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INVESTIGATION ON THE SUITABILITY OF PUMICE AND SCORIA AGGREGATES IN RIBBED-SLAB CONSTRUTION

By

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ABSTRACT

This thesis presents the results of an investigation on the suitability of pumice and scoria aggregates in ribbed-slab construction. The aggregates were assessed for their utilization in topping and web construction of ribbed-slab. The suitability of using scoria as both fine and coarse aggregate; and pumice as fine aggregate in all-lightweight concrete production is assessed. The properties of scoria-scoria concrete (ScScC) and scoria-pumice concrete (ScPC) are evaluated by conducting comprehensive series of tests on workability, density and strength.

Experimental and theoretical investigations were conducted to study the strength and deformation characteristics of ribbed-slab with 60 mm topping.

Part of the experimental program was dedicated to the study of mix design for the production of all-lightweight structural concrete. The second part of the experimental program was concerned with full size slab testing. Theoretical investigations were conducted parallel to the experimental investigations.

Developed ScScC mixtures have attained required strength and density to be accepted as structural lightweight concrete; however, ScPC cannot be used as structural concrete.

Comparison of test results showed that ribbed-slabs can be constructed using scoria aggregates with 47% fine content, 1.6 A/C ratio and 0.4 W/C in range of normal cement content.

Keywords: *Scoria, Pumice, Lightweight aggregates, Lightweight concrete, Ribbed-Slab, mix design, Density, Strength.*

1. INTRODUCTION

The use of lightweight aggregate concrete can be traced to as early as 3000 B.C, when the famous towns of Mohenjo-Daro and Harappa were built during the Indus Valley civilization. In Europe, earlier use of lightweight aggregate concrete occurred about two thousand years ago when the Romans built the Pantheon, the aqueducts, and the Colosseum in Rome. It is interesting to note that pumice is still used today as an aggregate for structural concrete in certain countries such as Germany, Italy, Iceland, and Japan [1].

Earlier lightweight aggregates were of natural origin, mostly volcanic: pumice, scoria, tuff, etc. These have been used both as fine and coarse aggregates. They function as active pozzolanic materials when used as fine aggregates. These interact with the calcium hydroxide generated from the binder during hydration and produce calcium silicate hydrate which strengthens the structure and modifies the pore structure, enhancing the durability properties [1].

The most obvious characteristic of lightweight concrete, as its name implies, is its density, which is always less than that of the ordinary gravel or crushed stone and sand-concrete. The practical range of densities of lightweight concrete is between about 300 and 2000kg/m^3, while that of normal weight concrete ranges from 2300 to 2500 kg/m^3 [2, 3].

Researches have been conducted worldwide on a large number of natural and artificial lightweight aggregates to manufacture mortar and concrete. Natural lightweight aggregates include diatomite, pumice, scoria, sawdust, oil palm shells, bottom ash, and starch-based aggregates. Artificial aggregates include expanded shale, slate, perlite, sintered fly ash, bonded fly ash, solidified blast furnace slug, and vermiculite. Use of natural lightweight aggregates instead of processed artificial aggregates can significantly reduce the cost of such concretes [7].

The primary use of structural lightweight concrete is to reduce the dead load of concrete structure, which then allows the structural designer to reduce the size of columns, footings and other load bearing elements [7].

The use of lightweight concrete is usually preferred for lower overall cost of structures. Although lightweight concrete may cost higher per cubic meter than normal weight concrete, the structure may cost less as a result of reduced dead weight and lower foundation cost [2]. This is the basic reason, in most cases, for using structural lightweight concrete.

In seismic resistant structures, lightweight concrete is more attractive than ordinary concrete because of its lower modulus of elasticity and its lower specific gravity. Even lightweight concrete is more favorable when the structure is higher and the span larger [11].

Structural lightweight aggregate concretes are suitable for high fire ratings and in this respect are superior to normal weight concretes since they (a) exhibit a lower strength reduction at high temperature, (b) provide more insulation and (c) have lower thermal expansions which result in less spalling [4]. In addition, depending upon the density and strength, the concrete can be easily cut, nailed, drilled, and chased with ordinary wood-working tools [1].

Following Italy, Chile, and Ecuador; Ethiopia is the 4th leading producer of pumice and scoria aggregates in the world [7]. The use of these abundantly produced natural lightweight materials, in the construction industry has been studied in Ethiopia. Most of these studies [2, 3, 7, and 10] examined the use of scoria and pumice as a source of aggregate or as a partial replacement of normal weight aggregates for the production of structural concrete.

This study was undertaken to investigate the suitability of Pumice and Scoria Aggregates in Ribbed Slab Construction. The study also presents the results of experimental investigation studying mix design, strength and density characteristics of pumice and scoria concretes. Theoretical and experimental investigations are carried out to determine the strength and deformation characteristics of ribbed slab.

Investigation of ribbed-slab made with scoria lightweight concrete revealed that it has satisfactory resistance against both ultimate and service loads.

2. LITERATURE REVIEW

2.1 Introduction

In this chapter, the properties of lightweight aggregates and lightweight aggregate concrete in general are reviewed. The classifications, definitions and limitations of lightweight aggregate concrete are discussed. The geological sources, chemical composition, properties of scoria and pumice aggregates; scoria and pumice aggregate concretes are discussed.

2.2 Lightweight Aggregate

2.2.1 Introduction, Definitions and limitations

The aggregates used in structural lightweight concrete may be a combination of fractions of both lightweight coarse and fine materials and lightweight coarse material with an appropriate, natural fine aggregate.

Any aggregate with a particle density of less than 2000 kg/m^3 or a dry loose bulk density of less than 1200 kg/m^3 is defined as lightweight [6]. However, this necessary dual qualification in definition highlights a practical difference from most other aggregates used in structural concrete where particle densities greater than 2000 kg/m^3 are used. In the case of an appropriate lightweight aggregate the encapsulated pores within the structure of the particle have to be combined with both the interstitial voids and the surface vesicles. Nevertheless, these features in combination should not increase the density of the compacted concrete either by significant water absorption or cement paste pervasion into the body of the aggregate particle when the aggregate is mixed into concrete [4].

2.2.2 Types of Lightweight Aggregate

Lightweight aggregate can be divided in two categories:

i. Those occurring naturally and are ready to use only with mechanical treatment, i.e., crushing and sieving. Important examples for this type of aggregate are *volcanic aggregates*, or *pumice* and *scoria aggregates* [1].

ii. Artificial lightweight aggregates such as Foamed Slag, Expanded clay, Sintered PFA, Blast furnace slag, Expanded slate, Expanded shale, etc. According to Clarke J.L. [4], the manufacturing process, shape or texture, dry loose bulk density and the concrete strength of artificial lightweight aggregates is given in Table 2.1.

Table 2.1 Artificial Lightweight aggregates according to Clarke J.L. [4]

Aggregate Type	Manufacturing Process	Shape/Texture	Dry loose bulk density (kg/m^3)	Concrete strength (N/mm^2)
Foamed Slag	Foaming bed	Angular/ vesicular	750	< 40
Expanded clay	Rotary kiln	Rounded/ smooth	425	< 30
Sintered PFA	Sinter strand	Rounded/fine	825	> 40
Blast furnace slag	Pelletisation	Irregular/ smooth	900	> 40
Expanded slate	Rotary kiln	Irregular/ rough	700	> 40
Expanded shale	Rotary kiln	Rounded/ smooth: fine	650	> 40

2.2.3 Characteristics of lightweight Aggregate

The characteristics of chemically stable lightweight aggregate can affect the properties of the concrete made with it, the same way as or more than a normal weight aggregate does those of an ordinary concrete. The characteristics include particle shape and surface texture, strength, relative density, bulk density, moisture content and absorption, grading, and modulus of elasticity [2].

The present study is limited to the use of pumice and scoria for lightweight concrete. Consequently, these two specific aggregates will be discussed in detail.

i) Particle Shape and Surface Texture

Lightweight aggregates from different sources may differ considerably in particle shape and texture. Shape may be cubical and reasonably regular, essentially rounded, or angular and irregular. Surface textures 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 aggregates influence proportioning of mixtures in such factors as workability, fine-to-coarse aggregate ratio, binder content, and water requirement. These effects are analogous to those obtained with normalweight aggregates with such diverse particle shapes as exhibited by rounded gravel, crushed limestone, trap-rock, or manufactured sand [4, 12].

ii) Relative density

Due to their cellular structure, the relative density of lightweight-aggregate particles is lower than that of normalweight aggregates. The lightweight particle relative density 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 coarse lightweight aggregate relative densities, corrected to the dry condition, is from almost 1/3 to 2/3 that for normalweight aggregates. Particle densities below this range may require more cement to achieve the required strength and may thereby fail to meet the density requirements of the concrete [12].

iii) Bulk Density

The bulk density of lightweight aggregate is significantly lower, due to the cellular structure, than that of normalweight aggregates. For the same grading and particle shape, the bulk density of an aggregate is essentially proportional to particle relative densities. Aggregates of the same particle density, however, may have markedly different bulk densities because of different percentages of voids in the dry-loose volumes of aggregates of different particle shapes. The situation is analogous to that of rounded gravel and crushed stone, where differences may be as much as 160 kg/m^3, for the same particle density and grading, in the dry-rodded condition. Rounded and angular lightweight aggregates of the same particle density may differ by 80 kg/m^3 or more in the dry-loose condition, but the same mass of either will occupy the same volume in

concrete. This should be considered in assessing the workability when using different aggregates. Table 2.2 summarizes the maximum densities for the lightweight aggregates listed in ASTM C330 and C331 [13].

Table 2.2 Bulk-density requirements of ASTM C330 and C331 [13] for dry, loose, lightweight aggregates

Aggregate Size and Group (ASTM C330 and C331)	Maximum Density (kg/m^3)
Fine aggregate	1120
Coarse aggregate	880
Combined coarse and fine aggregates	1040

iv) 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. For compressive strengths up to approximately 35 MPa, there is no reliable correlation between aggregate strength and concrete strength.

The concept of "strength ceiling" may be useful in indicating the maximum compressive and tensile strength attainable in concrete made with a given lightweight aggregate using a reasonable quantity of cement.

A mixture is near its strength ceiling when similar mixtures containing the same aggregates and with higher cement contents have only slightly higher strengths. It is the point of diminishing returns, beyond which an increase in cement content does not produce a commensurate increase in strength. The strength ceiling for some lightweight aggregates may be quite high, approaching that of some normalweight aggregates.

The strength ceiling is influenced predominantly by the coarse aggregate. The strength ceiling can be increased appreciably by reducing the maximum size of the coarse aggregate for most lightweight aggregates. This effect is more apparent for the weaker and more friable aggregates. In one case, the strength attained in the laboratory for concrete containing 19 mm maximum size of a specific lightweight aggregate was 35 MPa; for the same cement content, the strength was increased to 42 and 52 MPa when the maximum size of the aggregate was reduced to 13 and 10

mm, respectively, whereas concrete unit weights were concurrently increased by 48 and 80 kg/m^3 [12].

v) Moisture Content and Absorption

Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normalweight aggregates. Based on a standard ASTM C 127 absorption test expressed at 24 h, lightweight aggregates generally absorb from 5 to 25% by mass of dry aggregate, depending on the aggregate pore system [13].

In contrast, most normalweight aggregates will absorb less than 2% of moisture. The moisture content in a normalweight aggregate stockpile, however, may be as high as 5 to 10% or more. The important difference is that the moisture content with lightweight aggregates is absorbed into the interior of the particles as well as on the surface, while in normalweight aggregates, it is largely surface moisture [12].

For an individual aggregate particle the amount of water absorbed and the rate of absorption depend primarily on: [4]

(a) the pore volume,
(b) the distribution of pores within the particle and
(c) the structure of the pores (i.e. whether connected or disconnected).

vi) Grading

Grading requirements for lightweight aggregates deviate from those of normalweight aggregates ASTM C 33 [13]; by requiring a larger mass of the lightweight aggregates to pass through the finer sieve sizes. This modification in grading ASTM C 330 [13] recognizes the increase in density with decreasing particle size of lightweight expanded aggregates. This modification yields the same volumetric distribution of aggregates retained on a series of sieves for both lightweight and normalweight aggregates.

Normalweight sand replacement will typically increase the equilibrium concrete density from about 80 to 160 kg/m^3. Using increasing amounts of cement to obtain high-strength concrete may increase the density from 32 to 96 kg/m^3 [12].

vii) Modulus of Elasticity of Lightweight Aggregates

The modulus of elasticity of concrete is a function of the modulus of elasticity of its constituents. Concrete may be considered as a two-phase material consisting of coarse-aggregate inclusions within a continuous mortar fraction that includes cement, water, entrained air, and fine aggregate. Dynamic measurements made on aggregates alone have shown a relationship corresponding to the function $E = 0.008p^2$, where E is the dynamic modulus of elasticity of the particle, in MPa, and p is the dry mean particle density, in kg/m^3.

Dynamic modulus of elasticity for typical expanded aggregates has a range of 10 to 16 GPa, whereas the range for strong normalweight aggregates is approximately 30 to 100 GPa [17].

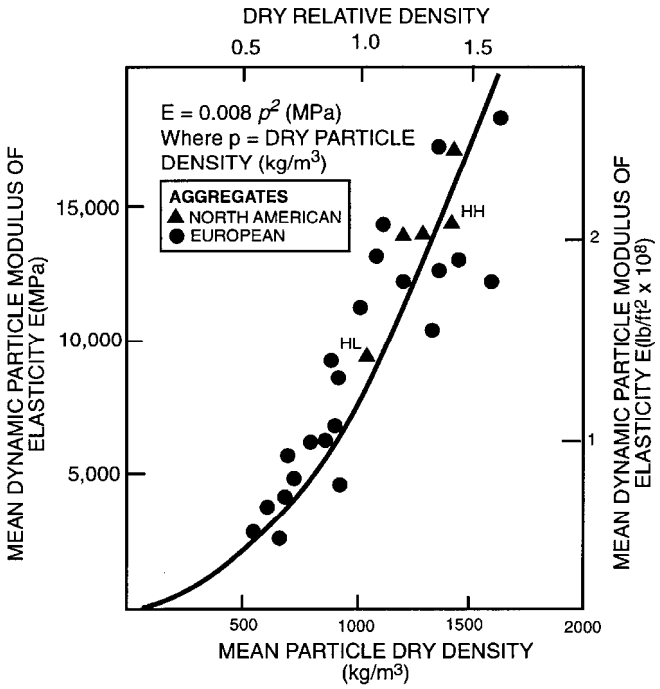


Fig. 2-1 Relationship between mean particle density and the mean dynamic modulus of elasticity for the particles of lightweight aggregates [17]

2.3 Pumice and Scoria Aggregates

2.3.1 Introduction

The use of Pumice and Scoria aggregates is not a new invention in Building Technology. Sumerians used these materials in building Babylon in the 3rd millennium B.C. The Greeks and the Romans used pumice in building construction. Some of these magnificent ancient structures

still exist, like St. Sofia Cathedral or Hagia Sofia, in Istanbul, Turkey, built by two engineers, Isidore of Miletus and Anthemius of Tralles, commissioned by the Emperor 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 [1].

2.3.2 Geological Sources

Pumice and scoria are a member of the family of igneous rocks, rocks that cool from a hot liquid to form crystals, which are widely recognized for their highly desirable concrete making properties. Igneous rocks are formally named according to their chemical composition, specifically on how much silicon (Si) and oxygen (O) they contain. These two elements are usually lumped together and reported as SiO_2 when chemical analyses are listed. This system results in these fine grained igneous rocks being named as follows: [19]

Name	SiO_2
Rhyolite	70% or more
Dacite	Approximately 65%
Andesite	Approximately 60%
Basaltic-Andesite	Approximately 55%
Basalt	50% or less

Pumice and scoria are commonly used as rock names but do not reflect the compositional meaning as noted above. According to the glossary of geology, pumice and scoria are defined as:

Pumice: is a very light, porous igneous rock that is formed during volcanic eruptions. It is an excessively cellular, glassy lava, usually rhyolite or dacite in composition. It is usually white-gray to yellow in color, but may be red, brown or sometimes black according to the mineral oxides or impurities it contains. Pumice is bubble rich and therefore has very low density. Due to this low density, pumice is very light and can even float in water. It has a bulk density of 500-900kg/m^3. The varieties of pumice, which are not too weak structurally, make a satisfactory concrete with a density of 700 to 1400 kg/m^3 and with good insulating characteristics, but high absorption and high shrinkage characteristics [2, 3, 18].

Scoria (red ash): Scoria is a volcanic cinder which generally has a rough surface and high porous nature, with its pores chiefly in the form of vesicles instead of the more tube like, interconnected pores of the pumice. Scoria varies in color often within the same cone and may be black, red, gray or brown in color. The black color is mostly due to its high iron content while the red color is caused by oxidation of iron in the scoria, which might have happened because of rainfall during the eruption. Scoria aggregate is found extensively in Ethiopia especially in the Great Rift Valley, which crosses the North-Eastern part of the country. It is mainly used as a base coarse material in road construction and as an aggregate in the manufacturing of masonry blocks [2, 3, 18, 19].

2.3.3 Chemical Composition of Pumice and Scoria

The contents of such volcanic glassy raw material commonly can be established most easily and accurately by chemical analysis. Pumice and scoria are particularly rich in SiO_2, Al_2O_3. They also contain other oxides such as K_2O, Na_2O, Fe_2O_3, CaO, MgO, SO_3, MnO, P_2O_5, H_2O, FeO, etc. The approximate chemical composition for scoria and pumice aggregates is shown in Table 2.3.

Table 2.3 The approximate chemical composition of Pumice and Scoria [19]

Chemical Composition	Pumice	Scoria
Silica (SiO_2)	Approx. 55.0%	Approx. 47.0%
Alumina (Al_2O_3)	Approx. 22.0%	Approx. 15.0%
Alkalis ($K_2O + Na_2O$)	Approx. 12.0%	Approx. 2.3%
Ferric Oxide (Fe_2O_3)	Approx. 3.0%	Approx. 2.0%
Lime (CaO)	Approx. 2.0%	Approx. 12.5%
Magnesia (MgO)	Approx. 1.0%	Approx. 9.0%
Titania (TiO_2)	Approx. 0.5%	Approx. 2.0%
Ferrous Oxide (FeO)	-	Approx. 10.0%
Manganese Oxide (MnO)	-	Approx. 0.2%
Phosphorous Pentoxide (P_2O_5)	-	Approx. 0.2%

2.4 Lightweight Aggregate Concrete

2.4.1 Introduction and Definitions

Structural lightweight concrete is defined as having an oven-dry density of less than 2000 kg/m^3 [5]. The aggregates used may be a combination of fractions of both lightweight coarse and fine materials and lightweight coarse material with an appropriate, natural fine aggregate. However, the general term lightweight concrete refers to any concrete produced to an oven-dry density of less than 2000 kg/m^3 [4].

Structural lightweight-aggregate concrete is concrete made with structural lightweight aggregate as defined in ASTM C 330. The concrete has a minimum 28-day compressive strength of 17 MPa, an equilibrium density between 1120 and 1920 kg/m^3, and consists entirely of lightweight aggregate or a combination of lightweight and normal-density aggregate [13].

2.4.2 Properties of Structural Lightweight Aggregate Concrete

i) Density

The density of structural lightweight aggregate concretes can range from approximately 1200 to 2000 kg/m^3 compared with 2300 to 2500 kg/m^3 for normal weight concretes.

As the behaviour of lightweight aggregate concrete is closely related to its density, it is essential to define what is meant by the following terms: [4]

Fresh concrete density: The bulk density of concrete when compacted to a practicable minimum air void volume.

Oven-dry density: The bulk density after drying for 24 h in air at 105°C.

Air-dry density: The density in equilibrium with a dry environment (moisture content of approx. 5 - 10% by volume). Approximately equal to fresh density less 100 - 200 kg/m^3 for lightweight coarse and fine aggregates and fresh density less 50 - 100 kg/m^3 for lightweight coarse and dense fine aggregate.

Saturated density: Approximately equal to fresh density plus 100 - 120 kg/m^3. It is suggested that the fresh concrete density is used as a basis for comparison.

The principal factors influencing density are: [4]

Cement content: A 100 kg/m^3 increase in cement gives approximately a 50 kg/m^3 increase in density.

Relative density of aggregates: A substitution of lightweight for dense fines increases the density by approximately 150 - 200 kg/m^3.

Entrained air: The resulting changes to the mix proportions decrease density by approximately 90 kg/m^3.

Moisture content of aggregates: A concrete made with water-saturated or partially saturated aggregates will have a higher fresh density.

Environmental conditions: Density changes in response to wetting or drying.

Table 2.4 Density classes and corresponding design densities of lightweight aggregate concrete according to ENV 206 [5]

Density Class		1.0	1.2	1.4	1.6	1.8	2.0
Oven-dry density ρ (kg/m^3)		901-1000	1001-1200	1201-1400	1401-1600	1601-1800	1801-2000
Density (kg/m^3)	Plain Concrete	1050	1250	1450	1650	1850	2050
	Reinforced Concrete	1150	1350	1550	1750	1950	2150

ii) Compressive Strength

The various types of lightweight aggregates available will not always produce similar compressive strengths for concrete of a given cement content and slump.

Compressive strength of structural concrete is specified according to design requirements of a structure. Normally, strengths specified will range from 21 to 35 MPa and less frequently up to 48 MPa or higher. Although some lightweight aggregates are capable of producing very high strengths consistently, it should not be expected that concrete made with every lightweight aggregate classified as "structural" can consistently attain the higher strength values. All aggregates have strength ceilings, and with lightweight aggregates, the strength ceiling generally can be increased by reducing the maximum size of the coarse aggregate [12].

Table 2.5 Strength classes and characteristic compressive strengths f_{lck} of lightweight aggregate concrete (in N/mm^2) according to Euro code 2 [5].

Strength	LC 12/15	LC 16/20	LC 20/25	LC 25/30	LC 30/37	LC 35/45	LC 40/50	LC 45/55	LC 50/60
f_{lck}	12	16	20	25	30	35	40	45	50

Concrete of strength classes LC 12/15 or less, and concrete of classes higher than LC 50/60 should not be used unless their use is appropriately justified.

iii) Tensile Strength

Tensile strength is important when considering cracking in concrete elements. The factors influencing compressive strength also influence tensile strength. The principal differences between lightweight aggregate concrete and normal weight concrete are due to:

Fracture path: This travels through, rather than around, lightweight aggregate particles. The behaviour is similar to normal weight concrete made with crushed aggregates in that the flexural/compressive strength ratio is higher (Fig. 2-2).

Total water content: This is higher for lightweight aggregate concrete due to the absorption of the lightweight aggregate.

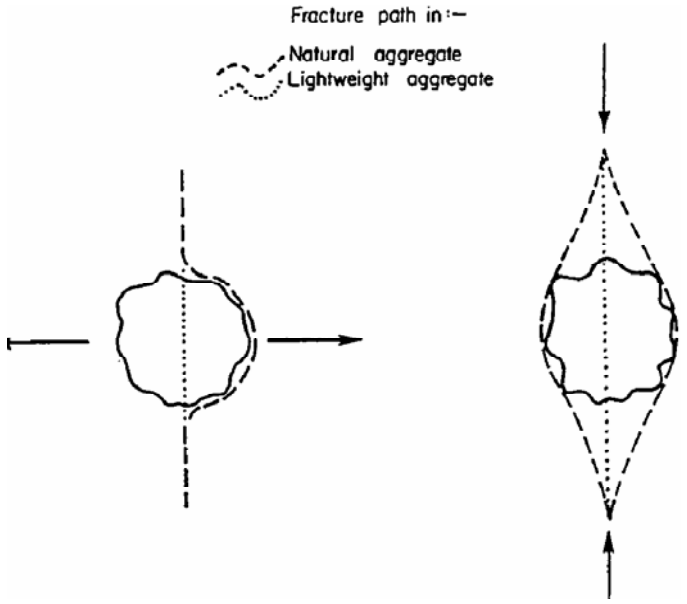


Fig. 2-2 Fracture paths in lightweight and normal weight concretes

---- Natural aggregate; …lightweight aggregate.

a) Splitting Tensile Strength

The splitting tensile strength of concrete cylinders is an effective method of measuring tensile strength.

For lightweight concrete with a compressive strength up to 35 MPa, splitting tensile strength is used for estimating the diagonal tension resistance of lightweight concrete in structures [12].

A more recent method of measuring the tensile strength of concrete is by the cylinder splitting test in which the standard concrete cylinder is subjected to compression along its side. According to ASTM C 469, the splitting tensile strength is given by:

$$T = \frac{2P}{\pi LD} \qquad [2\text{-}1]$$

Where, T = Splitting tensile strength in MPa

P = Maximum applied split load in N

L = length in mm

D = Diameter in mm

Lightweight concrete splitting tensile strengths vary from approximately 75 to 100% of normalweight concrete of equal compressive strength. Replacing lightweight fine aggregate with normalweight fine aggregate will normally increase tensile strength. Further, natural drying will increase tensile-splitting strengths [2].

b) Flexural Tensile Strength (Modulus of Rupture)

The modulus of rupture is also a measure of the tensile strength of concrete. Codes [BS, ASTM] recommend the following formulas for the calculation of flexural strength of concrete [3, 6, 13].

For two point loading when the fracture occurs within the middle third of the span length of the test beam, the flexural strength is calculated from:

$$f_{cf} = \frac{PL}{bd^2} \qquad [2\text{-}2]$$

Where, f_{cf} = Flexural strength in MPa P = Breaking load in N

L = Span length in mm b = Width of specimen in mm

d = Depth of specimen in mm

For two point loading when the fracture is outside the middle third with length of fracture not more than 5% of the span length, the flexural strength is calculated from:

$$f_{cf} = \frac{3Pa}{bd^2} \quad [2\text{-}3]$$

Where a = distance between line of fracture and nearest support measured along the centerline of the bottom surface of the beam (mm).

For one point loading the flexural strength is calculated from:

$$f_{cf} = \frac{3Pa}{2bd^2} \quad [2\text{-}4]$$

iv) Modulus of Elasticity

The modulus of elasticity of concrete depends on the relative amounts of paste and aggregate and the modulus of each constituent. Normalweight concrete has a higher E_c because the moduli of sand, stone, and gravel are greater than the moduli of lightweight aggregates. Generally, the modulus of elasticity for lightweight concrete is considered to vary between 1/2 to 3/4 that of sand and gravel concrete of the same strength.

Variations in lightweight aggregate grading usually have little effect on modulus of elasticity if the relative volumes of cement paste and aggregate remain fairly constant.

According to ACI [2], for values of ρ between 1440 and 2480 kg/m^3 and strength levels of 21 to 35 MPa;

$$E_c = 0.043\rho^{1.5}\sqrt{f_{ck}} \text{ MPa} \quad [2\text{-}5]$$

Although the *E*-value is not directly related to strength and density, a useful empirical relationship which provides an approximate *E*-value for most purposes is: [4]

$$E_c = \rho^2\sqrt{f_{cu}}\times 10^{-6} \text{ kN/mm}^2 \quad [2\text{-}6]$$

where E, ρ and f_{cu} are modulus, nominal density and cube strength respectively.

For calculating elastic deformation using BS 8110: Part 2 [8], the E-values are derived from the values for normal weight concrete ($E_{c,28} = K_o + 0.2\times f_{cu,28}$, where K_o varies from 14 to 26 N/mm^2) multiplying by $(\rho/2400)^2$, where ρ is the density of lightweight concrete and K_o is coefficient given by $M/f_{ck}bd^2$.

v) Slump

Slump should be the lowest value consistent with the ability to satisfactorily place, consolidate, and finish the concrete and should be measured at the point of discharge [12]. According *to DOE method* [28] typical values of reasonable slumps are given in Table 2.6.

Table 2.6 Some typical values of reasonable slumps

Type of Construction	Suitable Slump (mm)	
	Minimum	Maximum
Uncongested precast concrete	0	25
Mass concrete	0	50
Slabs	25	75
Columns	25	100
Congested narrow sections	100	175

vi) Durability of Lightweight Aggregate Concrete

The durability of concrete can be defined as its ability to resist adverse external influences such as climatic conditions (resistance to freezing and thawing, to salt scaling), chemical attack and mechanical damage resulting from abrasion or impact [3,4]. It has been reported that in countries with temperate and tropical climate such as Ethiopia, the problem of freezing and thawing does not practically exist; however it is quite possible that a concrete in service become exposed to chemical attack [2].

(a) Freeze/thaw behaviour. As for normal weight concrete the performance of lightweight aggregate concrete under freeze/thaw conditions depends mainly on the mix proportions, the type of aggregate and its moisture content and the level of air entrainment. Laboratory tests have shown that for the majority of aggregate types both in the pre-soaked and air-dry condition non-air-entrained lightweight aggregate concrete is potentially more durable under freeze/thaw conditions than equivalent strength non-air-entrained normal weight concrete [22], particularly when natural fines are used [23]. For air-entrained concrete made with pre-soaked aggregates the performance of lightweight aggregate concrete is not significantly different from that of normal

weight concrete, while air-entrained concrete made with lightweight aggregate in the air-dry condition shows a significant improvement over similar normal weight concrete [22].

(b) Chemical resistance. Lightweight aggregates are stable since they are fired at approximately 1200°C and do not react with alkalis. However, most structural grades of lightweight aggregate concrete are made with dense fines and these should be checked for potential reactivity. In addition, the matrix has a lower free water/cement ratio and higher cement content which should reduce penetration [4, 12].

(c) Abrasion resistance. As with normal weight concrete, the resistance to abrasion of lightweight aggregate concrete increases with compressive strength [12]. However, if the matrix of lightweight aggregate concrete is abraded to expose the aggregate particles, it will deteriorate relatively rapidly. Resistance can be improved by combining relatively soft coarse aggregate with a hard fine aggregate, improving the quality of the matrix and the use of surface treatments.

(d) Water absorption. Most lightweight aggregates exhibit significantly higher water absorptions than normal weight aggregates. This results in lightweight aggregate concretes having higher absorptions than typical normal weight concretes on a mass basis [12], although the difference is not as large as expected since the aggregate particles in lightweight aggregate concrete are surrounded by a high-quality matrix. It has been shown that water absorption of lightweight concrete does not relate directly to durability [24] and this may be due to the inappropriateness, when comparing concretes, of using absorption values based on mass rather than volume [25].

(e) Carbonation. Concrete, when exposed to the atmosphere, interacts with carbon dioxide which is found in nature. The interaction is mainly with the calcium hydroxide that was produced during the hydration of Portland cement. The calcium silicate hydrate also reacts with carbon dioxide. This process is known as carbonation. Calcium hydroxide exists in the pores of concrete. It provides alkalinity to the concrete and protects the reinforcement bars from corrosion. In concrete, the pH is normally 13.5, which is from the alkalis in cement. When carbon dioxide reacts with calcium hydroxide, the alkalinity is reduced from 12.5 to 8.5, which is measured by determining the change in the pH value. Carbonation depth is determined by

measuring the pH value of the liquid phase in equilibrium with the solid mass. The carbonation process is shown schematically in Fig. 2-3 [1].

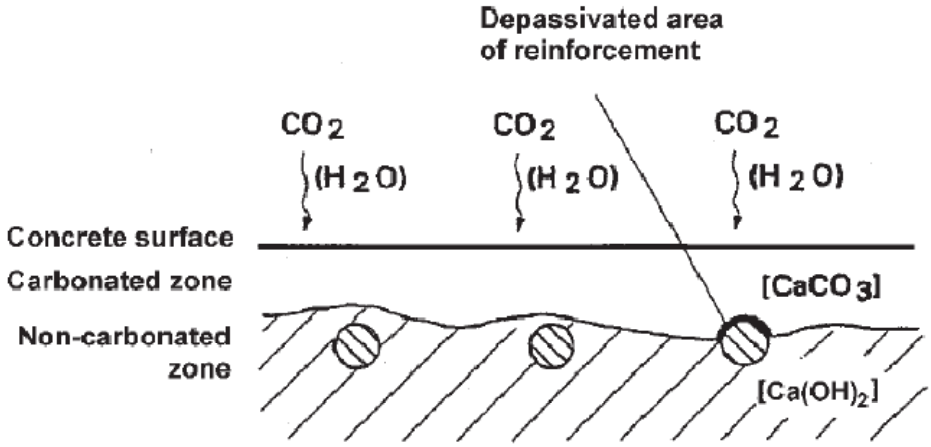


Fig. 2-3 Schematic representation of the carbonation process

The basic chemical reaction involved in the carbonation process is as follows:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O + q$ joules [2-7]

where q = 2430 J/g of reacted CaO.

This reaction takes place in the presence of moisture, [32] that is, the adsorbed CO_2 gas, coming into contact with water, gets dissolved and then penetrates further; while this reaction dominates, others also take place.

Berger, et al., [33] reported the following reaction:

$C_3S + yH_2O + (3\text{-}x)\ CO_2 \rightarrow CS_yH + (3\text{-}x)\ CaCO_3$ [2-8a]

$C_2S + yH_2O + (2\text{-}x)\ CO_2 \rightarrow CS_yH + (2\text{-}x)\ CaCO_3$ [2-8b]

Carbon dioxide lowers the pH value by forming carbonic acid. It interacts and forms highly insoluble calcium carbonate. Water containing aggressive carbon dioxide causes the carbonate in the outer layer to transform into soluble calcium bicarbonate.

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ [2-9a]

$C_3S_2H_3 + 3CO_2 \rightarrow CaCO_3 + S_2 + 3H_2O$ [2-9b]

$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2$ [2-9c]

Most lightweight aggregate particles are more porous and penetrable than normal weight aggregate particles and this, in common with normal weight aggregates of higher porosities [4], will allow more diffusion of gases such as carbon dioxide.

(f) Corrosion of steel. The higher cement content in lightweight aggregate concrete provides a highly alkaline environment to inhibit corrosion. This, together with the increased likelihood of achieving good compaction, reduces the corrosion risk [25]. However, low cement contents (less than approximately 300 kg/m^3) may lead to early corrosion. Although BS 8110 [8] requires greater cover for lightweight aggregate concrete, performance in practice suggests that this may not be required in most cases.

vii) Bond Strength

The bond strength of lightweight aggregate concrete is similar to that of normal weight concrete but, as for normal weight concrete, excessive water contents should be avoided. Anchorage in lightweight aggregate concrete is lower than in normal weight concrete due to the lower bearing strength caused by the relative weakness of lightweight aggregates which requires careful detailing. BS 8110 [8] requires that the bond stresses used to determine lap and anchorage lengths for lightweight aggregate concrete be taken as 80% of those for the same grade of normal weight concrete. However, research shows that this factor is conservative [4].

ACI 318 [2] includes a factor for development length of 1.3 to reflect the lower tensile strength of lightweight-aggregate concrete and allows that factor to be taken as $6.7\sqrt{f_{ck}}/f_{ct} \geq 1.0$ if the average splitting strength f_{ct} of the lightweight aggregate concrete is specified. In general, design provisions require longer development lengths for lightweight aggregate concrete.

viii) Fire resistance

Structural lightweight aggregate concretes are more resistant to fire than normal weight concrete [12, 25] since:

(a) they experience a lower reduction in strength at high temperature due to the inherent stability of lightweight aggregate,

(b) they provide more insulation due to their improved thermal conductivity and,

(c) they have reduced thermal expansions, causing less spalling.

2.4.3 Mix Design

Concrete mix design is the process of choosing suitable ingredients of concrete and determining their relative quantities with the objective of producing the most economical concrete while retaining the specified minimum properties such as strength, durability, and consistency [26].

The increased absorption, decreased density and range of available lightweight aggregates should be considered when designing a concrete mix. Of particular importance is water absorption. All aggregates, whether natural or artificial, absorb water at a rate which diminishes with time. Such absorption is important in that for unsaturated or partially saturated aggregate it will influence such properties of fresh concrete as workability and density and also affect such hardened properties as density, thermal insulation, fire resistance and freeze/thaw resistance [4].

Various methods of proportioning are used to obtain mixes of the desired properties. One commonly used procedure is the *DOE method* [28] recommended by the Department of Environment in the United Kingdom. The design process involves five stages, each which deals with a particular aspect of the design and ends with a required mix parameter. Accordingly, stages I and II deal with target strength and workability leading to the determination of free-water/ cement ratio and free-water content respectively. Stage III combines the results of stages I and II to give the cement content. Stage IV deals with the determination of the total aggregate content; and stage V deals with the selection of the fine and coarse aggregate contents.
The *ACI (American Concrete Institute) method* [27] of proportioning makes use of the slump test together with a set of tables that, for variety of conditions (e.g. types of structures, dimensions of members, degree of exposure to weathering, etc.), permits one to estimate proportions that will result in the desired properties. These preliminary selected proportions are checked and adjusted by means of trial batches to result in concrete of the desired quality. Inevitably strength properties of concrete of a given proportions vary from batch to batch. It is, therefore, necessary to select proportions that will furnish an average strength sufficiently greater than the specified design strength.

The mix design procedure used for the present investigation is called *Trial-Batch method*. According to this method, by selecting a water cement ratio from existing recommendations, one

produces several trial batches with varying amounts of aggregate to obtain the required strength, consistency, and other properties with a minimum amount of paste. The water cement-ratio, aggregate-cement ratio and fines content are based on recommendations provided by Khandaker M. Anwar Hossain [11].

i) Influence of Mix Constituents

In the design of lightweight aggregate concrete mixes the cement content, grading of aggregates and the free water content are some of the important parameters that affect the properties of fresh and hardened concrete.

a) Cement Content

To ensure adequate workability, durability and protection of embedded reinforcement against corrosion, the cement content should in general not be less than 300 kg/m^3 of compacted concrete [3]. For a given workability, strength increases with cement content, the increase depending on the type of aggregate used. Generally greater cement contents are required for lightweight aggregate concrete than for normal weight aggregate concrete. It is believed that on average for lightweight aggregate concrete a 10% increase in cement content will give approximately a 5% increase in strength. Increased cement content also increases creep and shrinkage, heat of hydration during hardening, and the danger of cracking. The cement content therefore should not exceed 500 kg/m^3 [3, 29].

b) Aggregate Grading

For structural lightweight concrete the relationship between particle grading, water requirement and concrete strength is generally valid but there are also other aspects to be considered. For most lightweight aggregates the modulus of deformation, strength and density of the aggregate particles decrease for larger particle sizes. The use of very large lightweight aggregate particles in lightweight concrete causes weakening of the concrete owing to lower aggregate strength and partly as a result of weakening the matrix network around the aggregates. The maximum particle diameter should be limited therefore to 25 mm [29].

c) Free water

The water, which is available to react with the cement, is termed the free water content of the concrete and influences the strength, durability and workability of the concrete critically. It is the sum of

- the mix water
- the surface water of the aggregates
- the water content of admixtures

less

- the water absorbed by the aggregate in the time between the mixing and the setting of the concrete.

The free water content is generally determined by a compromise between workability requirements and strength and durability needs [28].

ii) Mix Parameters Specification

It was previously the general custom to specify concrete by a system of proportions or ratios, e.g. 1:2:4 (being the proportions of cement: fine aggregate: coarse aggregate) either by mass or by volume, or as cement/aggregate ratio, water/cement ratio and fine aggregate/coarse aggregate ratio, usually by mass. Such systems have certain merits in terms of simplicity of expression. However, they are not so convenient when discussing the effect of mix parameters on the characteristics of the concrete, nor do they adequately describe the quantity of cement required to cast a given volume of concrete [30].

The most fundamental way to specify mix parameters is in terms of the absolute volumes of the different materials required in a concrete mix. A more practical method, based on similar principles, which has been adopted in this investigation, is to refer to the mass of materials in a unit volume of fully compacted concrete.

In order to use this approach, knowledge is required of the expected density of the fresh concrete. This depends primarily on the relative density of the aggregate and the water content of the mix.

The method of mix design given in this investigation results in the mix being specified in terms of the mass in kilograms of the different materials required to produce one cubic meter of finished concrete.

3. PROPERTIES OF MATERIALS

3.1 Introduction

The materials used in the investigation are described with respect to their sources and physical properties.

3.2 Cement

Portland cement can be varied in type by changing the relative proportions of its prominent chemical compounds, by the degree of fineness of the clinker grinding and/or by adding some pozzolanic materials. As a result, there are several types of cements for different purposes. Some of them are: Ordinary Portland cement (OPC), Rapid Hardening Portland Cement, Sulphate Resisting Portland Cement, Low heat Portland cement, Portland Pozzolana Cement. But, only Ordinary Portland Cement and Portland pozzolana cement are produced in Ethiopia.

In this investigation, all trial and final mixes were conducted using Portland Pozzolana Cement (PPC) from Muger Cement Factory.

According to Ethiopian Standard ES C.D5.210 [31], Portland pozzolana Cement is defined as cement resulting from a homogenous mixture of finely ground Portland clinker and less than 25 percent by mass of pozzolana.

Pozzolanic property is assessed by comparing the quantity of $Ca(OH)_2$ present in a liquid phase in contact with the hydrated cement with the quantity of $Ca(OH)_2$ capable of saturating a medium of the same alkalinity. Pozzolanic cement means cement resulting from a homogeneous mixture of finely ground Portland clinker from 25 to 40 percent by mass of pozzolana.

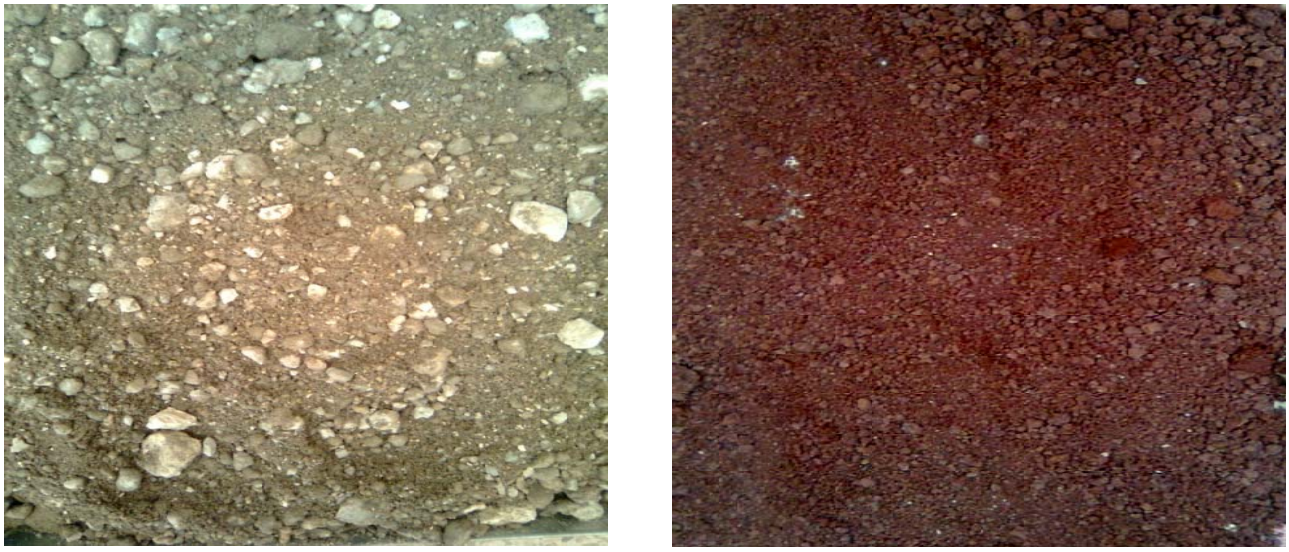
In the same standard the pozzolana is defined as a natural volcanic material having pozzolanic properties such as diatomaceous earth, calcined clay and pulverized fuel ash. Pozzolanic properties mean the ability of a material to combine with lime at ambient temperature and in the presence of water in order to produce compounds that set and hardened with the formation of hydrated phases.

3.3 Water

The water used in the preparation of all mixes was ordinary tap water.

3.4 Aggregates

Pumice aggregates obtained from Dire near Debrezeit and Scoria aggregates collected from Tulu Dimtu near Akaki sources consisted of lumps of various sizes ranging from 1 mm to 40 mm but bigger blocks were also available. Both coarse and fine pumice and scoria aggregates of various grading could be produced from these sources by sieving. In this study, scoria was used as both coarse and fine aggregates in the manufacture of scoria concrete (ScC). Pumice was used as only fine aggregate in the manufacture of scoria pumice concrete (ScPC). Fig. 3-1 shows non-graded pumice and scoria aggregates.



a) Pumice Aggregates b) Scoria Aggregates

Fig. 3-1 Pumice and Scoria Aggregates

The maximum size of coarse aggregates was 19.5 mm and that of fine aggregates was 4.75 mm.

3.5 Hollow Concrete Blocks

The hollow concrete blocks used in the investigation were collected from Girma Amberbir Block Production Enterprise located between CMC and Kottebe. Fig. 3-2 shows the size and shape of hollow concrete blocks.

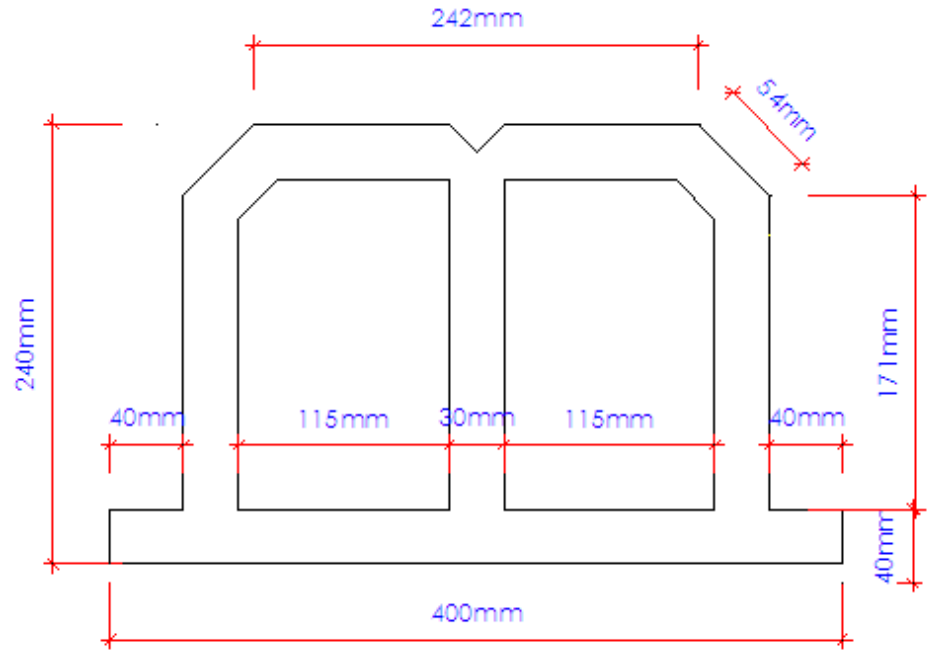


Fig. 3-2 The shape and Size of Hollow Concrete Blocks

According to Ethiopian Standard [31], the 28 days compressive strength of a sample of six pieces taken from every 4000 hollow concrete blocks and individual strength of each of the samples is given in Table 3.1.

Table 3.1 Compressive strength of hollow concrete blocks

Class of hollow concrete blocks	Average compressive strength of six pieces (MPa)	Individual compressive strength (MPa)
A	4.2	3.8
B	4	3.2
C	2	1.8

In the present investigation, the average compressive strength of hollow concrete blocks was 0.42 MPa. This is less than the minimum requirement for class C hollow concrete block, because the area of load application is larger than those hollow concrete blocks used in wall construction.

4. LIGHTWEIGHT CONCRETE USING PUMICE/SCORIA AGGREGATES FOR RIBBED SLAB CONSTRUCTION

4.1 Introduction

Research has been conducted [2, 3], on Ethiopian pumice and scoria aggregates to produce lightweight structural concrete. However, in this study, these materials are reinvestigated by constructing actual size of ribbed-slab. The topping and joists of ribbed slab were constructed using all scoria lightweight structural concrete.

4.2 Grading of Aggregates

The aggregates obtained from the quarry did not meet the code requirements. As a result, the aggregates are blended to satisfy code requirements. 45% of the sample mass with size of 12.5 mm finer and 9.5 mm coarser scoria aggregates was added during coarse Scoria aggregate blending. Similarly, 47% by mass of the sample passing 1.18 mm sieve is added during fine scoria aggregate blending. The particle size distributions of the aggregates are performed according to ASTM C 136 and presented in Table 4.1.

Table 4.1 Grading of Aggregates

Sieve opening (mm)	Coarse Aggregates (% finer)		Fine Aggregates (% finer)		
	Scoria Aggregates	ASTM C-330	Scoria Aggregates	Pumice Aggregates	ASTM C-330
25	100	95-100			
19	94	-			
12.5	58	25-60			
9.5		-			100
4.75	8	0-10	100	100	85 – 100
2.36			53	74	-
1.18			69	79	40 – 80
0.30			35	35	10 – 35
0.15			25	25	5 – 25

4.3 Investigation on Scoria-Pumice Concrete and Scoria-Scoria Concrete

4.3.1 Mix Design

After many trial mixes, suitable ones were selected as shown in Tables 4.2 and 4.3. With each mix type, six 150mm cubes and one 152 mm x 305 mm cylindrical specimens were casted. The cubes were then cured in a water tank at laboratory conditions and tested for strength at 7 and 28 days. The cylinder specimens were kept in oven at 105^{o}C for 72 hours to determine the oven dried unit weight.

Table 4.2 Mix Design for Structural Concrete

No	Mix Type	Date of Mixing	Coarse Agg. (%)	Fine Agg. (%)	Mix proportions in kg/m^3 of Concrete				W/C Ratio	A/C Ratio	Slump (mm)
					Cement (kg/m^3)	Coarse Agg. (kg)	Fine Agg. (kg)	Water (lit)			
1	ScSc	10/06/10	(53%)	(47%)	500	424	376	225.5	0.45	1.60	60
2	ScSc	10/06/10	(53%)	(47%)	500	424	376	250.5	0.50	1.60	130
3	ScSc	11/06/10	(53%)	(47%)	450	477	423	202.9	0.45	2.00	30
4	ScSc	11/06/10	(47%)	(53%)	450	423	477	225.5	0.50	2.00	74
5	ScP	12/06/10	(62%)	(38%)	450	552	339	216.4	0.48	1.98	2
6	ScP	12/06/10	(47%)	(53%)	450	338	382	225.5	0.50	1.60	56
7	ScP	12/06/10	(53%)	(47%)	450	477	423	202.9	0.45	2.00	88
8	ScP	12/06/10	(47%)	(53%)	450	423	477	225.5	0.50	2.00	103
9	PSc	18/06/10	(53%)	(47%)	450	382	338	202.9	0.45	1.60	75
10	PSc	18/06/10	(47%)	(53%)	450	338	382	225.5	0.50	1.60	160
11	PSc	18/06/10	(53%)	(47%)	450	477	423	202.9	0.45	2.00	30
12	PSc	18/06/10	(47%)	(53%)	450	423	477	225.5	0.50	2.00	80
13	ScSc	02/07/10	(65%)	(35%)	365	475	225	164.6	0.45	2.00	25
14	ScSc	02/07/10	(53%)	(47%)	365	387	343	164.6	0.45	2.00	53
15	ScSc	05/07/10	(53%)	(47%)	400	424	376	180.4	0.45	2.00	25
16	ScSc	05/07/10	(53%)	(47%)	400	339	300	180.4	0.40	1.60	35
17	ScSc	06/07/10	(53%)	(47%)	365	310	274	164.6	0.45	1.60	115

4.3.2 Specimen Preparation, Testing and Test Results

Graded coarse and fine aggregates were soaked in water for 24 hours and measurements were taken to determine the free moisture before mixing them with other ingredients. The concrete production was made using a pan mixer of 0.16m^3 capacity. The mixes were mixed dry in the mixer for 2 minutes. The specified quantity of water was then added, and the mixture subsequently mixed for another 4 minutes. Concrete from the mixer was fed directly in to the cube moulds and compacted by vibration for slumps less than 75mm and by tamping for slumps greater than 75mm.

Six specimens were cast for each trial mix and compressive strength tests were conducted at the age of 7 and 28 days. Fig. 4-1 shows the experimental set up for compressive strength test.



Fig. 4-1 Test set up for Compressive Strength of concrete cubes

It was observed in the experiment that both pumice and scoria aggregates crush before the cement mortar reaches ultimate value. As expected the fracture path travels through, rather than around, lightweight aggregate particles.



Fig. 4-2 Fracture Path in concrete specimens



Fig. 4-3 Scoria Aggregates Crushing

The mean value of test results of scoria and pumice concrete specimens are shown in Tables 4.2 and 4.3.

Table 4.3 Strength test results at the age of 7 days and Fresh Unit Weight

No	Mix Type	Date of Testing	Cement Content (kg/m^3)	W/C Ratio	Fine Content	A/C Ratio	Compressive Strength of			Average Compressive Strength (MPa)	Fresh Unit Weight (kg/m^3)
							Sp.1	Sp.2	Sp.3		
1	ScSc	17/06/10	500	0.45	47	1.60	19.69	19.83	19.84	19.79	1984.4
2	ScSc	17/06/10	500	0.50	47	1.60	18.10	16.67	17.31	17.36	2024.9
3	ScSc	18/06/10	450	0.45	47	2.00	16.60	17.36	16.54	16.83	2039.1
4	ScSc	18/06/10	450	0.50	53	2.00	14.96	14.63	15.06	14.88	1967.4
5	ScP	19/06/10	450	0.48	38	1.98	9.84	9.92	12.00	10.59	1775.0
6	ScP	19/06/10	450	0.50	53	1.60	8.54	9.95	9.56	9.35	1682.6
7	ScP	19/06/10	450	0.45	47	2.00	8.84	8.95	9.56	9.12	1722.2
8	ScP	19/06/10	450	0.50	53	2.00	7.65	7.59	7.78	7.67	1618.4
9	PSc	25/06/10	450	0.45	47	1.60	9.88	9.95	9.38	9.74	1756.1
10	PSc	25/06/10	450	0.50	53	1.60	9.03	9.12	9.02	9.06	1669.4
11	PSc	25/06/10	450	0.45	47	2.00	8.91	8.88	8.92	8.90	1711.8
12	PSc	25/06/10	450	0.50	53	2.00	8.79	7.87	8.30	8.32	1678.8
13	ScSc	09/07/10	365	0.45	35	2.00	15.58	15.70	15.38	15.55	1995.7
14	ScSc	09/07/10	365	0.45	47	2.00	14.27	15.33	15.61	15.07	2056.0
15	ScSc	12/07/10	400	0.45	47	2.00	16.92	15.10	17.15	16.39	2059.8
16	ScSc	12/07/10	400	0.40	47	1.60	16.20	16.46	16.06	16.24	2072.1
17	ScSc	13/07/10	365	0.45	47	1.60	14.89	15.67	14.79	15.12	1937.2

Table 4.4 Strength test results at the age of 28 days and Oven-dried Unit Weight

No	Mix Type	Date of Testing	Cement Content (kg/m^3)	W/C Ratio	Fine Content	A/C Ratio	Compressive Strength of			Average Compressive Strength (MPa)	Oven-dried Unit Weight (kg/m^3)
							Sp.1	Sp.2	Sp.3		
1	ScSc	17/06/10	500	0.45	47	1.60	30.97	28.84	31.54	30.45	1646.7
2	ScSc	17/06/10	500	0.50	47	1.60	28.67	28.39	28.19	28.42	1611.3
3	ScSc	18/06/10	450	0.45	47	2.00	27.52	27.44	30.58	28.51	1647.1
4	ScSc	18/06/10	450	0.50	53	2.00	26.39	27.39	26.95	26.91	1636.7
5	ScP	19/06/10	450	0.48	38	1.98	18.54	18.50	17.89	18.31	1325.5
6	ScP	19/06/10	450	0.50	53	1.60	16.06	16.55	16.07	16.23	1210.4
7	ScP	19/06/10	450	0.45	47	2.00	15.35	14.98	15.56	15.30	1318.3
8	ScP	19/06/10	450	0.50	53	2.00	13.33	13.02	13.46	13.27	1186.5
9	PSc	25/06/10	450	0.45	47	1.60	14.91	15.06	14.36	14.78	1261.0
10	PSc	25/06/10	450	0.50	53	1.60	12.70	13.66	13.59	13.32	1308.1
11	PSc	25/06/10	450	0.45	47	2.00	13.46	13.04	13.56	13.35	1276.1
12	PSc	25/06/10	450	0.50	53	2.00	13.07	13.12	12.10	12.76	1220.4
13	ScSc	09/07/10	365	0.45	35	2.00	27.05	27.43	27.01	27.16	1646.7
14	ScSc	09/07/10	365	0.45	47	2.00	26.44	25.96	27.13	26.51	1650.5
15	ScSc	12/07/10	400	0.45	47	2.00	29.78	29.25	28.96	29.33	1656.2
16	ScSc	12/07/10	400	0.40	47	1.60	30.74	31.51	32.15	31.47	1673.1
17	ScSc	13/07/10	365	0.45	47	1.60	28.43	28.17	26.17	27.59	1614.7

5. ANALYSIS AND DESIGN OF RIBBED SLAB SYSTEM

5.1 General

The design principles involved in the ribbed-slab system are illustrated using a single span element with span length of 3.0 m. Fig. 5-1 shows the ribbed-slab system used in the present investigation.

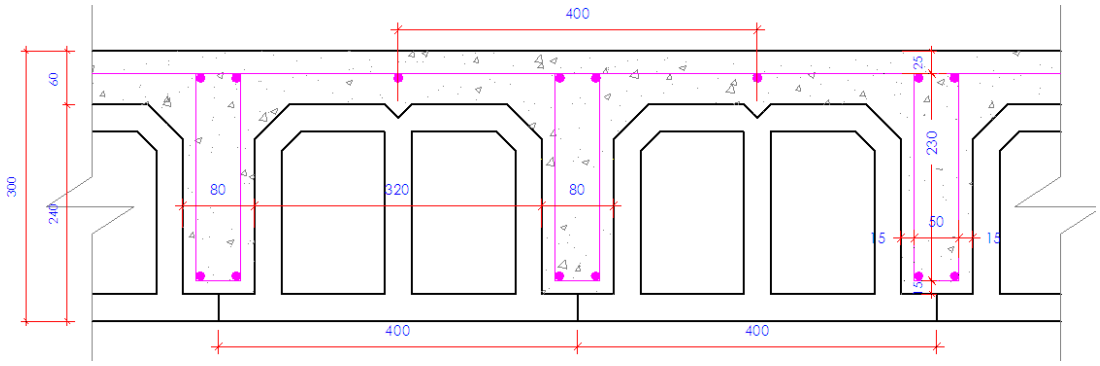


Fig. 5-1 Slab Cross-Section

5.2 Geometry and Loading

According to EBCS 2- 1995[15], ribs shall not be less than 70mm in width; and shall have a depth, excluding any topping, of not more than 4 times the minimum width of the rib. The rib spacing shall not exceed 1.0 m. Thickness of topping shall not be less than 40mm, nor less than 1/10 the clear distance between ribs.

c/c distance between ribs	=	400mm
Width of ribs	=	80mm
Thickness of topping	=	60mm

Permanent Load (G_k):

Topping ..... = (0.40 - 0.08) * 0.06 * 17 = 0.33 kN/m

Ribs ..... = 0.08 * 0.27 * 17 = 0.37 kN/m

Floor Finishing ..... = 0.05 * 23 * 0.40 = 0.46 kN/m

Ceiling plaster (10mm) ..... = 0.01* 23 * 0.40 = 0.09 kN/m

HCB under ribbed slab ..... = 0.40 * 1.8 = 0.72 kN/m

Partition walls..... = 1 * 0.40 = 0.40 kN/m

G_k = 2.37 kN/m

Variable Load (Q_k):

For multipurpose buildings, EBCS-1 1995 prescribes a characteristic uniform live load of $3kN/m^2$.

$Q_k = 3kN/m^2 * 0.40m =$ **1.20 kN/m**

Design Load (P_d):

$P_d = 1.3\ G_k + 1.6\ Q_k =$ **5.00 kN/m**

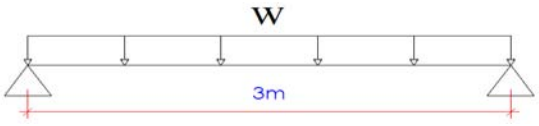


Fig. 5-2 System and Loading

5.3 Analysis and Design

$M_{max} = wl^2/8 = 5*3^2/8 = 5.625$ kN-m

According to EBCS-2 1995, for $f_{yk} = 373$ MPa and $f_{cu} = 28$ MPa;

$f_{cd} = (0.85*f_{ck})/\gamma_c = 0.85*0.8*28/1.5 = 12.69$ MPa

$f_{yd} = f_{yk}/\gamma_s = 373/1.15 = 324.35$ MPa

Using general design chart of ECBS-2 1995, Part 2 [9] and neglecting the contribution of the top reinforcement,

$$\mu_{sd,s} = \frac{M_{sd,s}}{f_{cd} b d^2} = \frac{5.625*10^6}{12.69*400*270^2} = 0.015$$

⇨ $k_x = 0.06$ => $x = k_x * d = 0.062 * 270 = 16.2$ mm ~ neutral axis lies within the flange.

$k_z = 0.98$ => $z = 0.98*270 = 264.6$ mm

$$A_s = \frac{M_{sd,s}}{f_{yd} z} = 65.54\ mm^2$$

Use 2Ø8 = $100.53mm^2$ for both top and bottom reinforcement of the rib.

6. THEORETICAL ANALYSIS AND TEST RESULTS OF RIBBED SLAB

6.1 Introduction

Full-size ribbed slab spanning 3.0 m was constructed to investigate the strength and deformation characteristics under service and ultimate loads. The predicted ultimate loads of the slab are calculated using the idealized parabolic-rectangular stress block for concrete and elastic-perfectly plastic relationship for reinforcement.

The theoretical yield moment capacities of the interior and edge beams are presented. The yield capacities of the cross sections were chosen in lieu of the ultimate capacities for strength comparison purposes because of the physical limitations with regard to deflection measurements after yielding of the reinforcement.

The mean compressive strength of the control cubes at the age of 28 days and the mean yield strength of the reinforcing bars were found to be 28 MPa and 373 MPa respectively.

6.2 Theoretical Strength Determination

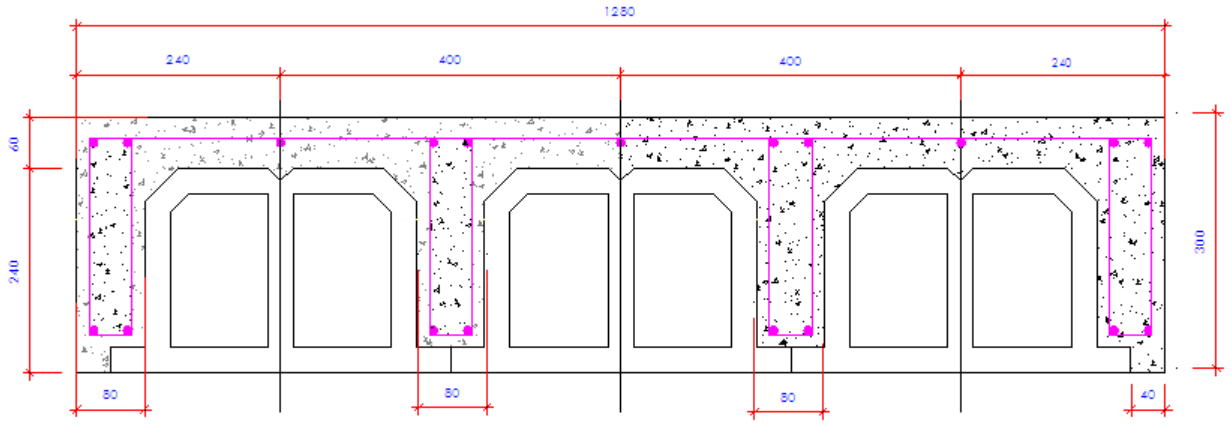


Fig. 6-1 Cross section of the ribbed slab

i) Yield Capacity of Interior Beam

The effective width of the flange is:

$$b_{eff} \leq \begin{cases} b_w + \frac{le}{5} \\ c/c\ beam\ spacing \end{cases}$$ According to EBCS 2- 1995. [6-1]

$$b_{eff} \leq \begin{cases} 80 + \frac{3000}{5} = 680\ mm \\ 400\ mm \end{cases} \quad => b_{eff} = 400\ mm$$

Where,

b_w is the width of the web

l_e is the effective length of the beam

Having determined the effective width, the dimensions of the structural components are shown in Fig. 6-2.

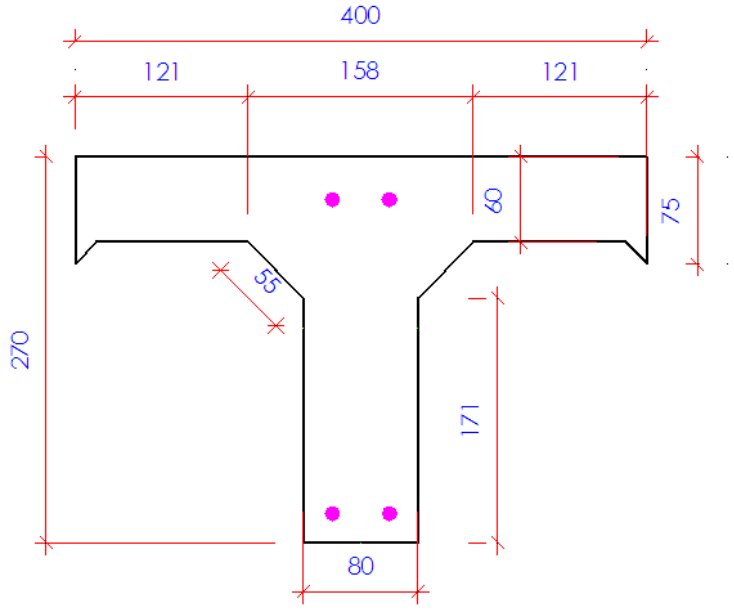


Fig. 6-2 Cross-section of structural component

The assumed strain diagram shown in Fig. 6-3 is based on the assumption that the neutral axis lies within the flange and bottom reinforcement yields before crushing of concrete.

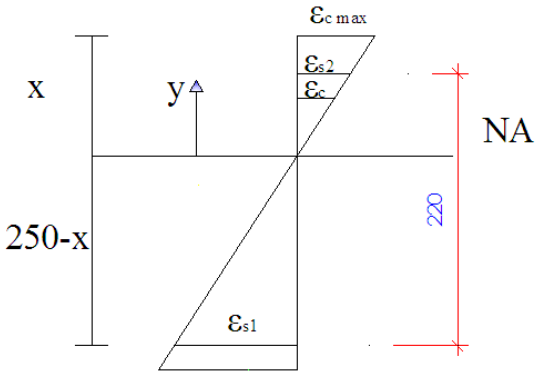


Fig. 6-3 Strain diagram for the interior beam

The designations in Fig. 6-3 represent:

$\varepsilon_{c,max}$ = maximum strain in the concrete

ε_c = strain in the concrete at a distance y from the neutral axis

ε_{s1} = strain in the bottom steel

ε_{s2} = strain in the top steel

x = the neutral axis depth

The yield strain of steel:

$$\varepsilon_{s1} = \frac{f_y}{E} = \frac{373}{200{,}000} = 0.001865 \qquad [6\text{-}2a]$$

From similarity of triangles the expressions ε_c, ε_{s2}, $\varepsilon_{c,max}$ are:

$$\varepsilon_c = \frac{\varepsilon_{s1}}{250-x} * y = \frac{0.001865}{250-x} * y \qquad [6\text{-}2b]$$

$$\varepsilon_{s2} = \frac{\varepsilon_{s1}}{250-x} * (x-30) = \frac{0.001865}{250-x} * (x-30) \qquad [6\text{-}2c]$$

$$\varepsilon_{c,max} = \frac{\varepsilon_{s1}}{250-x} * x = \varepsilon_{c,max} = \frac{0.001865}{250-x} * x \qquad [6\text{-}2d]$$

The location of the neutral axis is determined using:

$$\int_A dF = 0 \qquad [6\text{-}3]$$

A = the total area of the cross-section

Equation 6.3 can be written as:

$F_{\ compressive} = F_{\ tensile}$

Resultant compressive force in the compression zone is calculated using the idealized rectangular/parabolic stress distribution. According to EBCS-2 1995: [9, 10]

$f_c = 1000\,\varepsilon_c\,(1\text{-}250\,\varepsilon_c) f_{ck}$ *for* $\varepsilon_c \le 0.002$

$f_c = f_{ck}$ *for* $0.002 \le \varepsilon_c \le 0.0035$ [6-4]

$F_{concrete} = \int_{A_c} f_c dA$ [6-5]

Assuming that the strain in the extreme fiber is less than 0.002, Eq. 6-5 can be written as:

$F_{concrete} = \int_0^x 1000\varepsilon_c(1 - 250\varepsilon_c)\, f_{ck} * 400 d_y$ [6-5a]

$F_{concrete} = 400 * 0.8 * 28 * 10^3 \int_0^x \varepsilon_c(1 - 250\varepsilon_c) * dy$ [6-5b]

$F_{concrete} = 16710.4 \int_0^x (\frac{y}{250-x} - \frac{0.46625*y^2}{(250-x)^2})dy$ [6-5c]

Integrating Eq. 6-5c,

$F_{concrete} = 8355.2*\frac{x^2}{250-x} - 2597.07*\frac{x^3}{(250-x)^2}$ [6-6]

The forces on the reinforcement bars are determined based on the idealized elastic-plastic stress distribution.

$F_{s1} = A_{s1} f_y$, $F_{s2} = A_{s2} f_{s2}$ [6-7]

Where,

$f_{s2} = E\varepsilon_{s2} = 200000*\frac{0.001865*(x-30)}{250-x} = \frac{373*(x-30)}{250-x}$ [6-8]

$A_{s1} = A_{s2} = 2*\pi*8^2/4 = 100.53\ mm^2$

Therefore, the forces in the reinforcement bars are:

$F_{s1} = 100.53*373 = 37497.7$

$F_{s2} = 100.53* \frac{373*(x-30)}{250-x} = 37497.7* \frac{(x-30)}{250-x}$ [6-9]

Equating the tensile and compressive forces:

$8355.2*\frac{x^2}{250-x} - 2597.07*\frac{x^3}{(250-x)^2} + (37497.7 * \frac{(x-30)}{250-x}) = 37497.7$ [6-10]

Solving for x,

x = 32mm

Checking for assumptions:

x = 32 mm ≤ 60 mm Ok!

$\varepsilon_{c,max} = \frac{0.001865}{250-32} * 32 = 0.000274 \leq 0.002$ Ok!

Yield Moment Capacity:

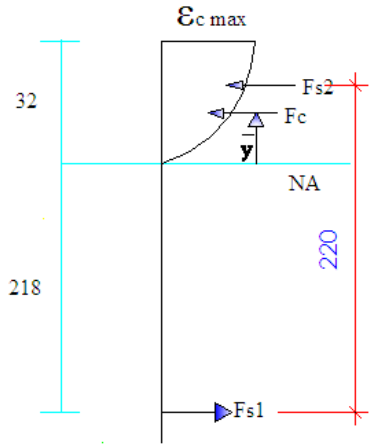


Fig. 6-4 Stress Resultants

Taking the bottom steel as a moment center,

$M_y = F_{concrete} * (218 + \bar{y}) + F_{s2} * 220$ [6-11]

$$\bar{y} = \frac{\int_0^x y f_c dA}{F_c} = \frac{\int_0^{32} y*1000\varepsilon_c(1-250\varepsilon_c)f_{ck}*400dy}{(F_c)}$$ [6-12]

$$F_c = 8355.2*\frac{32^2}{250-32} - 2597.07*\frac{32^3}{(250-32)^2} = 37455.75$$

$$\varepsilon_c = \frac{0.001865}{250-32} * y = 8.555 * 10^{-6}y$$

Substituting in to equation 6-12,

$$\bar{y} = \frac{\int_0^{32}(y*1000*8.555*10^{-6}*y*(1-250*8.555*10^{-6}*y)*28*0.8*400)dy}{37455.75}$$

$\bar{y}$ = 21.21 mm.

$$M_y = 37455.75*(218+21.21) + 37497.7*\frac{(32-30)}{250-32}*220 = 9.04 \text{ kNm}$$

ii) Yield Capacity of Edge Beam

The effective width of flange for an edge beam according to EBCS 2-1995 is:

$$b_{eff} \leq \begin{cases} b_w + \frac{le}{10} \\ b_w + c/c\ beam\ spacing \end{cases} \quad [6\text{-}13]$$

However, the actual effective width of the experiment slab edge beam was 240 mm.

Fig. 6-5 shows the cross section of an edge beam:

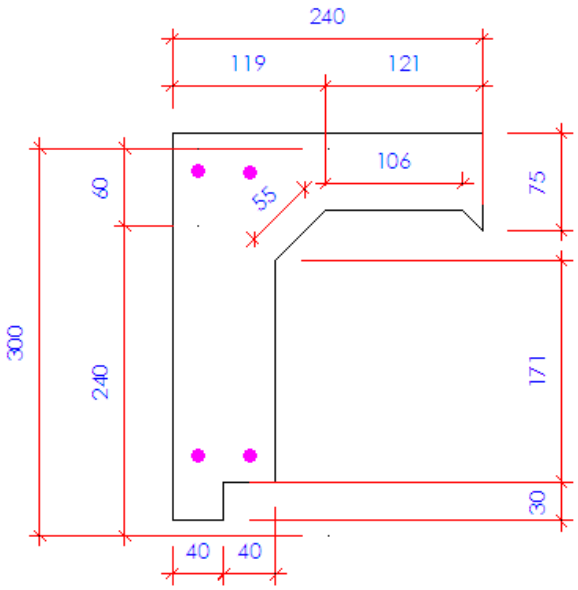


Fig. 6-5 Structural component of the edge beam

The assumed strain diagram shown in Fig. 6-6 is based on the following assumptions:

1. The neutral axis lies in the flange.
2. The bottom reinforcement yields before crushing of the concrete.

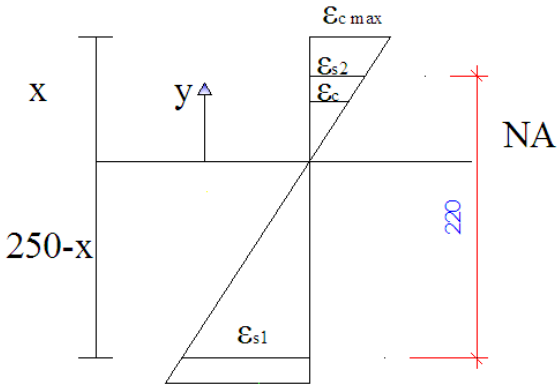


Fig. 6-6 Strain diagram for the edge beam

$\varepsilon_{s1} = 0.001865$

From similarity of triangles the expressions ε_c, ε_{s2}, $\varepsilon_{c,max}$ are:

$$\varepsilon_c = \frac{\varepsilon_{s1}}{250-x} * y = \frac{0.001865}{250-x} * y \quad \text{(a)} \quad [6\text{-}14]$$

$$\varepsilon_{s2} = \frac{\varepsilon_{s1}}{250-x} * (x-30) = \frac{0.001865}{250-x} * (x-30) \quad \text{(b)}$$

$$\varepsilon_{c,max} = \frac{\varepsilon_{s1}}{250-x} * x = \varepsilon_{c,max} = \frac{0.001865}{250-x} * x \quad \text{(c)}$$

The compressive force, assuming that the strain in the concrete is less than 0.002,

$$F_{concrete} = \int_0^x 10^3 \varepsilon_c (1 - 250\varepsilon_c)\, f_{ck} * 240 d_y \quad [6\text{-}15]$$

Integrating and simplifying Eq.6-15

$$F_{concrete} = 5013.12 * \frac{x^2}{250-x} - 1558.2448 * \frac{x^3}{(250-x)^2} \quad [6\text{-}16]$$

The forces on the reinforcement bars are:

$F_{s1} = 37497.7$

$$F_{s2} = 37497.7 * \frac{(x-30)}{250-x} \quad [6\text{-}17]$$

Equating the tensile and compressive forces:

$$5013.12 * \frac{x^2}{250-x} - 1558.2448 * \frac{x^3}{(250-x)^2} + \left(37497.7 * \frac{(x-30)}{250-x}\right) = 37497.7 \quad [6\text{-}18]$$

x = 39.9 mm

Checking for assumptions:

x = 39.9 mm ≤ 60 mm Ok!

$$\varepsilon_{c,max} = \frac{0.001865}{250-39.9} * 39.9 = 0.000354 \leq 0.002$$ Ok!

Yield Moment Capacity:

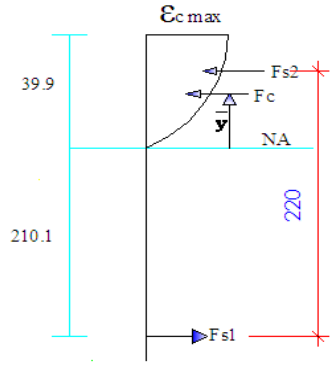


Fig. 6-7 Stress Resultants

Taking the bottom steel as a moment center,

$$M_y = F_{concrete} * (210.1 + \bar{y}) + F_{s2} * 220 \qquad [6\text{-}19]$$

$$\bar{y} = \frac{\int_0^x y f_c dA}{F_c} = \frac{\int_0^{39.9} y*1000\varepsilon_c(1-250\varepsilon_c)f_{ck}*240dy}{(F_c)} \qquad [6\text{-}20]$$

$$F_c = 5013.12*\frac{39.9^2}{250-39.9} - 1558.2448*\frac{39.9^3}{(250-39.9)^2} = 35744.03$$

$$\varepsilon_c = \frac{0.001865}{250-39.9} * y = 8.8767 * 10^{-6}y$$

Substituting in to equation [6-20],

$$\bar{y} = \frac{\int_0^x (y*1000*8.8767*10^{-6}*y*(1-250*8.8767*10^{-6}*y)*28*0.8*240)dy}{35744.03}$$

$\bar{y}$ = 26.39 mm.

$$M_y = 35744.03*(210.1 + 26.39) + 37497.7*\frac{(39.9-30)}{250-39.9}*220 = 8.84 \text{ kNm}$$

6.3 Experiments on actual size of Ribbed Slab

It was intended to cast three ribbed slabs, nevertheless, due to limited finance only one slab spanning 3.0 m was constructed and loaded until the reinforcements started yielding. The specimen and test setup are shown in Fig. 6-8 to Fig. 6-11. The aim of the experiment was to study the strength and deformation characteristics of the slab system and to demonstrate the use

of pumice and scoria aggregates in Ethiopian building technology which is used in many countries.



Fig. 6-8 Formwork for ribbed-slab



Fig. 6-9 Placing of HCB, Reinforcement layout, Supporting System



Fig. 6-10 Ribbed-Slab, experimental setup with gauges

The uniformly distributed load (sacks filled with sand) was applied over the middle portion of the slab to avoid dispersion of load directly to the supporting brick piers. The loading was gradually increased until the reinforcement had started yielding. This stage of load was characterized by rapid increase in deflection at which time the dial gauges were removed and the load increment was almost simultaneously stopped.

The load corresponding to the yielding of the slab is taken from the load versus mid span deflection curve shown in Fig. 6-12. The yielding loads plus self weight for the ribbed slab was 1050kg. Deflection reading corresponding to further increase in loading was recorded as long as the physical limitations of approximately maximum dial readings allowed.



Fig. 6-11 Ribbed-Slab under load

Table 6.1 Mid Span deflection of ribbed-slab

Load (kg)	Dial Reading (0.01mm)	Load (kN)	Deflection (mm)
Initial dial reading = 300			
0	0	0.00	0.00
800	320	7.85	0.20
1600	378	15.70	0.78
1700	400	16.68	1.00
2400	460	23.54	1.60
2800	488	27.47	1.88
3200	530	31.39	2.30

3800	560	37.28	2.60
4000	575	39.24	2.75
4400	610	43.16	3.10
4800	667	47.09	3.67
5200	702	51.01	4.02
5600	723	54.94	4.23
6000	772	58.86	4.72
6400	803	62.78	5.03
6800	846	66.71	5.46
7000	863	68.67	5.63
7200	886	70.63	5.86
7600	918	74.56	6.18
8000	952	78.48	6.52
8400	1030	82.40	7.30
8800	1069	86.33	7.69
9200	1105	90.25	8.05
9600	1160	94.18	8.60
10000	1233	98.1	9.33
10400	1315	102.024	10.15
10800	1418	105.948	11.18
11000	1650	107.91	13.5
11100	1775	108.891	14.75
11200	1790	109.872	14.9
11300	1802	110.853	15.02
11420	1968	112.0302	16.68
11550	2030	113.3055	17.3
11600	2250	113.796	19.5

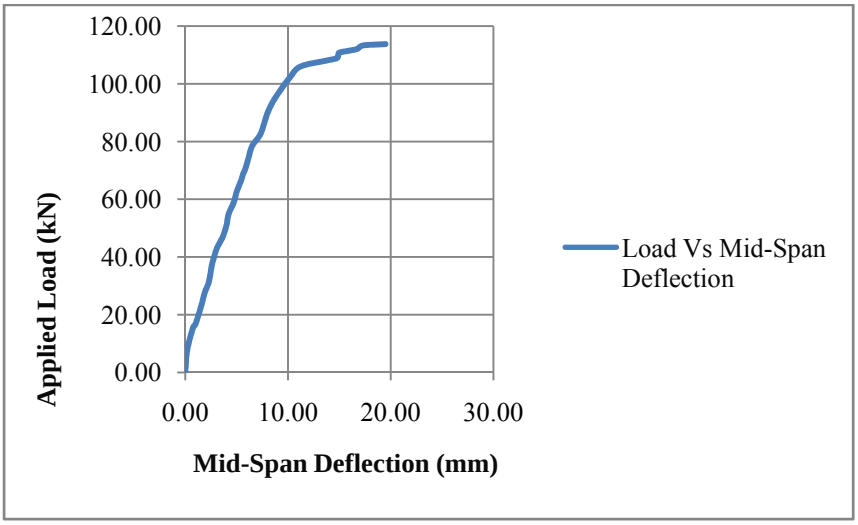


Fig. 6-12 Load versus mid-span deflection of ribbed slab

6.4 Comparison of Test and Analytical Results

In the following sections, the internal yield moments for the interior and edge beams of the test ribbed slab subjected to loading that corresponds to the yielding of the reinforcement will be determined.

6.4.1 Interior Beam

Loading:

Load from applied load = 105 KN*0.4m/(1.28m x 3m) = 10.94 kN/m

Self weight = 0.0426*17 = 0.72 kN/m

System and Loading:

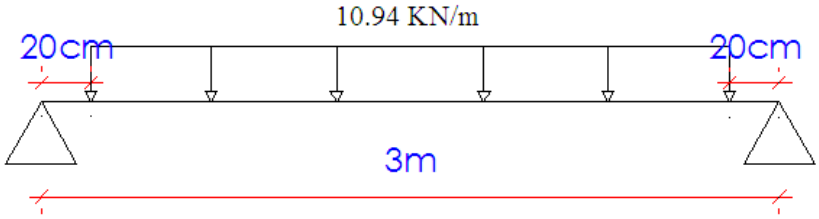


Fig. 6-13 System and loading-interior beam

The maximum moment at mid span,

$M_{max} = \frac{wl^2}{8} = \frac{(0.72+10.94)*3^2}{8}$ = 13.1 kN-m

6.4.2 Exterior Beam

Loading:

Load from applied load = 105 KN*0.24m/(1.28m x 3m) = 6.56 kN/m

Self weight = 0.033*17 = 0.56 kN/m

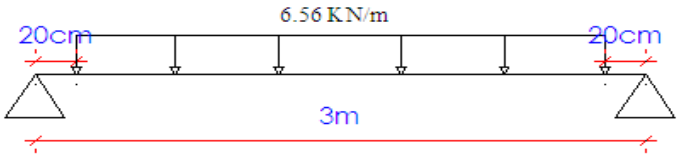


Fig. 6-14 System and loading-exterior beam

The maximum moment at mid span,

$M_{max} = \frac{wl^2}{8} = \frac{(0.56+6.56)*3^2}{8}$ = 8.01 kN-m

6.5 Comparison of the Results and Discussion

Comparisons of moment capacities of the beams at yield from experimental and analytical results are shown on Table 6-2.

The experimental and theoretical yield moment capacities of exterior beams compare quite well. On the other hand, the experimental yield moment capacity of interior beams is greater than that found analytically.

Table 6-2 Theoretical versus experimental yield moment capacities

Theoretical Yield moment (kN-m)		Experimental Result (kN-m)	
Exterior beam	Interior Beam	Exterior beam	Interior Beam
8.84	9.04	8.02	13.10

In the experiment slab, tension cracks were formed first due to flexural stress. Fig. 6-15 shows the cracking pattern in the experiment slab. The width and length of the cracks were well controlled and uniform because of the presence of longitudinal reinforcement.

However, diagonal tension crack near the face of support was observed and this crack extended deep in to the compression zone.



Fig. 6-15 Crack pattern in experiment slab

At the instant the diagonal tension crack develops, the simultaneous bending stress combines with the shear stress to increase the diagonal tension stress further.

The beams of the experiment slab, although reinforced with longitudinal reinforcement, are not provided with any other reinforcement to offset the effects of diagonal cracking. This made the diagonal crack to be much more decisive in the strength and performance of the ribbed-slab beam than the flexural tension cracks.

Therefore, the failure mode of the experiment slab was due to flexural shear crack. However, the thesis work is still under investigation.

7. CONCLUSIONS AND RECOMMENDATIONS

The use of widely available natural volcanic materials; pumice and scoria for the construction of ribbed-slab has been studied.

Based on laboratory test results and experimental investigation of ribbed-slab produced using all-scoria lightweight concrete, the following recommendations and conclusions can be drawn:

1) Structural scoria lightweight concrete can be produced up to strength of 30 MPa by using locally available well-graded scoria coarse and fine aggregates with cement content of 360 kg/m^3 and above.
2) Structural concrete to be used in ribbed slabs and other reinforced concrete structures cannot be produced with both coarse and fine pumice aggregates within the normal cement contents (200 to 450 kg/m^3).
3) Unlike crushed gravel aggregates, the water absorption of pumice and scoria aggregates are significantly affected by weather conditions. Therefore, great care should be exercised during addition of water.
4) Sometimes the pumice aggregates obtained from quarries might be used without grading; nevertheless, grading of both coarse and fine scoria aggregates is necessary before the aggregate is used in the mix design.
5) Mix proportions of scoria coarse aggregates with scoria fine aggregates possessed a desirable quality with regard to strength; therefore, Scoria concrete with 47% fine content, 0.45 water cement ratio and 400 kg/m^3 of cement content was used for casting the experiment slab.
6) Basic mechanics of reinforced concrete can be used for the design and analysis of ribbed slab systems with Ethiopian scoria aggregates.
7) In almost all the trial-mixes the oven-dried unit weight is less than 17kN/m^3. Therefore, this type of construction becomes suitable for the desired purpose of enabling the designer to reduce the size of structural elements, the amount of reinforcement and with it the overall cost of the structure.

Further investigations can be carried on the following titles:

i) The effect of shrinkage and creep on concrete made using Ethiopian Pumice and Scoria aggregates.
ii) Structural lightweight concrete using partial replacement of natural sand and/or crushed gravel.
iii) In the present study, although it was intended to cast three ribbed-slabs for experimental investigation; due to limited budget, only one ribbed-slab was cast and the experimental yield moment capacity was compared with theoretical ones. Therefore further investigations shall be carried on more than two ribbed-slabs. Furthermore, actual size solid slabs, columns can be studied.

8. BIBLOGRAPHY

[1] Satish C. and Lief B., Lightweight Aggregate Concrete, Chalmers University of Technology Göteborg, Sweden, 2002.

[2] Mikyas Abayneh, Concrete making properties of Lightweight Aggregate Concrete made with Ethiopian Pumice and Scoria, Msc. Thesis for Israel Institute of Technology, Haifa, 1970.

[3] Daniel Abebayehu, Studies on Pumice Blocks and Scoria Bricks as the basis of Standardization, Addis Ababa University, Addis Ababa, 1998.

[4] Clarke J.L., Structural Lightweight Aggregate Concrete, Blackie Academic & Professional, London, 2005.

[5] ENV 1992-Euro Code No 2: Design of Concrete Structures Parts 1-4; the use of lightweight aggregate concretes with closed structures; Final Draft; 1992.

[6] BSI Document 92/17688: European Draft Standard Specification for Lightweight Aggregates. CEN/TC154/SC5, Sub-Committee Lightweight Aggregates, 1992.

[7] Hossain, Khandaker MA, Lachemi, The Mixture Design, Strength, Durability, and Fire Resistance of Lightweight Pumice Concrete, Canada, 2007.

[8] BS 8110: Structural Use of Concrete: Part 2: Code of practice for special circumstances, British Standards Institution, London, 1985.

[9] Zerayohannes G., Ethiopian Building Code Standard, EBCS 2 - Part 2, Design Aids for Reinforced Concrete Sections Based on EBCS 2-Part 1, Ministry of Works & Urban Development, 1995.

[10] Zerayohannes G., Zekaria A., Experimental and Theoretical Study of Precast Beam-Slab Construction, Addis Ababa University, 2008.

[11] Khandaker M. Anwar Hossain, Blended cement and lightweight concrete using scoria: mix design, strength, durability and heat insulation characteristics, Ryerson University, Toronto, Canada, 2006.

[12] ACI Committee 213, Guide for Structural Lightweight-Aggregate Concrete, American Concrete Institute, Farmington Hills, 2003.

[13] ASTM, Annual book of American Society for Testing and Materials, 1999.

[14] National Ready Mixed Concrete Association, Concrete in Practice, Silver Spring, 2003.

[15] Ethiopian Building Code Standard, EBCS 2 - Part 1, Structural Use of Concrete, Ministry of Works & Urban Development, 1995.

[16] Hanson, J. A., "Tensile Strength and Diagonal Tension Resistance of Structural Lightweight Concrete, ACI JOURNAL, Proceedings, 58 (No. 1; 1961), pp. 1-40.

[17] Bremner, T. W., and Holm T. A., "Elastic Compatibility and the Behavior of Concrete," ACI JOURNAL, Proceedings, 83 (No. 2, 1986), pp. 244-250.

[18] Abebe Dinku, The Need for Standardization of Aggregates For Concrete Production in Ethiopian Construction Industry, Addis Ababa, 2005.

[19] American Geological Institute, Glossary of Geology and Related Sciences, 1960.

[20] Mineral Prospects of Ethiopia, Ministry of Mines and Energy, Mineral Operations Department, 1998.

[21] ACI Committee 318, Building Code Requirements for Structural Concrete, American Concrete Institute, U.S.A, 2005.

[22] Klieger, P. and Hanson, J.A., Freezing and thawing tests of lightweight aggregate concrete, Journal of ACI, 57 (No. 7; 1961), 779-96.

[23] Lydon, F.D., Some freeze-thaw test results from structural lightweight aggregate concrete, Precast Concrete, 12 (1981).

[24] Hanson, J.A., Replacement of lightweight aggregate fines with natural sand in structural concrete, Journal of ACI, Proc. 61 (No. 7; 1964), 779-94.

[25] I.Struct. E./Conc. Soc., Guide to the Structural Use of Lightweight Aggregate Concrete, London, 1987.

[26] European Journal of Scientific Research, Equations for Mix Design of Structural Lightweight Concrete, 31 (No.1 2009), pp. 132-141.

[27] ACI Standards for concrete mix design: 211.1-77 and 211.3.75.

[28] Lightweight Concrete Mix Design, DOE method, Department of Environment, UK.

[29] CEB/FIP Manual of Design and Technology, Lightweight Aggregate Concrete, Long-man, 1977.

[30] Marsh B. K., Design of Normal Concrete Mixes, Transport Research Laboratory and the British Cement Association, 1992.

[31] Ethiopian Standards, Cement and Cement Products, 1990.

[32] Lea, F. M., The Chemistry of Cement and Concrete, Edward Arnold, London, 1971.

[33] Berger, R. L., Young, J. F., and Leung, K., Acceleration of Hydration of Calcium Silicates by Carbon Dioxide Treatment, Nat. Phys. Sci., 20(97):16, 1972.