other gas and is retained on cooling of the mass.
- Burning off combustible materials within a matrix. The cells in the aggregate particle may vary from microscopic to macroscopic in size, and be either predominantly interconnected or discrete.

2.2.2.1. Properties

Each of the properties of the lightweight aggregates may have some bearing on the properties of plastic and hardened concrete. However, those properties of lightweight concrete, in common with those of normal weight concrete, are greatly influenced by the quality of the cement paste. Specific properties of aggregates which may affect the properties of concrete as follows:

- *Particle shape and texture surface*: Lightweight aggregates with different sources or produced by different methods may differ considerably in particle shape and the texture. Shape may be cubical and reasonably regular, essentially rounded or angular and irregular. Surface texture may range from relatively smooth with small exposed pores to irregular with small to large exposed pores. Particle shape and surface texture of both fine and coarse aggregate influence proportioning of mixes in such factors as workability, fine to coarse aggregate ratio, cement content and water requirement.
- *Bulk specific gravity*: Due to their cellular structure, the specific gravity of lightweight aggregates is lower than that of normal weight aggregates. The bulk specific gravity of lightweight aggregate also varies with particle size, being highest for the fine particles and lowest for the coarse particles, with the magnitude of the differences depending on the processing methods. The practical range of bulk specific gravities of coarse lightweight aggregates, corrected the dry condition, and is about 1/3 to 2/3 of that for normal weight aggregates.
- *Unit weight*: unit weight of lightweight aggregate is significantly lower, due to cellular structure, than that of normal weight aggregates. For the same gradation and the particle shape, unit weight of aggregate is essentially proportional to specific gravity.
- *Maximum size*: The maximum size grading designations of lightweight aggregates generally available are 19 mm, 13 mm, 10 mm. Maximum size of aggregates influences such factors as workability, ratio of fine to coarse aggregate, cement content, optimum air content, potential strength ceiling and drying shrinkage.

- *Strength of lightweight aggregates*: The strength of aggregate particles varies with type and source and is measurable only in a qualitative way. Some particles may be strong and hard, and others weak and friable. There is no reliable correlation between aggregate strength and concrete strength and lower particle strength would not preclude use of an aggregate in structural concrete.
- *Moisture content and absorption*: Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normal weight aggregates. Based on 24hr absorption test, lightweight aggregates generally absorb from 5 to 20 percent by weight of dry aggregate, depending on the pore structure of the aggregate. The important difference is that the moisture content in lightweight aggregates is largely absorbed into the interior of the particles whereas in normal weight aggregates it is largely surface moisture [7].

2.2.3. Mix Design of Structural Lightweight Concrete

Lightweight aggregate concrete has a lower compressive strength than normal concrete with the same w/c ratio based on the assumption that the lightweight aggregate particles have lower strength than the hardened cement paste. There are several advantages in using lightweight aggregates. These are due to their bond with the cement paste and closeness of their coefficients of thermal expansion and the modulus of elasticity compared to those of the dry cement paste. As a composite material, this type of concrete leads to a more homogenous and coherent material with a minimum of micro-cracking. Another advantage is that compatibility between the aggregates particles and the cement paste does not need to be taken into account for mix design, unlike normal concrete. At mix design, cement may be partially replaced by natural pozzolan. All these influence the properties of fresh and hardened concrete.

The production procedure of lightweight aggregate concrete may often be more complicated than normal weight concrete. For example, it is necessary to take into consideration the water absorption of the porous aggregate from the fresh cement paste and that the lightweight aggregate particles have lower density than surrounding matrix. The absorption of water in the aggregate results in an increasing stiffness of the fresh concrete with time; the aggregate particles of low density may segregate by flowing to the upper surface of the concrete. Varying the density of the particles will also change the density and the strength of the concrete [9].

2.2.3.1. Aggregate Proportion

The aggregate proportion in the design mix is based on the volume as are all the other concrete constituents in the concrete mix. After mixing the concrete, the density of the compacted concrete seldom equals the calculated density. The variation is result of the following uncertain factors:

- The actual particle density of the LWA
- The water absorption of the LWA
- The air volume

The bulk density of loosely packed lightweight aggregate must be measured after the delivery of the materials. Based on the measured particle density and the bulk density, the ratio of bulk and particle density is calculated. This ratio is used to covert the measured bulk density to a calculated particle density which is used for the calculation of the LWA in the mix. Failure to measure the bulk density and the moisture content of the LWA my affect the density, strength, workability and volume of the mixed concrete [9].

2.2.3.2. Mixing Procedure

The mixing procedure of LWC is same as NWC and is produced in the same type of mixer or mixer plant. At times, lightweight dry fines cause the materials to for balls in the mixer. It can be avoided if less water is added at the start and then the amount is increased gradually. The rate of water absorption during the mixing process is relatively rapid for small size lightweight particles. When necessary, the water added during mixing should include water absorbed during transportation and water that may be added during compaction at the site [9].

2.2.4. Physical and Mechanical Properties of Structural Lightweight Concrete

2.2.4.1. Compressive Strength

Compressive strength levels required by the construction industry for the usual design strengths of cast-in-place, pre-cast or prestressed concrete can be obtained economically with the structural lightweight aggregates in use today. Design strengths of 20.0 MPa to 35.0 MPa are common. In precast and prestressing plants design strengths of 35.0 MPa are usual.

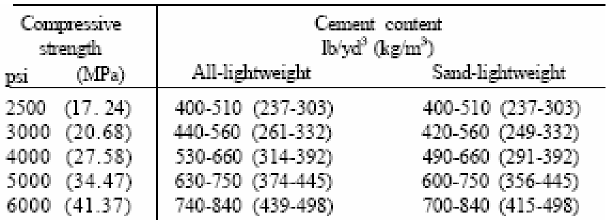
All aggregates have strength ceilings and with lightweight aggregates the strength ceiling generally can be increased at the same cement content by reducing the maximum size of the coarse aggregate. The compressive strength of lightweight aggregate concrete is usually related to cement content at a given slump rather than water-cement ratio. Water reducing or plasticizing admixtures are frequently used with lightweight concrete mixtures to increase workability and facilitate placing and finishing [7].

2.2.4.2. Cement Content

The cement and water contents required for a particular strength and slump have significant effects on the hardened concrete properties. With lightweight concrete, mix proportions are generally expressed in terms of cement content at a particular slump rather than by the water-cement ratio. Increasing the mixing water without increasing the cement content will increase slump and also increase the effective water cement ratio.

The usual range of compressive strengths may be obtained with reasonable cement contents with the lightweight aggregates being used for structural applications today. The Table 2.1. suggest the range of cement contents for 28 day compressive strengths for concretes with 75 mm to 100 mm of slump an 5 to 7 percent air contents [7].

Table 2.1. Approximate Relationship between Average Compressive Strength and Cement Content [7]



Compressive strength psi	(MPa)	Cement content lb/yd^3 (kg/m^3) All-lightweight	 Sand-lightweight
2500	(17. 24)	400-510 (237-303)	400-510 (237-303)
3000	(20.68)	440-560 (261-332)	420-560 (249-332)
4000	(27.58)	530-660 (314-392)	490-660 (291-392)
5000	(34.47)	630-750 (374-445)	600-750 (356-445)
6000	(41.37)	740-840 (439-498)	700-840 (415-498)

2.2.4.3. Unit Weight

Weight reduction for concrete of structural quality is the primary advantage of lightweight concrete. Depending upon the source of material structural grade lightweight concrete can be obtained in a dry weight range of 1440 kg/m^3 to 1840 kg/m^3 [7].

The density of concrete depends upon the grading of the aggregates, the moisture content, mix proportions, cement content, water-to-binder ratio, chemical and mineral admixtures, etc. Besides the materials, it also depends upon the method of compaction, curing conditions, etc [9].

2.2.4.4. Modulus of Elasticity

The modulus of elasticity of concrete depends on the relative amounts of paste and aggregate and the modulus of each constituent. Sand and gravel concrete has a higher E_c because the moduli of sand and gravel are greater than the moduli of structural lightweight aggregates. Generally the modulus of elasticity for structural lightweight aggregate concrete is considered to vary between ½ to ¾ that of sand and gravel concrete of same strength. Variations in lightweight aggregate gradation usually have little effect on modulus of elasticity if the relative volumes of cement paste and aggregate remain fairly constant.

The formula for $E_c = w_c^{1.5} \times 0.043 \times f_c'^{1/2}$ given in ACI 318 Building Code [10], may be used for values of weight (w) between 1440 kg/m^3-2480 kg/m^3 [7].

2.2.4.5. Poisson's Ratio

Test to determine Poisson's ratio of lightweight concrete by resonance methods showed that it varied only slightly with age, strength or aggregate used and that the values varied between 0.16 and 0.25 with the average being 0.21. While this property varies slightly with age, test conditions and aggregate used, a value of 0.20 may be usually assumed for practical design purposes [7].

2.2.4.6. Splitting Tensile Strength

The tensile strength for continuously moist cured lightweight concretes is correlated mainly with the compressive strength and may be considered equal to that of equal compressive strength normal weight concrete. The tensile strength of lightweight concretes which undergo drying is more relevant in respect to behavior of concrete in structures. During drying of the concrete, moisture loss progress at a slow rate into the interior of concrete members, resulting in the probable development of tensile stresses at the exterior faces and balancing compressive stresses in still moist interior zones. Thus the tensile resistance to external loading of drying lightweight concrete will be reduced from that indicated by continuously moist cured concrete. The splitting tensile strength of all-lightweight concretes varies from approximately 70 to 100 percent that of normal weight reference concrete when comparisons are made equal compressive strength [7].

2.2.4.7. Drying Shrinkage

Drying shrinkage is an important property that affects extent of cracking, prestress loss, effective tensile strength and warping. It should be recognized that large size concrete members, or those in high ambient relative humudities, may undergo substantially less shrinkage than that exhibited by small laboratory specimens stored at 50 percent relative humidity.

- *Normally cured concrete*: Fig.2.2. indicates wide range of shrinkage values after one year of drying all-lightweight and sand-lightweight concretes. Nothing the position within these ranges of the reference concrete, it appears that low-strength lightweight concrete generally has greater drying shrinkage than that of reference concrete. At higher strengths, however, some lightweight concretes exhibit lower shrinkage. Partial or full replacement of the lightweight fines by natural sand usually reduces shrinkage for concretes made with most lightweight aggregates.
- *Atmospheric steam-cured concrete*: The reduction of drying shrinkage obtained through steam curing may vary from 10 to 40 percent. The lower portion of this range is not greatly different from that for the reference normal weight concrete [7].

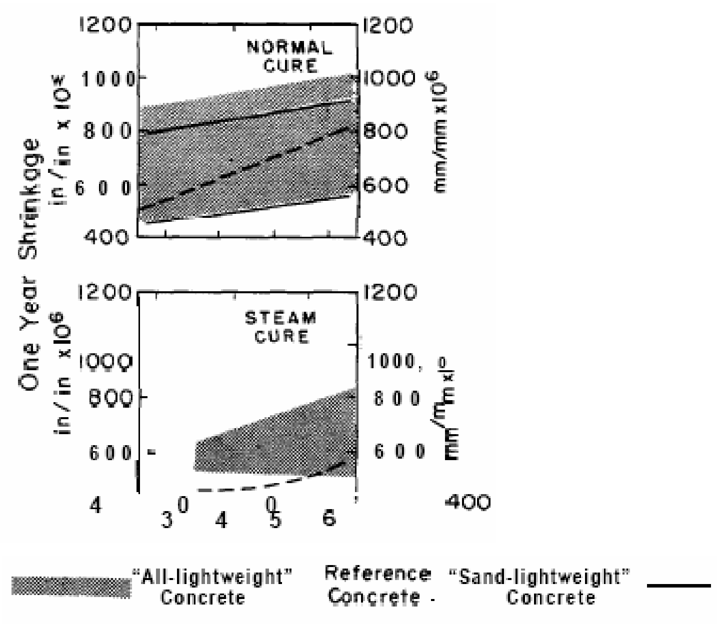


Figure 2.2. Wide Range of Shrinkage Values after One Year [7].

2.2.5. Durability of Structural Lightweight Concrete

Freezing and thawing durability and salt-scaling resistance of lightweight concrete are important factors, particularly horizontally exposed concrete construction such as access ramps, exposed parking floors, or bridge decks. Generally, deterioration is not likely to occur in vertically exposed members such as exterior walls or exposed columns, expect in areas where these structures are continually exposed to water. As in normal weight concretes, it has been demonstrated that air-entrainment provides a high degree of protection to lightweight concretes exposed to freezing and thawing and salt environments.

Many lightweight concretes can perform equivalent to or better than normal weight concretes. Limited salt-scaling tests have stated similar satisfactory performance. Natural sand provides for additional resistance at all strength levels. The use of water saturated aggregates at the time of mixing generally reduces freezing and thawing resistance of lightweight concrete. Under some conditions air-entrainment will improve the durability of concrete made with these saturated aggregates [7].

2.2.6. Uses of Structural Lightweight Concrete

Use of SLWAC instead of NWC, for example, as a floor slab in a multi-story building, depends on the relative costs and the potential savings that can occur by the use of a lighter material. SLWAC is about 28% lighter than normal concrete and, in a design where the dead load is equal to the live load, a saving of 14% energy intensive steel reinforcement can result. Equal or greater savings are achieved in columns and footings. For long-span bridges, the live load is a minor part of the total load and reduction in density is translated into reductions in not only mass, but also in section size. This is especially true where pre-stressing can introduce load balancing effects that compensate for the reduced modulus of SLWAC compared to NWC. The lower mass and the density are extremely important in seismic areas where a reduction in the initial effects of the dead load may mean the difference between section survival and section failure.

Normally, strength and stiffness decrease rapidly as a mineral develops higher porosity and this occurs with lightweight aggregates as well. However, when regular aggregates are replaced with LWA, only a modest strength reduction results. Normal weight aggregates are much stiffer than the cement paste matrix and the aggregates cause local stress concentrations. The regular aggregates, being much stronger than the matrix, have no problem resisting the stress, however, at the aggregate-cement paste interface, there is a zone of weakness which result in premature failure of the composite. With SLWAC, the stiffness of the aggregate closely matches the stiffness of the paste and a very uniform stress distribution results, leading to a higher strength than would normally be expected. Also, the cement paste matrix bonds very effectively to the expanded aggregates so no low strength interfacial layer is present. These two factors effectively allow the structural lightweight aggregate concrete to develop very high durability, and thus play an important role as a structural material.

Lightweight aggregate concrete though has another structure and other strength class, yet is an attractive building material. The low strength of lightweight aggregates leads one to believe that concrete made with them will not be of high strength, but the low strength of the aggregates may be compensated for by high strength cement paste. Today it is not difficult to produce SLWAC of 50 MPa, 15 cm, cube compressive strength, and with special proportioning up to 100 MPa [9].

2.2.7. Advantages and Disadvantages of Structural Lightweight Concrete

2.2.7.1. Advantages

- *Lower dead load*: Saving in the structural material can be achieved due to the reduced dead load, particularly for longer span bridges. These savings can also be reflected in the cost of foundations (particularly where pilings are required), and in formwork and false-work requirements. The lighter weight also results in savings in the handling and transportation of materials, pre-cast elements, etc. The lighter weight can permit the use of longer spans with a consequent reduction in the number of supports required.

- *Better physical properties*: Many properties of SLWAC can be some benefit. The lower modulus leads to lower pre-stress losses and reduces the adverse effects of differential settlements in continues bridges. The lower coefficient of thermal expansion reduces the induced thermal movements, which reduces the number of joints required in long bridges.
- *Improved durability*: The long tem durability of structures can be improved using SLWAC. This is because of the reduced likelihood of shrinkage and early thermal cracking, lower permeability, better bond between the cement paste and the aggregate, increased tolerance the insufficient external curing, and increased resistance to free-thaw cycles of SLWAC.
- *Reduced cost*: While SLWAC more expensive than normal concrete, savings can be achieved due to its lower dead loads and decrease in other materials and construction costs.
- *Environmental problems*: The benefit to the environment can be significant if industrial waste products are used to manufacture SLWAC. This can eliminate the need for stockpiling or disposing of large amounts of waste materials.
- *Demolition*: When a reinforced concrete structure is ready for demolition, there is considerable advantage if the concrete is a type of SLWAC. It has lower density and is easier, during the fragmentation process, on the stone crusher compared to normal concrete. The recycled material can be used for concrete production or as filling mass. The crushed SLWAC may even have pozzolanic and binding properties.

2.2.7.2. Disadvantages

- Reduce resistance to locally concentrated loads as they occur at pre-stressing anchorages or bearings, hence increased confining reinforcement is required,
- SLWAC is more brittle because of high strength cement paste,
- SLWAC may require more cement depending upon the aggregate chosen,
- The temperature rise due to heat of hydration is higher,

- Spalling of the concrete cover when it is exposed to hydrocarbon fire,
- Greater care is required in controlling water content, mixing, and supervision to maintain strength and workability requirements,
- Porous aggregates require special measures for pumpable concrete [9].

2.2.8. Examples of Structural Lightweight Concrete Applications

Wellington Stadium, with seating capacity of 40,000; is New Zealand's first modern sport stadium. It is also the first major structure in New Zealand to be built with lightweight aggregate concrete. Expanded shale aggregates, imported from California, USA, were used to produce LWAC for all the precast components in the man bowl structure. Concrete with a cylindrical strength of 35 MPa was chosen for durability reasons, and also achieve an overnight strength of 25 MPa for the efficient production of pre-tensioned units for the bleachers, long-span inclined beams, and pre-finished double tee flooring. The structure is located active earthquake fault lines and lightweight aggregate concrete, with a density of 1850 kg/m^3, reduced the seismic loads and offered a number of design and other construction advantages for the difficult site conditions.

The first lightweight concrete bridge in Sweden, was completed in October, 1975. The bridge is pre-stressed, slab-framed, and carries a footpath across the motorway Handen-Vendelsö. Except for the bottom slabs and pre-stressing anchor areas, the bridge is built structural lightweight aggregate concrete using sintered fly ash, called LB800 as aggregate. The concrete has compressive cube strength of 35 MPa at 28 days and a bulk density of 1800 kg/m^3.

In Norway, since 1989 six major bridges have been constructed using high-strength SLWAC. The first small pedestrian bridge was constructed in 1987 near the town of Stavanger. In all the bridges, the LWA used was high-strength expanded clay. The typical concrete grades were LC55 or LC60, with characteristic 28 day cube strength of 55 MPa-60 MPa, and a density of approximately 1900 kg/m^3.

In U.K, the first known reinforced concrete framed building using lightweight aggregate concrete was a three story office block in Brentford, constructed in 1958. This was followed by a small number of buildings. A very significant LC construction in the early 60s is the extension of hanger for British Airways. The Roxburgh Country Office for the Roxburgh Country Council was built in 1966/67. The whole construction above the basement was made with SLWAC.

In U.K., the two towers of Guys Hospital-Users Tower and Communication Tower, respectively, 122 m and 145 m high above ground. The tower was build in 1974. extensive use was made of SLWAC 31,000 m^3 with sintered fly ash coarse and fine aggregates of about 30 MPa compressive strength. The interesting feature is the lecture theatre on the 29th floor, where all the lightweight concrete raker beams cantilever 113 m above ground. The support concrete cladding also is lightweight concrete. Besides considerable savings in the foundation and framing, it added to two hours of fire resistance without any extra treatment [9].

CHAPTER 3

REVIEW OF RESEARCH ON
STRUCTURAL LIGHTWEIGHT CONCRETE

Lightweight aggregate concrete has been used successfully for structural purposes for many years. For structural application of lightweight aggregate concrete, the density is often more important than the strength. A decreased density for the same strength level reduces the self-weight, foundation size and construction costs [11].

Lightweight concrete is generally used to reduce the dead weight of a structure as well as to reduce the risk of earthquake damages to a structure because the earthquake forces that will influence the civil engineering structures and buildings are proportional to the mass of those structures and buildings. Thus, reducing to mass of the structure or building is of utmost importance to reduce their risk due to earthquake acceleration [12].

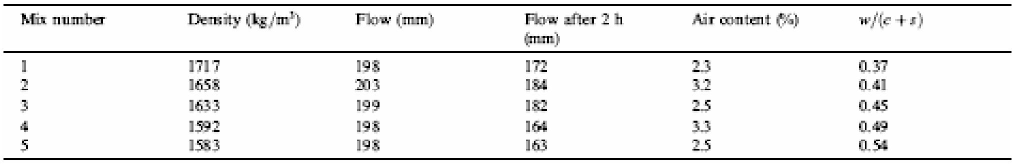
With the rapid development of concrete technology in recent year high-performance concrete can be produced more easily. Since 1980, several investigations on high-performance lightweight aggregate concrete have been reported and there are, of course, worldwide environmental, economic and technical impetuses to encourage the structural use of this material [11].

3.1. Strength and Durability of Structural Lightweight Concrete

Joao A. Rossignolo et.al. [11] have investigated the mechanical properties of high performance concrete using Brazilian lightweight aggregate (expanded clay). Five mixes were prepared and the cement (high-early strength portland cement) proportion varied from 440 kg/m^3 to 710 kg/m^3 (Table 3.1.). Silica fume was used in the dosage of 10% as a replacement of cement (by weight) and the w/cm ratio varied from 0.37 to 0.54. All mixes had 1.5% of accelerator superplasticizer by weight of cement. The flow for all mixes was in the range of 200±10mm. The 7day compressive strength and the dry unit weight varied from 39.7 MPa to 51.9 MPa and from 1460 kg/m^3 to 1605 kg/m^3, respectively (Table 3.2.).

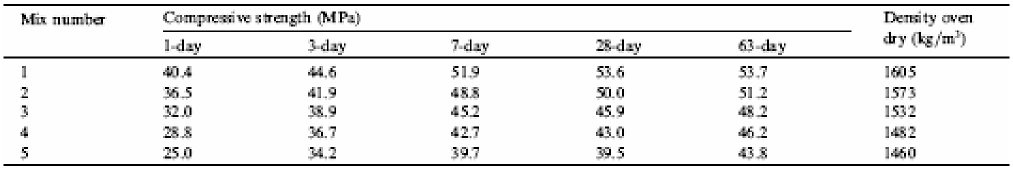
The result of compressive strength of high strength lightweight concrete was lower than those of the normal weight concrete (Figure3.1). However, the lightweight concrete showed high material efficiency ratio. The flexural and splitting tensile strength varied from 3.1 MPa to 5.3 MPa and from 2.7 MPa to 4.0 MPa (Table 3.3.). However, the tensile/compressive strength ratio was lower for high performance lightweight concrete than high performance normal weight concrete (Figure 3.2). The modulus of elasticity of the lightweight concrete (Table 3.4) was much lower than that of normal weight concrete of same strength (Figure 3.3) [11].

Table 3.1. Properties in the Fresh State [11]



Mix number	Density (kg/m^3)	Flow (mm)	Flow after 2 h (mm)	Air content (%)	$w/(c+s)$
1	1717	198	172	2.3	0.37
2	1658	203	184	3.2	0.41
3	1633	199	182	2.5	0.45
4	1592	198	164	3.3	0.49
5	1583	198	163	2.5	0.54

Table 3.2. Compressive Strength and Density [11]



Mix number	Compressive strength (MPa)					Density oven dry (kg/m^3)
	1-day	3-day	7-day	28-day	63-day	
1	40.4	44.6	51.9	53.6	53.7	1605
2	36.5	41.9	48.8	50.0	51.2	1573
3	32.0	38.9	45.2	45.9	48.2	1532
4	28.8	36.7	42.7	43.0	46.2	1482
5	25.0	34.2	39.7	39.5	43.8	1460

Table 3.3. 7 day Tensile Strength [11]

Mix number	7-Day tensile strength (MPa)	
	Flexural	Splitting
1	5.3	4.0
2	5.0	3.7
3	3.5	3.3
4	3.3	3.0
5	3.1	2.7

Table 3.4. Modulus of Elasticity [11]

Mix number	Modulus of elasticity (GPa)
1	15.2
2	13.5
3	12.9
4	12.3
5	12.0

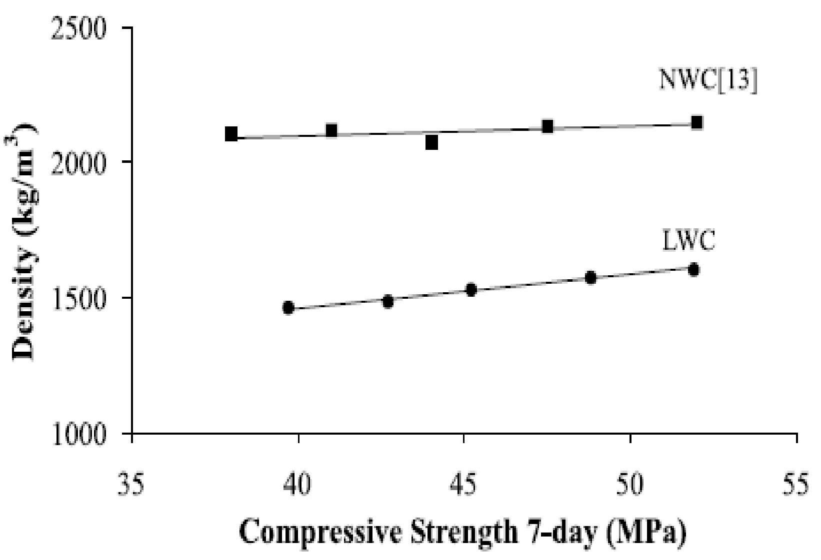


Figure 3.1. Relationship between 7 day Compressive Strength and Density [11]

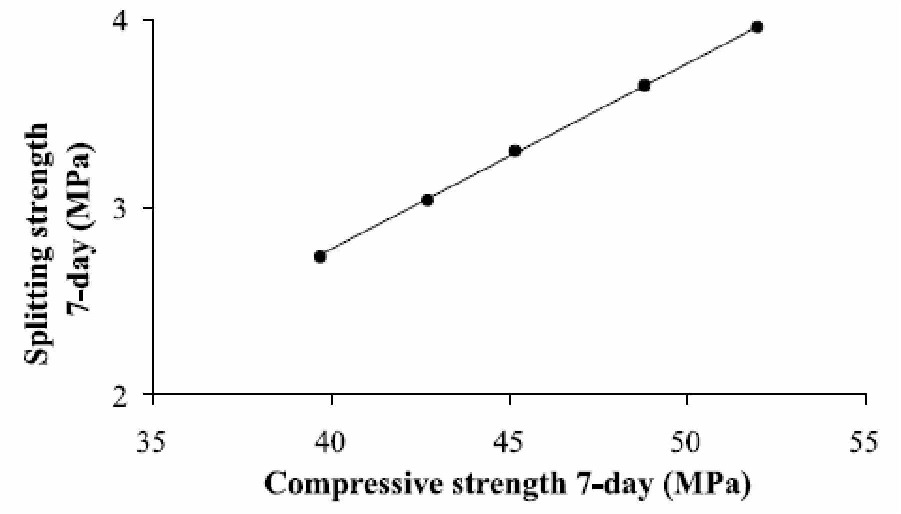


Figure 3.2. Relationship between Splitting Tensile Strength and 7 day Compressive Strength [11]

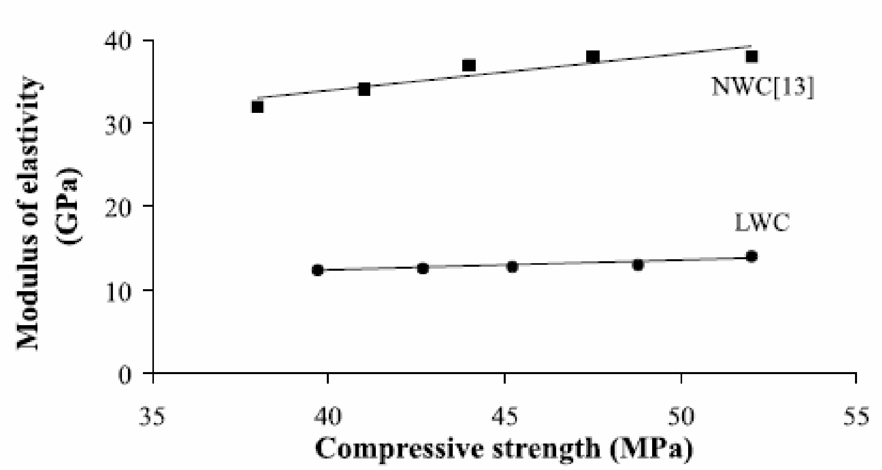
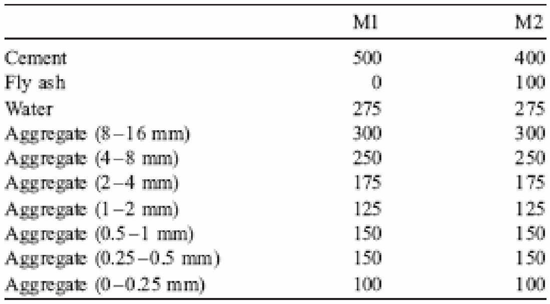


Figure 3.3. Relationship between Modulus of Elasticity and 7 day Compressive Strength [11]

Ergul Yaşar et.al. [12] have performed a study on design of structural lightweight concrete with the use of scoria (basaltic pumice) that will provide an advantage of reduction in dead weight of a structure; and second is to obtain a more economical and greener SLWC mixture with the use of fly ash. Approximate quantity of portland cement was 500 kg/m^3 and fly ash SLWC mixture was made by using 20% fly ash as portland cement replacement (Table 3.5). Air dry unit weights were 1860 kg/m^3 and 1850 kg/m^3 (20% fly ash) and the compressive strength at 28 day 28 MPa and 29 MPa (20% fly ash) (Figure 3.4). They have reported that SLWC with a cylinder compressive strength of 25 MPa can be produced by using lightweight aggregate. Also, an economical SLWC can be produced with the use of fly ash [12].

Table 3.5. Approximate Concrete Mixture Composition for a cubic meter [12]



	M1	M2
Cement	500	400
Fly ash	0	100
Water	275	275
Aggregate (8–16 mm)	300	300
Aggregate (4–8 mm)	250	250
Aggregate (2–4 mm)	175	175
Aggregate (1–2 mm)	125	125
Aggregate (0.5–1 mm)	150	150
Aggregate (0.25–0.5 mm)	150	150
Aggregate (0–0.25 mm)	100	100

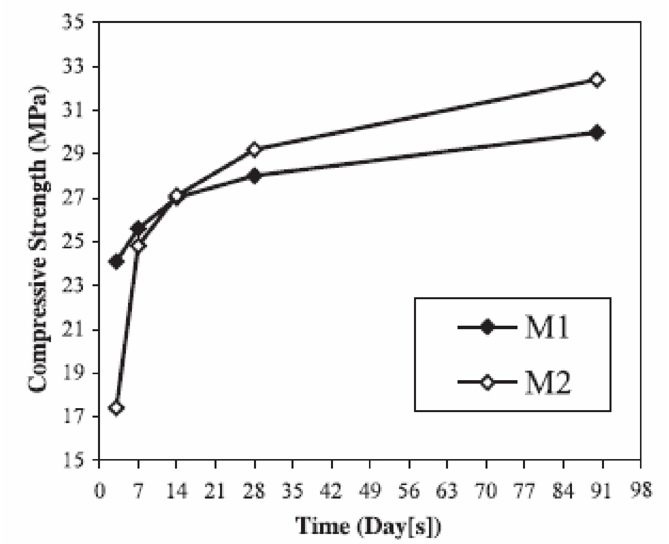
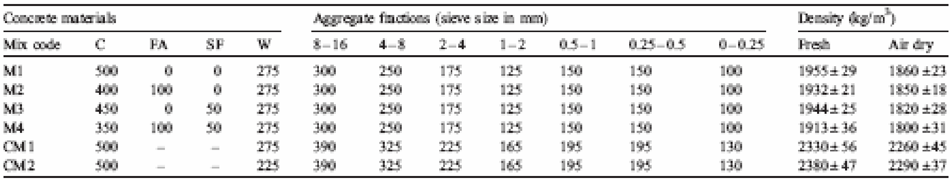


Figure 3.4. Compressive Strength of Concrete [12]

Ergul Yaşar et.al. [13] have continued to study of structural lightweight concrete with scoria to design a high strength structural lightweight concrete by the use of mineral admixture fly ash and silica fume together and separately. Six concrete mixtures were produced. Control lightweight scoria concrete, with a cement content of 500 kg/m^3, fly ash SLWC by using 20% fly ash as cement replacement, silica fume SLWC by using 10% silica fume as cement replacement and ternary SLWC mixture by using 20% fly ash and 10% silica fume as cement replacement (Table3.6). W/c ratio of lightweight concrete was kept constant at 0.55. Also two NWCs were produced for comparison with w/c ratio 0.55 and 0.45. Based on the research results it can be concluded that an SLWC with a cylinder compressive strength of 30 MPa can be produced by the use of lightweight aggregate (Figure 3.5). Also, an economical SLWC with cylinder strength of 30 MPa can be produced by fly ash. Also, SLWHSC with a cylinder compressive strength of 40 MPa can be produced with silica fume [13].

Table 3.6. Approximate Concrete Mixture Composition and Densities of a cubic meter [13]



Concrete materials					Aggregate fractions (sieve size in mm)							Density (kg/m^3)	
Mix code	C	FA	SF	W	8–16	4–8	2–4	1–2	0.5–1	0.25–0.5	0–0.25	Fresh	Air dry
M1	500	0	0	275	300	250	175	125	150	150	100	1955±29	1860 ±23
M2	400	100	0	275	300	250	175	125	150	150	100	1932±21	1850 ±18
M3	450	0	50	275	300	250	175	125	150	150	100	1944±25	1820 ±28
M4	350	100	50	275	300	250	175	125	150	150	100	1913±36	1800 ±31
CM 1	500	–	–	275	390	325	225	165	195	195	130	2330±56	2260 ±45
CM 2	500	–	–	225	390	325	225	165	195	195	130	2380±47	2290 ±37

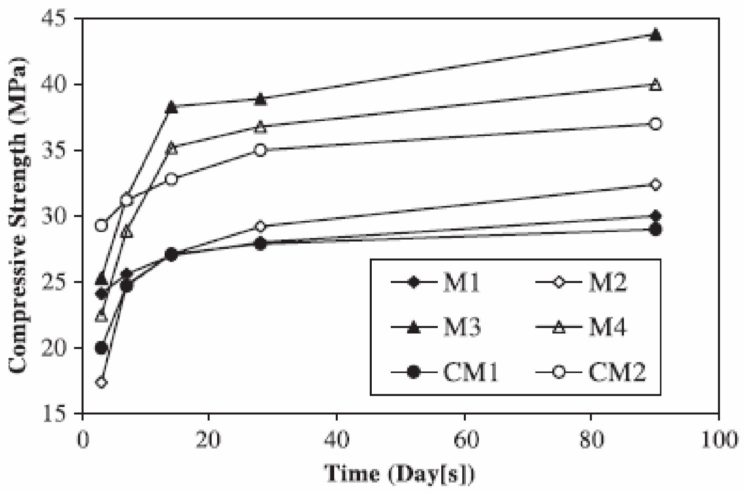
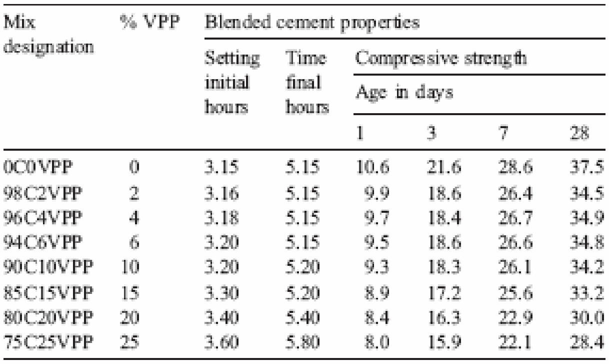


Figure 3.5. Compressive Strength of Concrete [13]

Khandaker M. and Anwar Hossain [15], have reported the suitability of volcanic pumice as cement replacement material and as coarse aggregate in lightweight concrete production. The study contains two parts as investigations on volcanic pumice powder (VPP) with blended cement and volcanic pumice aggregate (VPA) in lightweight concrete. Setting time and compressive strength of blended cement were investigated by using different percentages of volcanic pumice powder from 0% to 25%. The trend of variation of setting times shows an increase of both setting times with the increase of VPP content (Table 3.7). The compressive strength of blended cement is fond to decrease with the increase of VPP content. Also, the series of tests were performed to investigate the effect of different percentages of VPA on the strength, modulus of elasticity, shrinkage and permeability. The slump values for same w/c of 0.45 were found to decrease with the increase of VPA (Table 3.8). The compressive strength is decreased with the increase of %VPA due to replacement of normal strong crushed gravel aggregate by relatively weak pumice aggregate (Table3.9). The variation of tensile strength also shows trend, similar to that of compressive strength. The E of concrete is a function of compressive strength and normally E decreases wit the decrease of compressive strength.

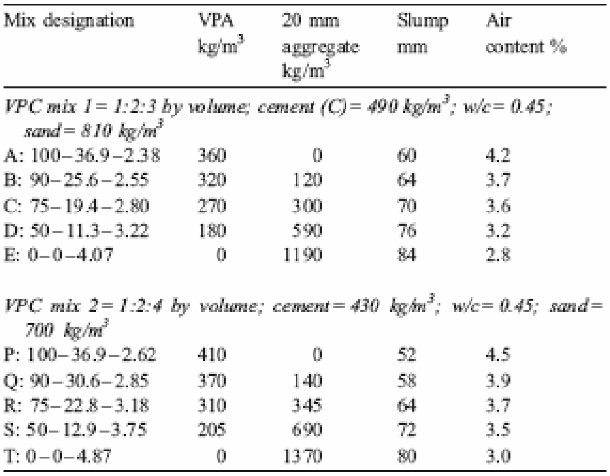
The shrinkage of the VPC is found to be higher than that of normal representative concrete (0% VPA) (Figure 3.6). However, the danger of shrinkage cracking can be compensated by the lower modulus of elasticity of VPC. Also, the permeability of concrete increase with the increase of VPA content (Figure 3.7). The higher permeability of VPC will allow higher moisture movement and have the harmful effect of corrosion needing special care for protection of reinforcement [15].

Table 3.7. Effect of VPP on the Properties of Blended Cement [15]



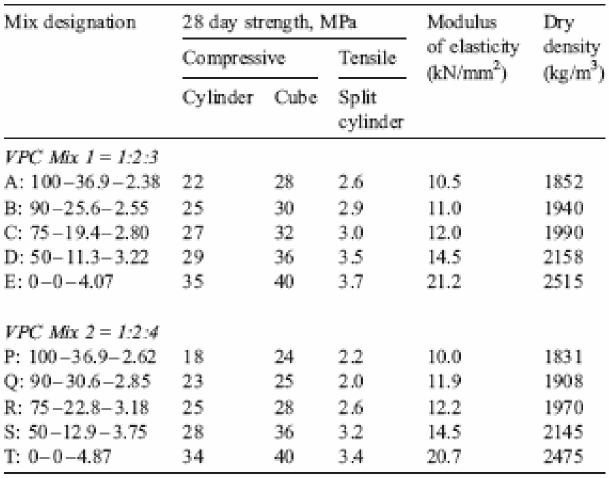
Mix designation	% VPP	Blended cement properties					
		Setting initial hours	Time final hours	Compressive strength			
				Age in days			
				1	3	7	28
0C0VPP	0	3.15	5.15	10.6	21.6	28.6	37.5
98C2VPP	2	3.16	5.15	9.9	18.6	26.4	34.5
96C4VPP	4	3.18	5.15	9.7	18.4	26.7	34.9
94C6VPP	6	3.20	5.15	9.5	18.6	26.6	34.8
90C10VPP	10	3.20	5.20	9.3	18.3	26.1	34.2
85C15VPP	15	3.30	5.20	8.9	17.2	25.6	33.2
80C20VPP	20	3.40	5.40	8.4	16.3	22.9	30.0
75C25VPP	25	3.60	5.80	8.0	15.9	22.1	28.4

Table 3.8. VPC Mix Details [15]



Mix designation	VPA kg/m^3	20 mm aggregate kg/m^3	Slump mm	Air content %
VPC mix 1 = 1:2:3 by volume; cement (C) = 490 kg/m^3; w/c = 0.45; sand = 810 kg/m^3				
A: 100–36.9–2.38	360	0	60	4.2
B: 90–25.6–2.55	320	120	64	3.7
C: 75–19.4–2.80	270	300	70	3.6
D: 50–11.3–3.22	180	590	76	3.2
E: 0–0–4.07	0	1190	84	2.8
VPC mix 2 = 1:2:4 by volume; cement = 430 kg/m^3; w/c = 0.45; sand = 700 kg/m^3				
P: 100–36.9–2.62	410	0	52	4.5
Q: 90–30.6–2.85	370	140	58	3.9
R: 75–22.8–3.18	310	345	64	3.7
S: 50–12.9–3.75	205	690	72	3.5
T: 0–0–4.87	0	1370	80	3.0

Table 3.9. Strength, Modulus of Elasticity and Density of VPC [15]



Mix designation	28 day strength, MPa			Modulus of elasticity (kN/mm^2)	Dry density (kg/m^3)
	Compressive		Tensile		
	Cylinder	Cube	Split cylinder		
VPC Mix 1 = 1:2:3					
A: 100–36.9–2.38	22	28	2.6	10.5	1852
B: 90–25.6–2.55	25	30	2.9	11.0	1940
C: 75–19.4–2.80	27	32	3.0	12.0	1990
D: 50–11.3–3.22	29	36	3.5	14.5	2158
E: 0–0–4.07	35	40	3.7	21.2	2515
VPC Mix 2 = 1:2:4					
P: 100–36.9–2.62	18	24	2.2	10.0	1831
Q: 90–30.6–2.85	23	25	2.0	11.9	1908
R: 75–22.8–3.18	25	28	2.6	12.2	1970
S: 50–12.9–3.75	28	36	3.2	14.5	2145
T: 0–0–4.87	34	40	3.4	20.7	2475

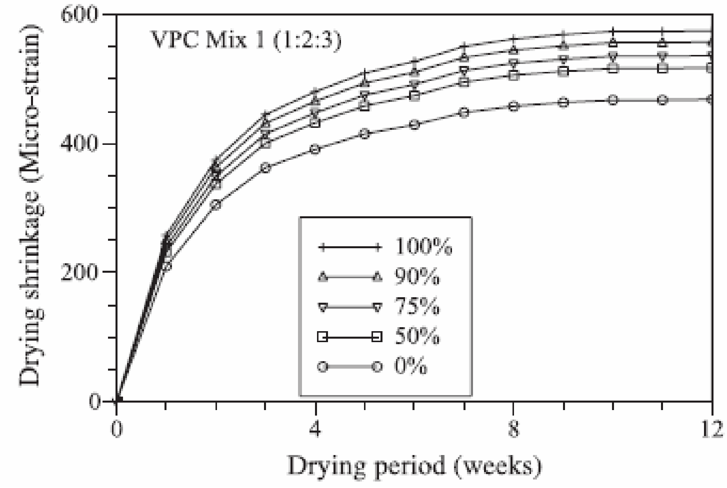


Figure 3.6. Effect of % of VPA and Age on the Drying Shrinkage of VPC [15]

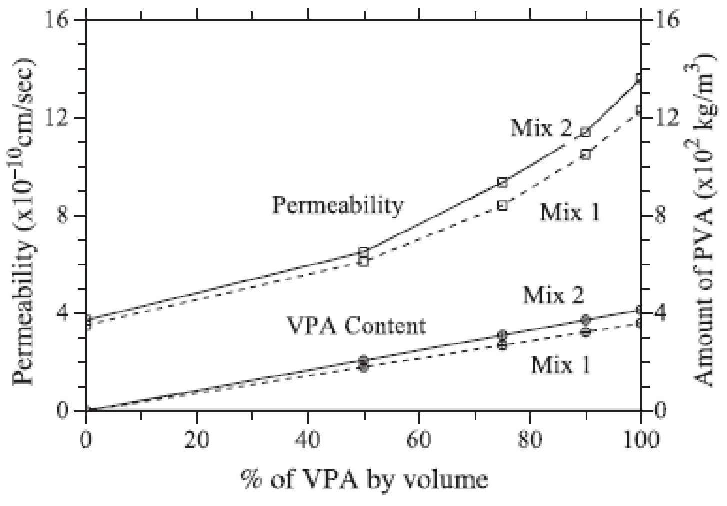


Figure 3.7. Effect of Various Parameters on the Permeability of VPC [15]

Chao-Lung Hwang and Meng-Feng Hung [16] have compared the performance of lightweight concrete under different w/c ratio and different cement paste content. The mixture proportions designed by the densified mixture design algorithm method.

This method is developed from the hypothesis that the physical properties will be optimum when the physical density is high. In this method, the aggregates phase forms the major skeleton by filling coarse particles with fine ones to minimize porosity and to increase density of solid materials, thus reducing the amount of cement paste. The paste phase in this method is for lubricating and filling pores to achieve concrete workability. In this research, slag was used as LWA, produced in local factories. Fly ash was used as mineral admixture. The results indicate that structural lightweight concrete could achieve high strength, flow-ability and excellent durability by the DMAD method. High w/c ratio and low water content (Figure 3.8a-b.) may affect early compressive strength, but the strength efficiency of cement still attains better value of LWC, if DMDA is applied (Figure 3.9.). Through physical packaging of aggregate, the reduction in water content and cement content will result in lower permeability and higher electrical resistance of LWC (Figure3.10.) [16].

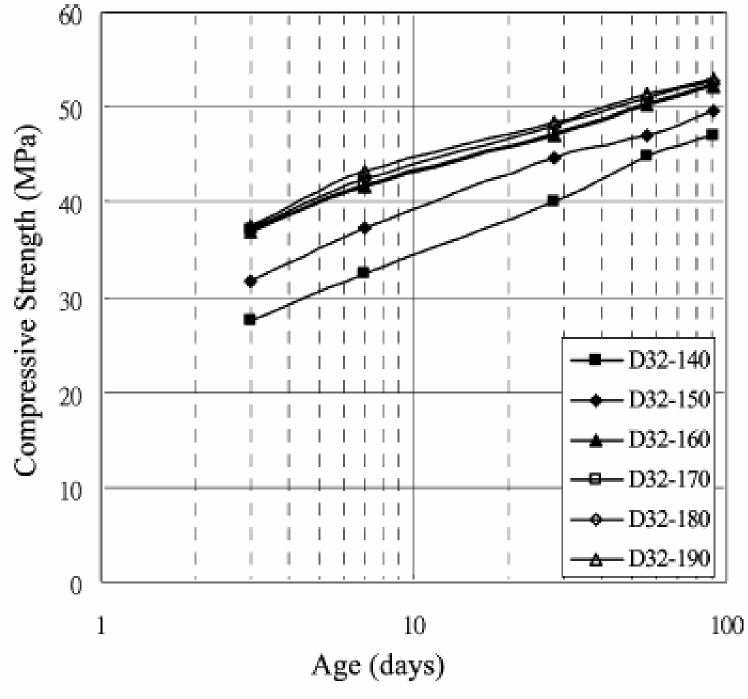


Figure 3.8a. The strength development of LWC with different water content by DMDA [16].

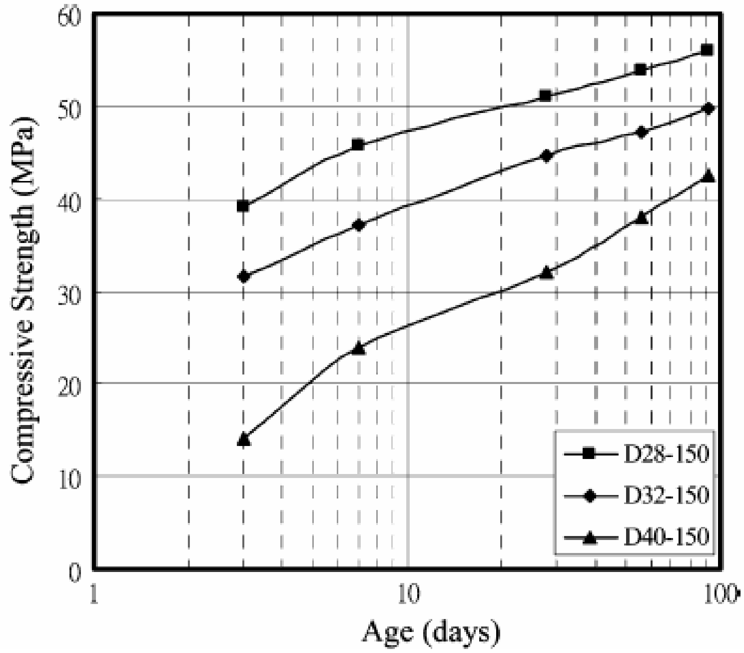


Figure 3.8b. The strength development of LWC with different w/cm by DMDA [16].

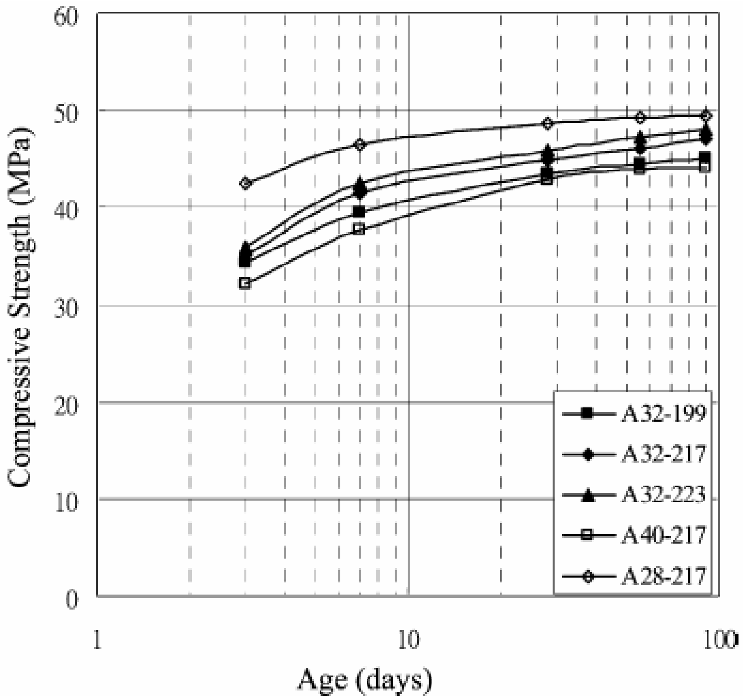


Figure 3.9. The strength development of LWC by ACI 211.2 [16].

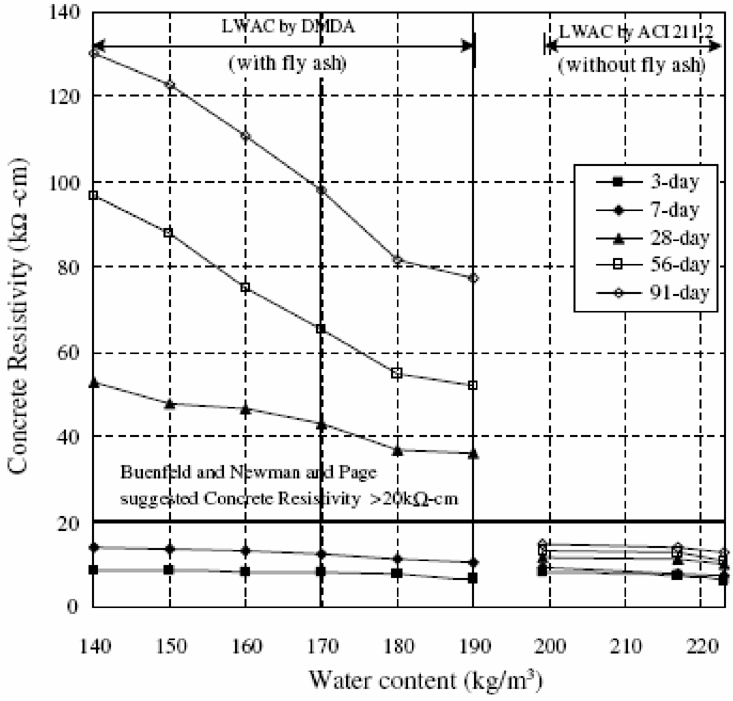
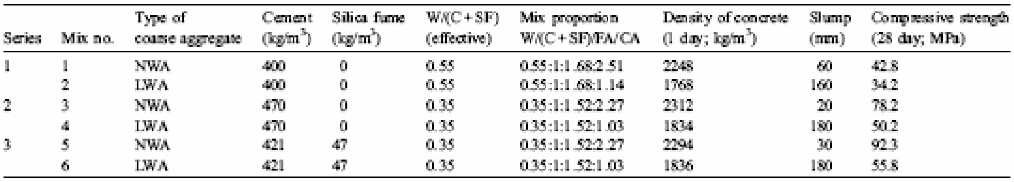


Figure 3.10. The influence of the water content on electric resistance of LWC [16].

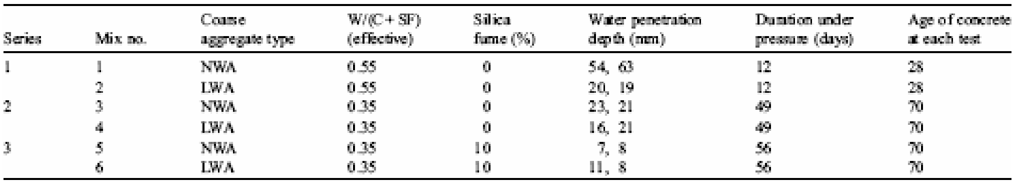
Kok Seng Chia and Min-Hong Zhang [17] have investigated the water permeability and chloride penetrability of high-strength lightweight aggregate concrete and compared to that of high-strength NWC with or without silica fume. The LWA used in this study was expanded clay and the fine aggregate used was natural sand. Three series of concrete mixes were prepared with w/c ratios 0.55 and 0.35 and with 10% silica fume as cement replacement with w/c ratio 0.35 (Table 3.10). The results indicated that a significant improvement in the permeability of the NWC from the strength level of about 40 MPa to 80 MPa due to reduced w/cm from 0.55 to 0.35; on the other permeability of the LWCs was similar at different w/cm ratios. The incorporation of 10% silica fume as cement replacement reduced the water permeability (Table 3.11) of the concrete further compared with that of the control concrete with equivalent w/cm. According to rapid chloride penetrability test (Table3.12), the resistances of concretes to chloride ion penetrations were increased with the reduction of w/c and with incorporation of silica fume [17].

Table 3.10. Mix Proportions of Concrete [17]



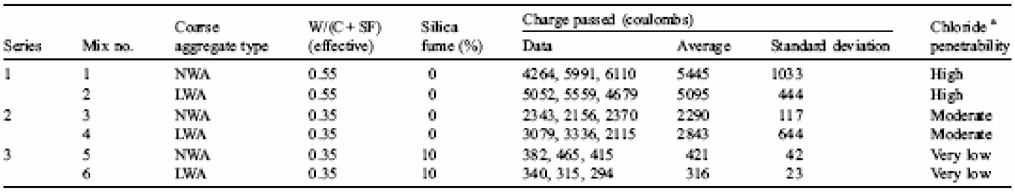
Series	Mix no.	Type of coarse aggregate	Cement (kg/m^3)	Silica fume (kg/m^3)	W/(C+SF) (effective)	Mix proportion W/(C+SF)/FA/CA	Density of concrete (1 day; kg/m^3)	Slump (mm)	Compressive strength (28 day; MPa)
1	1	NWA	400	0	0.55	0.55:1:1.68:2.51	2248	60	42.8
	2	LWA	400	0	0.55	0.55:1:1.68:1.14	1768	160	34.2
2	3	NWA	470	0	0.35	0.35:1:1.52:2.27	2312	20	78.2
	4	LWA	470	0	0.35	0.35:1:1.52:1.03	1834	180	50.2
3	5	NWA	421	47	0.35	0.35:1:1.52:2.27	2294	30	92.3
	6	LWA	421	47	0.35	0.35:1:1.52:1.03	1836	180	55.8

Table 3.11. Water Penetration Depths [17]



Series	Mix no.	Coarse aggregate type	W/(C+SF) (effective)	Silica fume (%)	Water penetration depth (mm)	Duration under pressure (days)	Age of concrete at each test
1	1	NWA	0.55	0	54, 63	12	28
	2	LWA	0.55	0	20, 19	12	28
2	3	NWA	0.35	0	23, 21	49	70
	4	LWA	0.35	0	16, 21	49	70
3	5	NWA	0.35	10	7, 8	56	70
	6	LWA	0.35	10	11, 8	56	70

Table 3.12. Rapid Chloride Penetrability (According to ASTM C 1202) [17]



Series	Mix no.	Coarse aggregate type	W/(C+SF) (effective)	Silica fume (%)	Charge passed (coulombs)			Chloride [a] penetrability
					Data	Average	Standard deviation	
1	1	NWA	0.55	0	4264, 5991, 6110	5445	1033	High
	2	LWA	0.55	0	5052, 5559, 4679	5095	444	High
2	3	NWA	0.35	0	2343, 2156, 2370	2290	117	Moderate
	4	LWA	0.35	0	3079, 3336, 2115	2843	644	Moderate
3	5	NWA	0.35	10	382, 465, 415	421	42	Very low
	6	LWA	0.35	10	340, 315, 294	316	23	Very low

3.2. Effect of Porous Lightweight Aggregate

T.Y. Lo and H.Z. Cui [18] have focused on the effect of porous aggregate on strength of concrete. They have examined the topography of the interfacial zone and the characteristic of the surface pores of the lightweight aggregate concrete. The experimental work in this research is based on LWC with cement content of 450 kg/m^3 and water/cement ratio of 0.36. The lightweight aggregate was a synthetic aggregate manufactured from expanded clay. Sand was used as fine aggregate. The concrete compressive strengths at 7 and 28 days were measured to be 46.5 MPa and 51 MPa, respectively. The results of studies and Scanning Electron Microscope views showed that the porous surface of LWA improved the interfacial bond between the aggregate and cement paste by providing interlocking sites for the cement paste forming a dense and uniform interfacial zone. (Figure 3.11.). The "Wall Effect" that appears in the normal weight concrete does not occur on the interfacial zone of LWC (Figure 3.12.). The resulting interfacial zone is about 5 μm –10 μm wide (Figure 3.13), which is much smaller than normal weight concrete. The shell of lightweight aggregate of 20 μm thick can be identified. Some cement paste has infiltrated the surface pores of the lightweight aggregate to some depth (Figure 3.14.) [18].

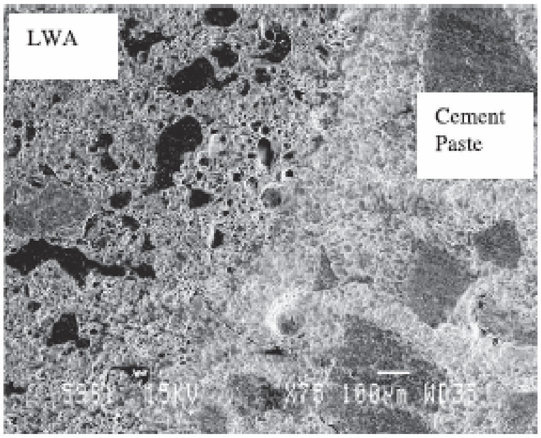


Figure 3.11. SEM View of LWC Showing the LWA Closely Bonded with Cement Matrix (x75) [18]

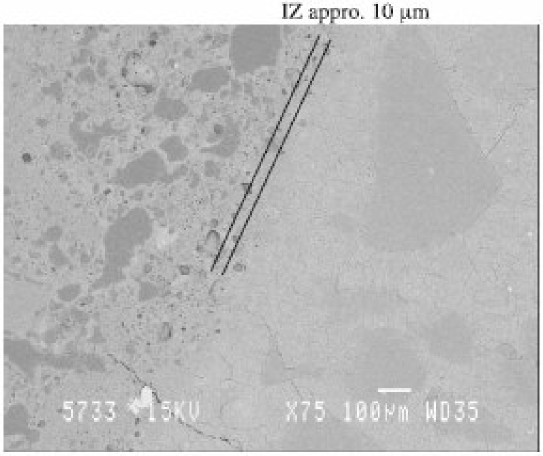


Figure 3.12. BSEI View of LWC Showing Diffusion of Cement Paste into Aggregate Surface (x75) [18]

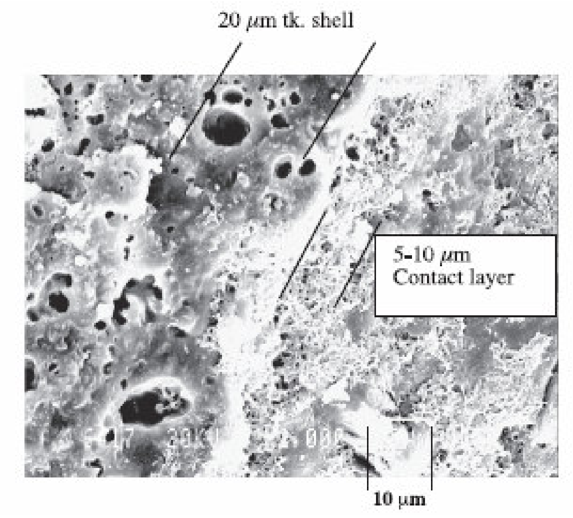


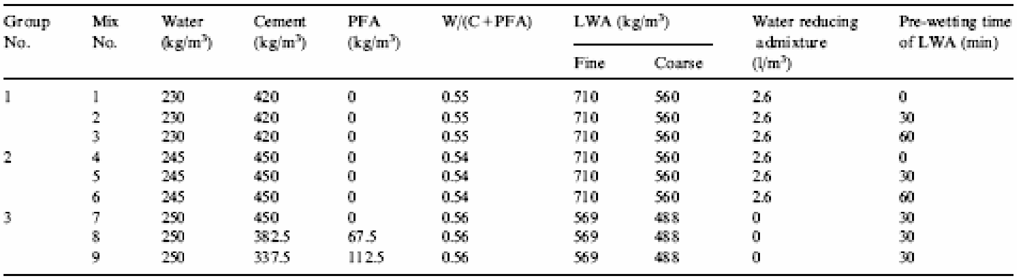
Figure 3.13. Aggregate Shell and IZ of the Concrete Composite (x2000) [18]

Figure 3.14. Porous Aggregate as Interlocking sites for HCP at the IZ (x5000) [18]

3.3. Effect of Aggregate Pre-wetting

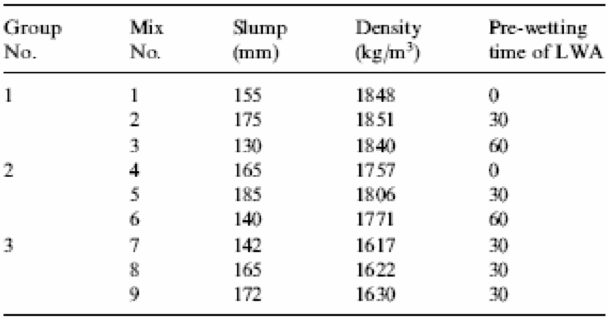
T.Y. Lo, H.Z. Cui and Z.G. Li [19] have investigated influence of pre-wetting on mechanical properties of concrete. The lightweight aggregate used in mixes originated from expanded clay and medium sand was used. Six mixed were prepared (Table 3.13.) which gives the total cementitious content from 420 kg/m^3 to 450 kg/m^3. The w/c ratios were between 0.54 to 0.56 and aggregate pre-wetting times were 0, 30 min. and 60 min. The slumps of the fresh LWAC mixes with the aggregate pre-wetted for 30 min. was found to be higher than those samples pre-wetted 60 min. and those without pre-wetting (Table 3.14.). According to test results (Table 3.15.), the compressive strength achieves its maximum value when the LWA pre-wetted for 30 min [19].

Table 3.13. Mix Proportions of LWAC [19]



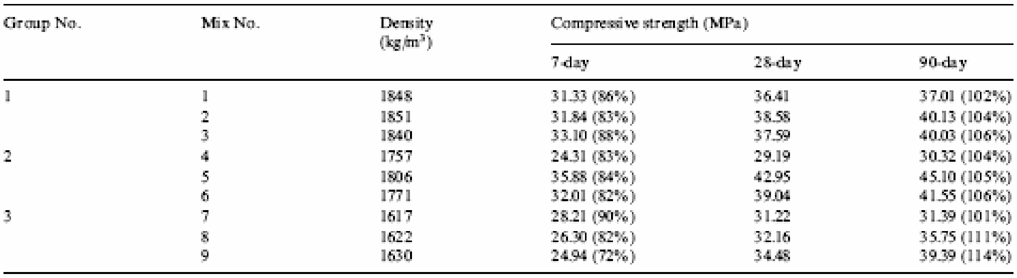
Group No.	Mix No.	Water (kg/m^3)	Cement (kg/m^3)	PFA (kg/m^3)	W/(C+PFA)	LWA (kg/m^3)		Water reducing admixture (l/m^3)	Pre-wetting time of LWA (min)
						Fine	Coarse		
1	1	230	420	0	0.55	710	560	2.6	0
	2	230	420	0	0.55	710	560	2.6	30
	3	230	420	0	0.55	710	560	2.6	60
2	4	245	450	0	0.54	710	560	2.6	0
	5	245	450	0	0.54	710	560	2.6	30
	6	245	450	0	0.54	710	560	2.6	60
3	7	250	450	0	0.56	569	488	0	30
	8	250	382.5	67.5	0.56	569	488	0	30
	9	250	337.5	112.5	0.56	569	488	0	30

Table 3.14. Workability and Density of LWAC [19]



Group No.	Mix No.	Slump (mm)	Density (kg/m^3)	Pre-wetting time of LWA
1	1	155	1848	0
	2	175	1851	30
	3	130	1840	60
2	4	165	1757	0
	5	185	1806	30
	6	140	1771	60
3	7	142	1617	30
	8	165	1622	30
	9	172	1630	30

Table 3.15. Compressive Strength of LWAC [19]



Group No.	Mix No.	Density (kg/m^3)	Compressive strength (MPa)		
			7-day	28-day	90-day
1	1	1848	31.33 (86%)	36.41	37.01 (102%)
	2	1851	31.84 (83%)	38.58	40.13 (104%)
	3	1840	33.10 (88%)	37.59	40.03 (106%)
2	4	1757	24.31 (83%)	29.19	30.32 (104%)
	5	1806	35.88 (84%)	42.95	45.10 (105%)
	6	1771	32.01 (82%)	39.04	41.55 (106%)
3	7	1617	28.21 (90%)	31.22	31.39 (101%)
	8	1622	26.30 (82%)	32.16	35.75 (111%)
	9	1630	24.94 (72%)	34.48	39.39 (114%)

3.4. Effect of Initial Curing

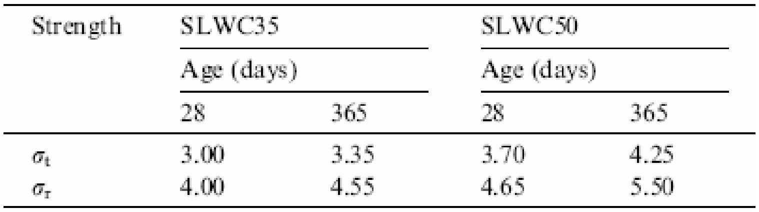
M.N Haque, H.Al-Khaiat and O.Kayali [14] have reported the strength development and durability performance of 35 MPa and 50MPa SLWCs up to period of 12 months after different periods of initial curing. Two sand-lightweight concretes using Lytag were made two evaluate their strength and durability. The slump of the two sand-lightweight concrete varied between values of 80 mm to100 mm. The average value of fresh concrete density of SLWC35 and SLWC50, were 1775 and 1800 respectively. The specimens initially cured as given; full curing, 1day curing, 3day curing and 7day curing. The test results (Table 3.16a-b-c-d) showed that the period of initial curing in water increased compressive strength also increased for all testing ages (Figure 3.15). Seven days of initial water curing resulted in almost similar strength to those of continuously water cured cubes at the age of 12 months. The indirect tensile and modulus of rupture vales of the two concretes are about 1/15th and 1/11h of the corresponding compressive strength, respectively. 1 and 7 days of initial water curing gave very similar E values to those of the continuously water cured specimens.

Water penetrability of concrete is indicative of its durability. First, in both concretes, the greater the extent of initial water curing the lesser is the depth of water penetration and hence better is the quality of concrete. These results also suggest that compressive strength is less sensitive to lack of curing. Also sand-lightweight concrete has lower penetrability than the corresponding total LWC. The report also includes depth of carbonation, sulphate contents and chloride penetration. The results suggest that the higher the water penetrability of a given concrete (Figure 3.16.), the higher is the penetration of damaging species. Further, the depth of water penetrability of a concrete can be used as an indicator of its durability [14].

Table 3.16a. Compressive Strength of SLWC (MPa) after 1 year [14].

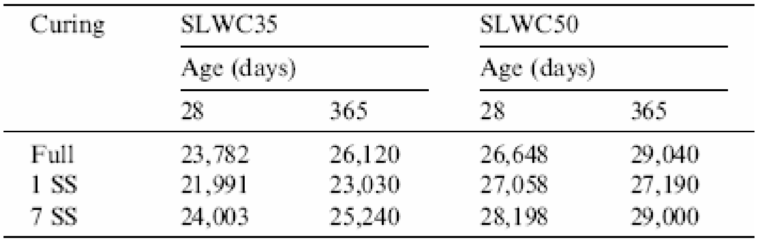
Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
Full	38.0	48.0	49.5	64.5
1 SS	40.0	41.0	49.5	52.5
7 SS	42.5	47.0	57.0	62.5

Table 3.16b. Indirect Tensile Strength and Modulus of Rupture of fully cured SLWC (MPa) after 1 year [14].



Strength	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
σ_t	3.00	3.35	3.70	4.25
σ_r	4.00	4.55	4.65	5.50

Table 3.16c. Modulus of Elasticity of SLWC (MPa) after 1 year [14].



Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
Full	23,782	26,120	26,648	29,040
1 SS	21,991	23,030	27,058	27,190
7 SS	24,003	25,240	28,198	29,000

Table 3.16d. Water penetrability of SLWC (mm) after 1 year [14].

Curing	SLWC35		SLWC50	
	Age (days)		Age (days)	
	28	365	28	365
Full	40	34	26	24
1 SS	73	115	35	65
7 SS	49	72	26	43

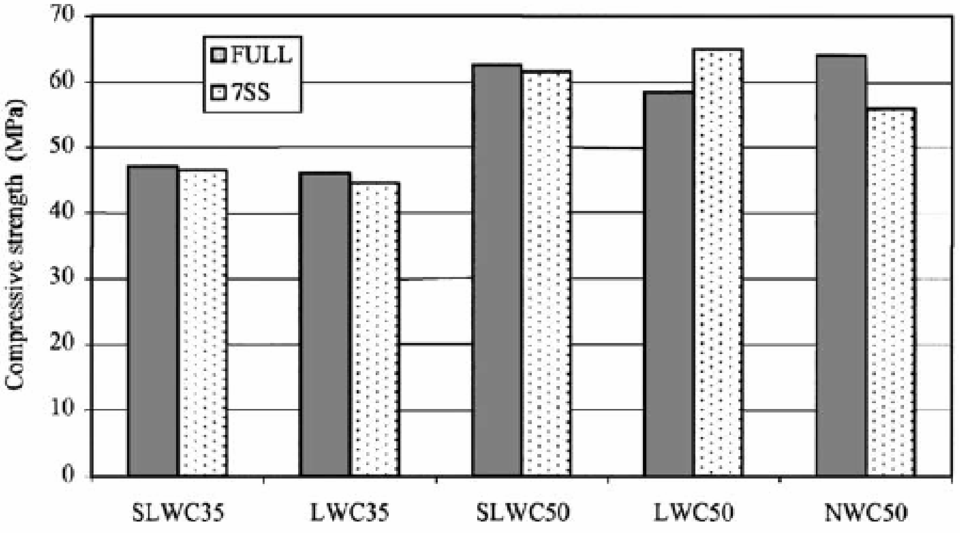


Figure 3.15. Compressive Strength of Sand LWC, Total LWC and NWC after 270 day Water Curing and Exposure on Seaside [14].

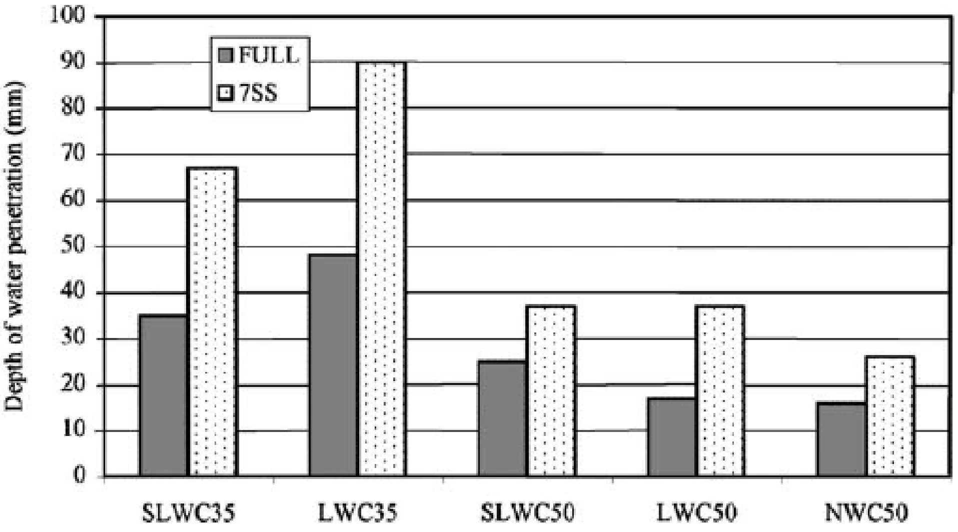
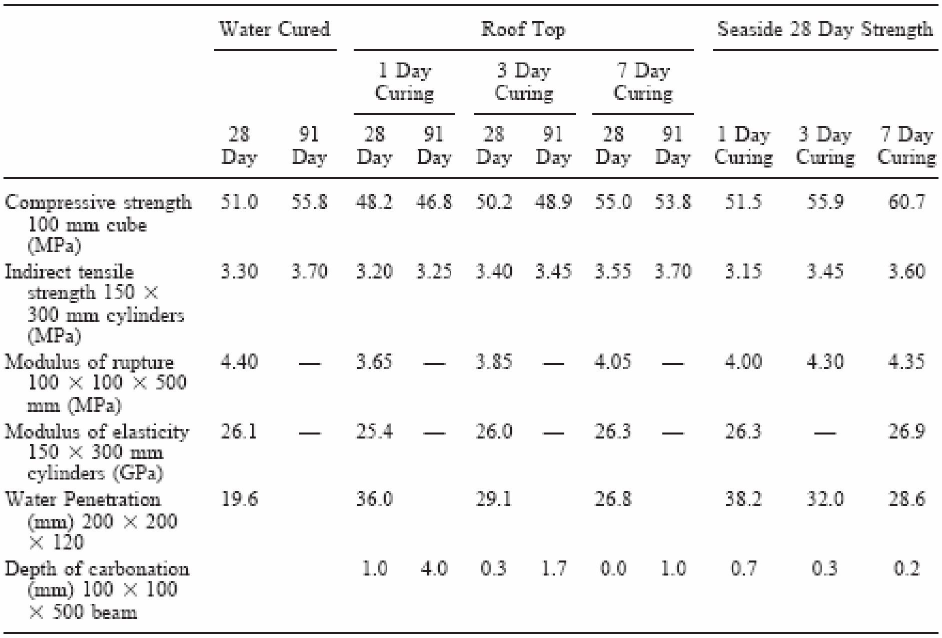


Figure 3.16. Depth of Water Penetration of Sand LWC, Total LWC and NWC after 270 day Water Curing and Exposure on Seaside [14].

H. Al-Khaiat and M.N. Haque [20] have investigated effect of initial curing on early strength and physical properties of a lightweight concrete. They have used a high strength structural lightweight concrete using Lytag LWA with a slump of about 100mm, fresh unit weight of 1800 kg/m^3 and 28 day cube compressive strength of approximately 50 MPa. The specimens initially cured as; full curing, 1day curing, 3 day curing and 7 day curing. In addition to continuous water curing, specimens were placed on the rooftop of the concrete laboratory and an exposure site near the sea at Yacht Club after different curing regimes. According to test results (Table 3.17.), the compressive strengths of SLWC seems to be less sensitive to lack of curing than the NWC, at least in the first month of exposure. This is attributed to the "inner water" stored in the porous aggregate of the SLWC. However, lack of curing seems to affect long-term strength development of SLWC. The depth of water penetration, which is indicative of permeability, was found to be much more sensitive to the extend of initial curing of SLWC [20].

Table 3.17. Strength and Physical Characteristics of LWAC [20]



	Water Cured		Roof Top						Seaside 28 Day Strength		
			1 Day Curing		3 Day Curing		7 Day Curing				
	28 Day	91 Day	28 Day	91 Day	28 Day	91 Day	28 Day	91 Day	1 Day Curing	3 Day Curing	7 Day Curing
Compressive strength 100 mm cube (MPa)	51.0	55.8	48.2	46.8	50.2	48.9	55.0	53.8	51.5	55.9	60.7
Indirect tensile strength 150 × 300 mm cylinders (MPa)	3.30	3.70	3.20	3.25	3.40	3.45	3.55	3.70	3.15	3.45	3.60
Modulus of rupture 100 × 100 × 500 mm (MPa)	4.40	—	3.65	—	3.85	—	4.05	—	4.00	4.30	4.35
Modulus of elasticity 150 × 300 mm cylinders (GPa)	26.1	—	25.4	—	26.0	—	26.3	—	26.3	—	26.9
Water Penetration (mm) 200 × 200 × 120	19.6		36.0		29.1		26.8		38.2	32.0	28.6
Depth of carbonation (mm) 100 × 100 × 500 beam			1.0	4.0	0.3	1.7	0.0	1.0	0.7	0.3	0.2

CHAPTER 4

EXPERIMENTAL STUDY

4.1. Introduction

The objective of this study was to design a structural lightweight aggregate concrete with the use of natural perlite aggregate that will provide an advantage of reducing dead weight of structure and to obtain a more economical structural lightweight concrete by the use of mineral admixture perlite powder as a replacement of the cement. Six mixes were produced with different cement content and with or without perlite powder. Six mixes divided into two groups according to their cement content. First group had a cementitious materials content of 300 kg/m^3 and second group had cementitious materials content of 500 kg/m3; also the w/cm ratios of groups were 0.49 and 0.35 respectively. Moreover, each group had three sub-mixes with 20% and 35% of perlite powder as a replacement of cement and without perlite power. All mixes had 0.5%-1.8% of accelerator superplasticizer by weight of cement.

An experimental study was carried out to examine six mixtures made with natural perlite aggregate in order to produce structural lightweight aggregate concrete. The slump, air content and density of fresh concrete and compressive strength, density, tensile strength, elastic module, shrinkage and chloride penetration of hardened concrete were studied.

4.2. Materials

4.2.1. Portland Cement

An ordinary Turkish Portland Cement CEM I 42.5N was used throughout the tests. The physical properties and chemical composition of portland cement are given in Table 4.1. and Table 4.2., respectively.

Table 4.1. Physical Properties of Portland Cement

Type	Specific Density (g/cm^3)	Blaine Fineness (cm^2/g)	Setting Time (h:min)	
			Initial	Final
CEM I 42.5N	3.11	3412	2:30	3:30

Table 4.2. Chemical Properties of Portland Cement

Oxide Composition	(%)
SiO_2	20.16
Al_2O_3	5.08
Fe_2O_3	3.80
MgO	2.45
CaO	63.32
SO_3	3.02
Loss-on ignition	1.34

4.2.2. Aggregate

The natural perlite aggregate was used as the aggregate in the production of structural lightweight aggregate concrete. Perlite was obtained from natural deposits in ERZİNCAN, ER-PER, Turkey.

Physical properties of ERZİNCAN natural perlite aggregate and its gradation are shown in Table 4.3. and Figure 4.1., respectively.

Table 4.3. Physical Properties of Perlite Aggregate

Bulk Density (g/cm^3)		Water Absorption 24h (% by weight)	Los Angeles Abrasion (%)
SSD	DRY		
2.16	2.03	5.9	67

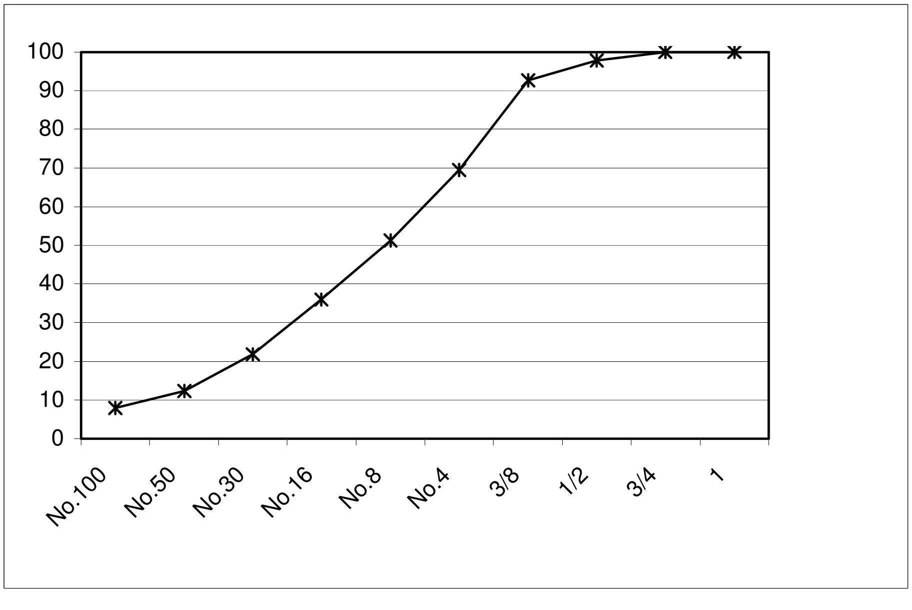


Figure 4.1. Gradation of Perlite Aggregate

4.2.3. Natural Pozzolan

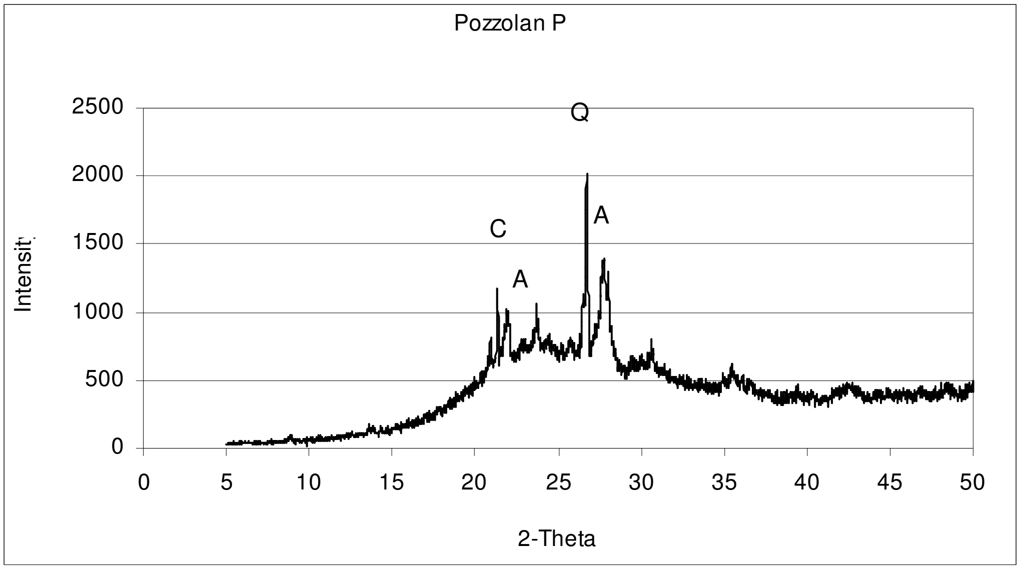
In the research, perlite powder obtained from grinding of natural perlite aggregate was used for production of structural lightweight aggregate concrete. A laboratory type grinding-mill which is 450 mm in length and 420 mm in diameter was used for grinding natural perlite aggregate. In each grinding 10 kg raw material were fed into mill and perlite powder of 80% material finer than 45 µm sieve was obtained. The chemical and physical properties of perlite powder are shown in Table 4.4.

Table 4.4. Chemical Composition of Perlite Powder

PERLITE POWDER	
Chemical Composition	**(%)**
SiO_2	70.96
Al_2O_3	13.40
Fe_2O_3	1.16
MgO	0.28
CaO	1.72
Na_2O	3.20
K_2O	4.65
Loss-on ignition	3.27
Physical Properties	
Specific Gravity	2.38
Fineness	
Passing 45-µm (%)	80
Specific surface, Blaine (m^2/kg)	413
Median particle size (µm)	19.1
Strength activity index* (%)	
7-days	78
28-days	80

*Strength activity index with portland cement in accordance with ASTM C 311.

Mineralogical composition of perlite powder used in this study was determined by X-Ray diffraction analysis by using CuKα radiation and diffraction patterns were given in Figure 4.2.



* Q: Quartz, C:Cristobalite, A: Albite

Figure 4.2. X-Ray Diffractogram of the Perlite Powder

4.2.4. Superplasticizer

Using of lightweight aggregate and pozzolanic addition increases the water requirement of fresh concrete for a given flow. A superplasticizer (Rhebuild 1000) of sulfonated, naphthalene formaldehyde dissolved in water was used in dosage between 0.5%-1.8 % by weight of total cementitious material as an admixture during mixing of fresh concrete. The properties of superplasticizer are given in Table 4.5.

Table 4.5. Physical and Chemical Properties of Superplasticizer

Density (g/cm^3), 20°C	1.2 – 1.22
% Chloride (EN 480-10)	< 0.1
Color	Brown
Homogeneity	Homogeny
Chemical Composition	Sulfonated naphthalene formaldehyde

4.3. Concrete Mixture Composition and Sample Preparation

The mixture proportions of concrete studied given with their abbreviated names and description in Table 4.6. Series 1 shown in the table consisted of structural lightweight aggregate concrete with cementitious material content of 300 kg/m^3 and w/cm ratio was 0.49. Series 2 consisted of structural lightweight aggregate concrete with a cementitious material content of 500 kg/m^3 and w/cm ratio was 0.35. The difference between mixtures of same series was the incorporation of 0%-20%-35% of perlite powder as cement replacement.

The materials were mixed in a mixer in the following order:

- One third of water and lightweight aggregate
- Cement, superplasticizers mixed with remaining water and perlite powder.
- Then the mixing was continued until a uniform concrete was obtained.

Cylindrical samples with 100 mm diameter and 200 mm length and prism samples 150x150x300 mm were cast from fresh concrete mixtures. The compaction of the samples was obtained by means of vibration.

All the test specimens were demoulded at 24hr and than cured at 23 °C±2 °C and 65% Rh for 6 day. Then, specimens were placed at room temperature in laboratory until the day of testing. (ASTM C330-99)

Table 4.6. Mix Proportions of Concretes

Series	Sub-mixes	C* (kg/m^3)	PP* (kg/m^3)	NPA (kg/m^3)	W / (C+PP)	Superplasticizer (% of C+PP)
3H	3H1	300	0	1451	0.49	1.5
	3H2	240	60	1451	0.49	1.6
	3H3	195	105	1451	0.49	1.8
5H	5H1	500	0	1288	0.35	0.5
	5H2	400	100	1288	0.35	0.6
	5H3	325	175	1288	0.35	0.65

* PP: Perlite Powder, C: Portland Cement, NPA: Natural Perlite Aggregate

4.4. Tests Performed on Structural Lightweight Concrete

4.4.1. Tests Performed on Fresh Concrete

4.4.1.1. Slump

Slump is a most important factor in achieving a good floor surface with lightweight concrete. A lower slump, imparts sufficient workability and also maintains cohesiveness and “body” there by preventing the lighter coarse particles from working up though the mortar to surface. In addition to “surface” segregation, excess slump will cause unnecessary finishing delays [7].

The slump test of fresh concrete was conducted according to ASTM C143 [21].

4.4.1.2. Density

The density of fresh concrete was determined according to ASTM C138 [22] “Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete” by calculating the net weight of the concrete in kilogram and subtracting the weight of the measure from the gross weight; to calculate the unit weight, dividing the net weight the volume of the measure used.

4.4.1.3. Air-Content

Air entrainment in lightweight concrete, improves durability. Moreover concrete with some lightweight aggregates, it is particularly effective means of workability of otherwise harsh mixtures. The mixing water requirement is than lowered while maintaining the same slump, thereby reducing bleeding and segregation.

The air content of mixtures was determined by pressure meter as per ASTM C231 [23] "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method"

4.4.1.4. Setting Time

The initial and final setting time of concrete mixtures were measured according to ASTM C403 [26]. The test consist of removing the mortar fraction of the concrete by passing it through a 4.75mm sieve, rodding into the containers and then measuring the force required to cause a needle to penetrate.

The initial set represents approximately the time which fresh concrete can no longer be properly handled and placed, while final setting approximates the time at which hardening begins. Although the time of setting of concrete is an arbitrary measurement, it is an important parameter for a number of reasons.
It is used:

- To help to regulate the times of mixing and transit,
- To gauge to effectiveness of various set-controlling admixtures.
- To help plan the scheduling of finishing operations.

4.4.2. Tests Performed on Hardened Concrete

4.4.2.1. Compressive Strength

The compressive strengths of concrete mixtures were determined at 3, 7, 28 and 90 days of age according to ASTM C39 [23]. Two groups of mixtures were prepared to determine the compressive strength of structural lightweight concrete with different cementitious materials contents. Also, three mixtures were prepared for each group to compare the effect of adding natural pozzolan on the compressive strength of structural lightweight aggregate concrete.

4.4.2.2. Splitting Tensile Strength

The splitting tensile strength of concrete mixtures was determined at 28 and 90 days of age according to ASTM C 496 [24]. The test is performed by application of diametrically opposite compressive loads to concrete cylinder laid on its side in the testing machine. Fracture or splitting occurs along the diametric plane. The splitting tensile strength is obtained by use of following formula:

$$f'_{ct} = 2P / \pi \times L \times D \qquad (4.1)$$

where f'_{ct} splitting tensile strength, P total applied load, D and L diameter and length of cylinder.

Two groups of mixtures were prepared to determine the splitting tensile strength of structural lightweight aggregate concrete with different cement contents. Also, three mixtures were prepared for each group to compare the effect of adding natural pozzolan on the splitting tensile strength of structural lightweight aggregate concrete.

4.4.2.3. Modulus of Elasticity

The modulus of elasticity of concrete mixtures was calculated based on the stress corresponding to 40% of ultimate load and the longitudinal strain produced by this stress. All the tests were conducted according to ASTM C 469 [25] at 28 and 90 days of age.

The formula for elastic module of structural concrete was given in ACI 318 [10], but concrete in service may comply with this formula only within a ±15 to 20 percent. The modulus of elasticity of structural lightweight aggregate concrete is important for design purposes so to make an accurate evaluation, modulus of elasticity of concrete mixtures was defined by laboratory tests.

4.4.2.4. Drying Shrinkage

The term drying shrinkage represents the strain caused by the loss of water from the hardened material. Inadequate allowance for the effects of drying shrinkage in concrete design and construction can lead to cracking or warping of elements of the structure due to restrains present during shrinkage.

The drying shrinkage test was conducted according to ASTM C157 [28]. This test method covers the determination of the length changes that are produced by causes other than externally applied forces and temperature changes in hardened concrete specimens made in the laboratory and exposed in the laboratory to controlled conditions of temperature and moisture. The length change of the 150*150*300mm prism concrete samples was measured 6 months of age.

4.4.2.5. Chloride Penetration

The rapid chloride penetrability test was conducted in accordance with ASTM C1202 [27]. This test method consists of monitoring the amount of electrical current passed through 51-mm thick slices of 102-mm nominal diameter cores or cylinders during a 6-h period. A potential difference of 60 V dc is maintained across the ends of the specimen, one of which is immersed in a sodium chloride solution, the other in a sodium hydroxide solution. The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration.

The chloride ion penetration of concrete mixtures was determined at 28 and 90 days of age. Two samples were cut from cylinders for each mixture. The effect of cement content and natural pozzolan adding on the chloride penetrability of structural lightweight aggregate concrete was investigated.

CHAPTER 5

TEST RESULTS AND DISCUSSIONS

5.1. Investigations on Fresh Concrete

The slump, density and air-content values of fresh concrete are tabulated in Table5.1. for different sub-mixes. Although the aggregates were used in the dry state, slump values of fresh concrete were between 50 mm-100 mm. The lightweight aggregate concrete used in this study was very cohesive and workable. The maximum and minimum values of the density of the fresh concrete were 1963 kg/m^3 and 1840 kg/m^3 respectively.

Table 5.1. Properties in Fresh State

Series	Sub-mixes	W/ (C+PP)	PP (%)	Slump (mm)	Air-content (%)	Density (kg/m^3)
3H	3H1	0.49	0	50	6	1853
	3H2	0.49	20	80	5	1840
	3H3	0.49	35	100	4	1845
5H	5H1	0.35	0	60	4.2	1963
	5H2	0.35	20	100	5	1920
	5H3	0.35	35	100	4.2	1925

The initial and final setting time of the mixes were presented in Table 5.2. From the results shown in Table 5.2., there was a reduction in the initial and final setting time of concrete from mixtures contain 300 kg/m^3 cement (Series 3H) to mixtures contain 500 kg/m^3 cement (Series 5H) because of high cement content. On the other hand, perlite powder addition to concrete as a cement replacement increased the initial and final setting time of concrete Series 3H, however initial and final setting time of concrete Series 5H did not change significantly with perlite powder addition.

Table 5.2. Initial and Final Setting Times

Series	Sub-mixes	PP (%)	Setting Times (h:min)	
			Initial	Final
3H	3H1	0	6:15	9:50
	3H2	20	7:05	11:05
	3H3	35	7:45	11:30
5H	5H1	0	3:45	6:00
	5H2	20	3:45	6:00
	5H3	35	3:45	6:10

5.2. Investigations on Hardened Concrete

5.2.1. Compressive Strength and Density

The compressive strength and density of the concrete are summarized in Table 5.3. The 28-day compressive strength and the air-dry concrete density varied from 20 MPa to 42 MPa and 1745 kg/m^3 to 1865 kg/m^3, respectively. In Series 3H, the 28-day cylindrical strength of SLWAC decreased when PP content varied from 0 to 35 percent by replacement of cement. In Series 5H, the 28-day cylindrical strength of SLWAC did not change significantly while PP content increased from 0 to 35 percent by replacement of cement. All concrete mixes essentially continued to gaining strength between the ages of 28 and 90 days.

Table 5.3. Compressive Strength and Density

Series	Sub-mixes	w/c	PP(%)	Compressive Strength (MPa)				Density (kg/m^3)	
				3 Day	7 Day	28 Day	90 Day	Air-dry	Oven-dry
3H	3H1	0.49	0	22	25	34	40	1855	1775
	3H2	0.49	20	14	17	22	32	1835	1765
	3H3	0.49	35	9	11	20	26	1795	1735
5H	5H1	0.35	0	26	28	42	52	1865	1810
	5H2	0.35	20	23	25	41	51	1800	1725
	5H3	0.35	35	25	28	39	51	1745	1610

If one takes the density of normal concrete 2300 kg/m^3, there is a saving in the self-weight between 20% to 25%. Figure 5.1 shows the relationship between the density of air-dry concrete and % perlite powder. As it can be seen from the figure, perlite powder addition decreases the density of concrete of both series.

The effect of perlite powder addition on the early compressive strength, 28-day compressive strength and 90-day compressive strength of SLWAC summarized in Figure 5.2, Figure 5.3, Figure 5.4, respectively. As can be seen from the figures, in Series 3H early compressive strength of SLWAC decrease with increase of perlite powder content; although early compressive strength of Series 5H concretes do not change significantly with increase of perlite powder content. The decrease in early strength is reasonable because of pozzolanic reaction of perlite powder. In Series 5H, cement content is high and w/cm is lower so early strength do not change significantly with the increase of perlite powder content.

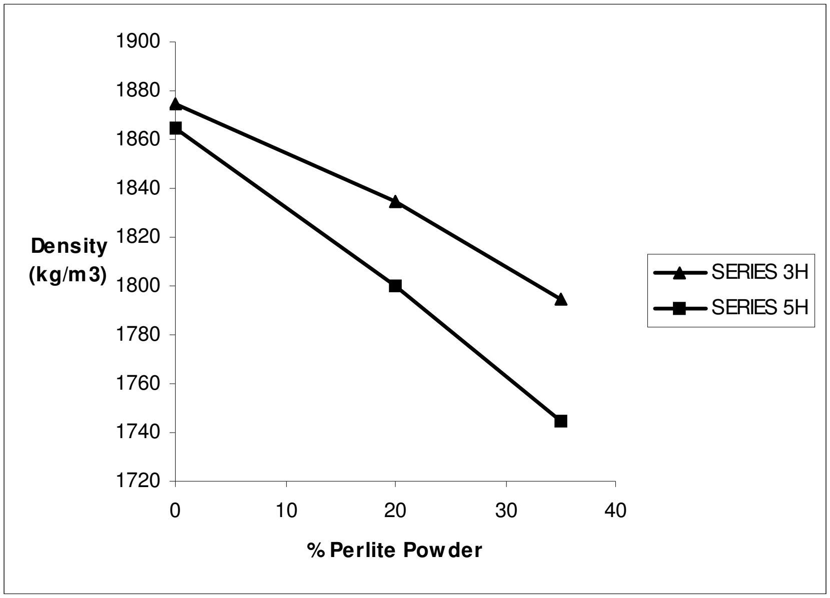


Figure 5.1. The effect of perlite powder addition on the density of SLWAC.

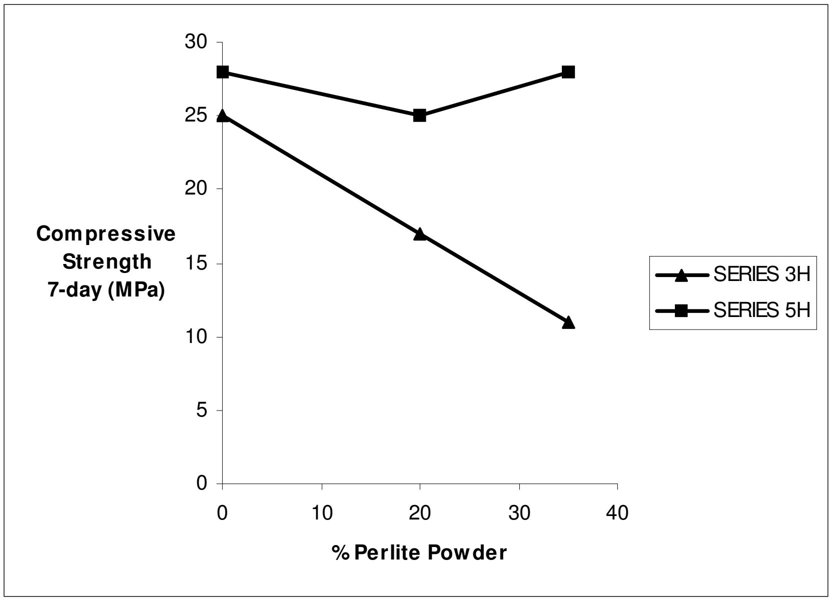


Figure 5.2. The effect of perlite powder addition on the early compressive strength of SLWAC.

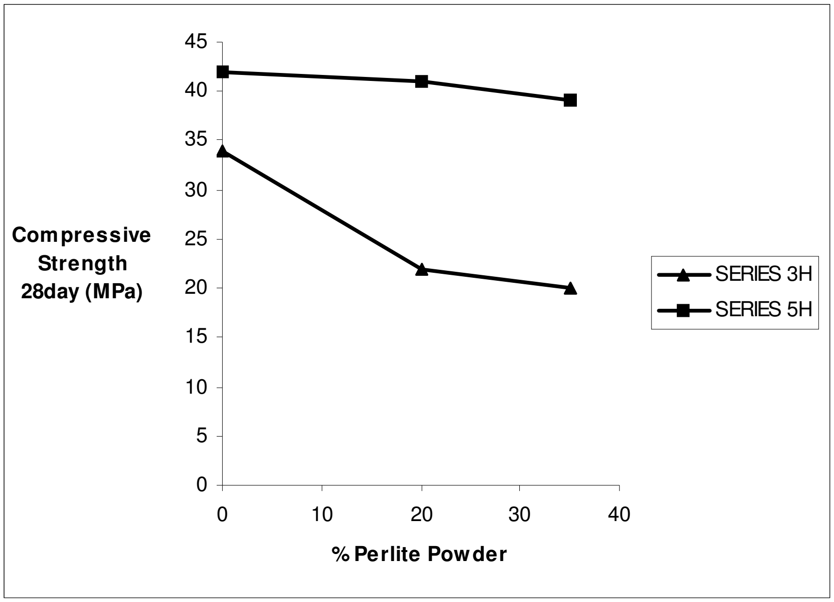


Figure 5.3. The effect of perlite powder addition on the 28 day compressive strength of SLWAC.

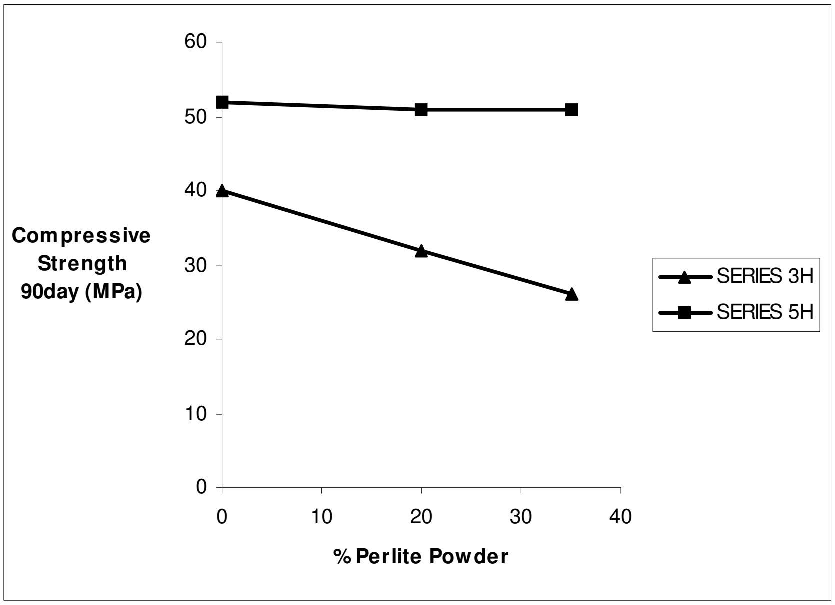


Figure 5.4. The effect of perlite powder addition on the 90 day compressive strength of SLWAC.

According to Figure 5.3. and Figure 5.4., in Series 3H, the strength reduction is decreased with the increase of age and in Series 5H, pozzolanic action of perlite powder contributes the enhancement of strength.

5.2.2. Tensile Strength

The average tensile strengths of the concrete studied were presented in Table 5.4. The 28-day splitting tensile strength of concrete varied from 1.6 MPa to 2.6 MPa. However, the tensile/compressive strength ratio of SLWAC change between 0.06-0.10 and the tensile/compressive strength ratio was lower for SLWAC than that of NWC. Figure 5.5. shows the observed relationship between the perlite powder content and 28-day tensile strength. As can be seen from the figure, increase of perlite powder content do not change tensile strength of SLWAC of Series 5H significantly, but in Series 3H, tensile strength of SLWAC decrease when %35 of perlite powder used as cement replacement.

Table 5.4. Tensile Strength

Series	Sub-mixes	W/(C+PP)	PP (%)	Tensile Strength (MPa)	
				28 Day	90 Day
3H	3H1	0.49	0	2.30	2.90
	3H2	0.49	20	2.30	2.90
	3H3	0.49	35	1.60	2.20
5H	5H1	0.35	0	2.50	3.80
	5H2	0.35	20	2.60	3.70
	5H3	0.35	35	2.60	3.70

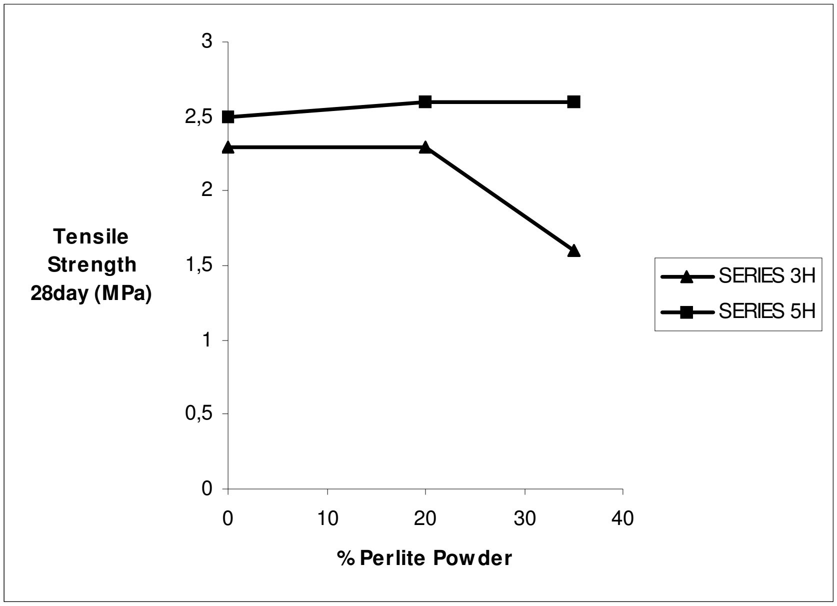


Figure 5.5. The relationship between the perlite powder content and 28-day tensile strength.

5.2.3. Modulus of Elasticity

Table 5.5. shows the results of modulus of elasticity for structural lightweight aggregate concrete. The modulus of elasticity of the structural lightweight aggregate concrete varied from 13350 MPa to 21300 MPa. Figure 5.6 shows the correlation between the modulus of elasticity and 28day compressive strength. As it can be seen from the figure, the modulus increase as the compressive strength increases. However, modulus of elasticity of SLWAC is nearly 50% of modulus of NWC.

Table 5.5. Modulus of Elasticity

Series	Sub-mixes	W/(C+PP)	PP (%)	Modulus of Elasticity (MPa)	
				28 Day	90 Day
3H	3H1	0.49	0	17150	19500
	3H2	0.49	20	14500	15400
	3H3	0.49	35	13350	14000
5H	5H1	0.35	0	21300	22000
	5H2	0.35	20	20500	19500
	5H3	0.35	35	19750	18715

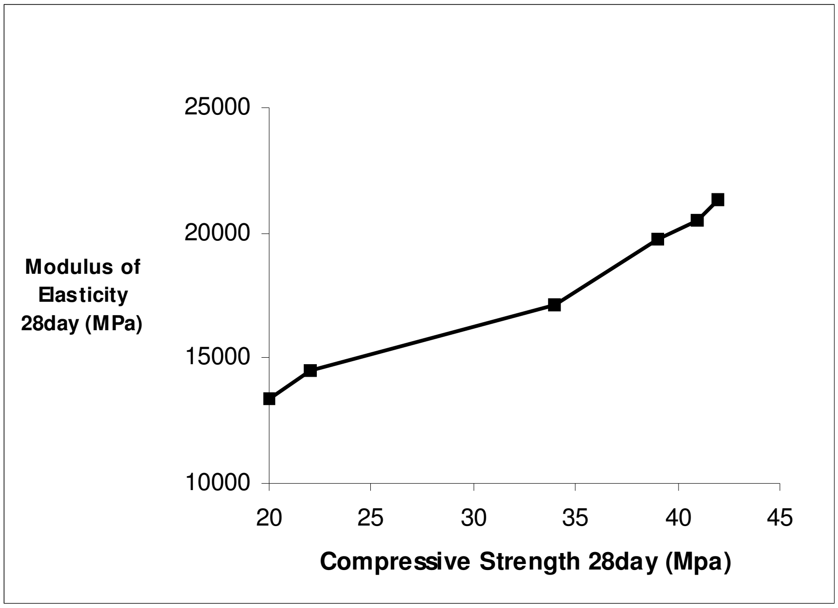


Figure 5.6. The correlation between the modulus of elasticity and 28day compressive strength.

5.2.4. Drying Shrinkage

Drying shrinkage for the structural lightweight aggregate concrete sub-mixes was presented in Figure 5.7. and Figure 5.8.

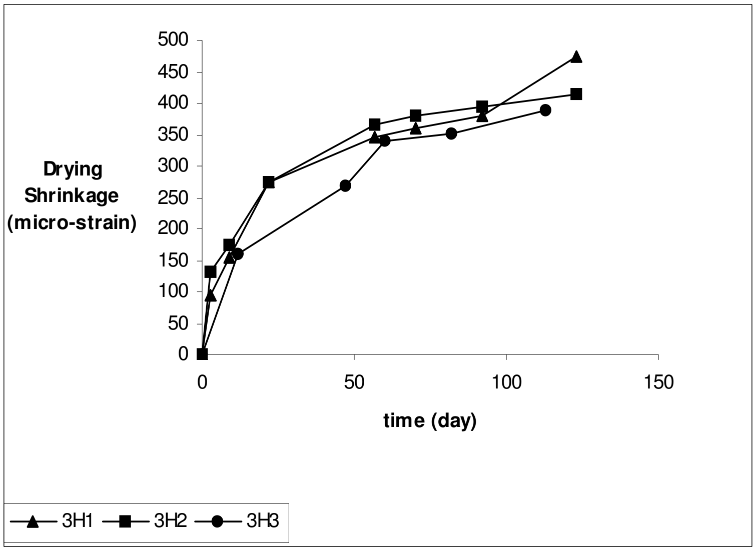


Figure 5.7. Effect of %PP and age on the drying shrinkage of SLWC (Series 3H).

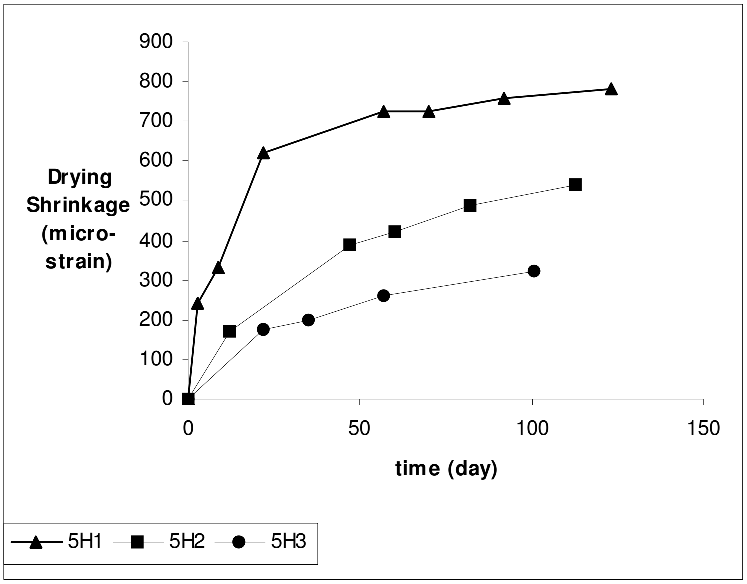


Figure 5.8. Effect of %PP and age on the drying shrinkage of SLWC (Series 5H).

5.2.5. Chloride Penetration

Table 5.6. and Table 5.7. summarizes the rapid chloride penetrability data of the structural lightweight aggregate concrete sub-mixes at 28 day and 90 day, respectively. The effect of perlite powder addition on the 28 day and 90 day chloride penetrability of SLWAC summarized in Figure 5.8. and Figure 5.9., respectively.

Table 5.6. Rapid Chloride Penetrability Data (28 Day)

Series	Sub-mixes	w/c	PP(%)	Charge Passed (coulombs)	Chloride Penetrability
3H	3H1	0.49	0	2056	Moderate
	3H2	0.49	20	2435	Moderate
	3H3	0.49	35	3127	Moderate
5H	5H1	0.35	0	3049	Moderate
	5H2	0.35	20	2480	Low
	5H3	0.35	35	1883	Low

Table 5.7. Rapid Chloride Penetrability Data (90 Day)

Series	Sub-mixes	w/c	PP(%)	Charge Passed (coulombs)	Chloride Penetrability
3H	3H1	0.49	0	246	Very Low
	3H2	0.49	20	1638	Low
	3H3	0.49	35	3045	Moderate
5H	5H1	0.35	0	916	Very Low
	5H2	0.35	20	700	Very Low
	5H3	0.35	35	415	Very Low

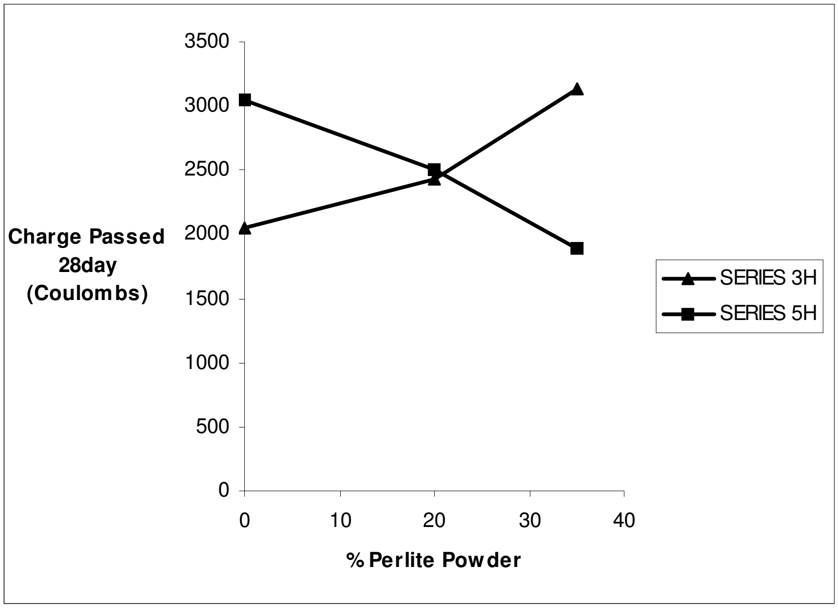


Figure 5.9. The effect of perlite powder addition on the 28 day chloride penetrability.

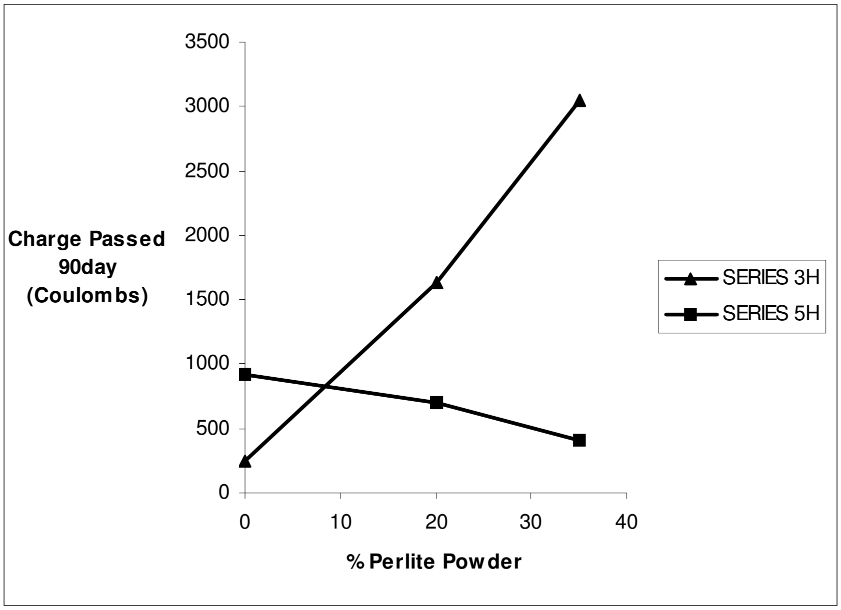


Figure 5.10.The effect of perlite powder addition on the 90 day chloride penetrability.

CHAPTER 6

CONCLUSIONS

Based on the test results obtained in the study, the following conclusions can be drawn;

- It is possible to produce structural lightweight aggregate concrete with natural perlite aggregate.
- Structural lightweight aggregate concrete with natural perlite aggregate has an advantage of reduced density since density of normal weight concrete is about 2300 kg/m^3. As a result of this, SLWAC has an advantage of reduced dead weight of the structure as well as reduced risk of earthquake damages to a structure because earthquake forces are proportional to mass of the structure.
- Structural lightweight aggregate concrete with a 28 day cylindrical compressive strength between 20 MPa-40 MPa can be produced by the use of natural perlite aggregate. Also, economical structural lightweight aggregate concrete with a 28 day cylindrical compressive strength between 20 MPa-40 MPa can be produced by the use of perlite powder as a natural pozzolan.
- Tensile strength/compressive strength ratio of structural lightweight aggregate concrete is between 0.06–0.10 which is lower than normal weight concrete.
- The modulus of elasticity of structural lightweight aggregate concrete is between 13350 MPa–21300 MPa, which is lower than normal weight concrete.
- The drying shrinkage of structural lightweight aggregate concrete decrease with the use of perlite powder as cement replacement. Use of natural

pozzolan more effective in Series 5H than in Series 3H. Decrease in drying shrinkage increase with the increase of perlite powder percent in SLWAC.

- The resistance of structural lightweight aggregate concrete to chloride penetration seems to be moderate and low according to ASTM C1202. Although lightweight aggregates have high porosity, their resistance to chloride penetration is better than normal weight concrete because pores are not interconnected.

CHAPTER 7

RECOMMENDATIONS

In this study, the performance of structural lightweight aggregate concrete produced by natural perlite aggregate was investigated. According to experimental results in the study following recommendations can be …

- The performance of structural lightweight aggregate concrete could be further studied with various cement content at constant w/c ratio.
- Properties of fresh and hardened structural lightweight aggregate concrete should be determined with addition of high content natural pozzolans. (50%)
- Chloride penetrability of structural lightweight aggregate concrete could be further studied with increased number of variables, such as cement content, w/cm ratio, perlite powder content…
- Structural lightweight aggregate concrete has internal moisture content so durability of reinforcements should be investigated.
- The thermal conductivity of structural lightweight concrete with natural perlite aggregate should be investigated.

REFERENCES

1. Erdoğan T.Y., Materials of Construction, Middle East Technical University, Ankara, 2002

2. Mindess, S., Young, J.F., Darwin D., Concrete, 2nd ed., Prentice-Hall, New Jersey, 2003.

3. Newman J., Choo B.S., Advanced Concrete Technology, Constituent Materials, Elsevier, Oxford, 2003

4. Erdoğan T.Y., Admixture for Concrete, Middle East Technical University, Ankara, 1997

5. Ramachandran V.S., Concrete Admixtures Handbook, 2nd ed., Noyes Publications, New Jersey, 1995

6. ASTM C 311, "Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete", 1993

7. ACI Committee 213, "Guide for Structural Lightweight Aggregate Concrete", American Concrete Institute, 1987

8. Short A., Kinniburgh W., Lightweight Concrete, C.R Books Limited, London, 1963

9. Chandra S., Berntsson L., Lightweight Aggregate Concrete, Noyes Publications, New York, 2003

10. ACI Committee 318, “Building Code Requirements for Structural Concrete and Commentary”, American Concrete Institute, 1999

11. Rossignola J.A., Agnessi M.V.C., Morais J.A., “Properties of High Performance LWAC for Precast Structures with Brazilian Lightweight Aggregate”, Cement and Concrete Composites, Vol.23, pp. 77-82, 2003

12. Yasar E., Atis C.D., Kılıç A., Gulsen H., “Strength Properties of Lightweight Concrete Made with Basaltic Pumice and Fly Ash”, Materials Letters, Vol. 57, pp. 2267-2270, 2003

13. Kılıç A., Atiş C.D., Yaşar E., Özcan F., “High-strength Lightweight Concrete Made with Scoria Aggregate Containing Mineral Admixtures”, Cement and Concrete Research, Vol. 33, pp. 1595-1599, 2003

14. Haque M.N., Al-Khaiat H., Kayali O., “Strength and Durability of Lightweight Concrete”, Cement and Concrete Composites, Vol. 26, pp. 307-314, 2004

15. Khandaker M., Hossain A., “Properties of Volcanic Pumice Based Cement and Lightweight Concrete”, Cement and Concrete Research, Vol. 34, pp. 283-291, 2004

16. Hwang C.L., Hung M.F., “Durability Design and Performance of Self-Consolidating Lightweight Concrete”, Construction and Building Materials, Vol. 19, pp. 619-626, 2005

17. Chia K.S., Zhang M.H., “Water Permeability and Chloride Penetrability of High-strength Lightweight Aggregate Concrete”, Cement and Concrete Research, Vol.32, pp. 639-645, 2002

18. Lo T.Y., Cui H.Z., “Effect of Porous Lightweight Aggregate on Strength of Concrete”, Materials and Letters, Vol.58, pp. 916-919, 2004

19. Lo T.Y., Cui H.Z, Li Z.G., "Influence of Aggregate Pre-wetting and Fly Ash on Mechanical Properties of Lightweight Concrete", Waste Management, Vol. 24, pp. 333-338, 2004

20. Al-Khaiat H., Haque M.N., "Effect of Initial Curing on Early Strength and Physical Properties of A Lightweight Concrete", Concrete and Cement Research, Vol. 28, pp.859-866, 1998

21. ASTM C 143, "Standard Test Method for Slump of Hydraulic-Cement Concrete", 1993

22. ASTM C 138, "Standard Test Method for Unit Weight, Yield and Air-content of Concrete", 1993

23. ASTM C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", 1993

24. ASTM C 496, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", 1993

25. ASTM C 469, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", 1993

26. ASTM C 403, "Standard Test Method for Time Setting of Concrete Mixtures by Penetration Resistance", 1993

27. ASTM C 1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration", 1993