ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

COMPARATIVE STUDY ON BOND BEHAVIOR OF STRUCTURAL CONCRETE MADE OF SCORIA AGGREGATES

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ABSTRACT

Scoria aggregate is one of the most widely found natural lightweight materials in Ethiopia. This research compares the bond behavior of reinforced concrete, produced by scoria aggregates with normal-weight aggregate concrete. In this study, pull-out tests were performed on cubic (150x150x150mm) and cylindrical (150x300mm) specimens, with embedded reinforcing bars (diameter 14mm, 16mm, and 20mm). Three concrete mix types were studied having; scoria coarse and fine aggregate (**Sc-Sc**), scoria coarse aggregate and natural sand (**Sc-Sa**), and natural sand fine aggregate and crushed stone/gravel coarse aggregate (**N**). The results of the experiment showed that scoria aggregate concrete has reasonably less bond strength as compared to normal-weight concrete. Moreover, the design bond strengths of the three concrete mixes used in the experiment were calculated using the provisions given by the two codes, Euro code-2 and ACI-318. Then comparison was done between the results of the two codes and that of the experiment. Consequently, the reduction in bond strength of scoria aggregate concrete obtained from the experiment was found to be lower than the results of the two codes. This signifies that equations given by both the ACI and Euro code are in safe range to be used for calculating the design bond strength and anchorage length of scoria aggregate concrete.

Key words: bond, bond strength, compressive strength, slip, pull-out, scoria, tensile strength

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background

Concrete is a composite material that is typically produced by mixing Portland cement, aggregates, water and sometimes admixtures with a predetermined proportion. One of the major shortcomings of using concrete as a construction material is its heavy self weight or low weight to strength ratio. This effect is especially observed in high rise buildings and long spanned slabs. In order to tackle this problem, making the material lighter is the most feasible solution. As concrete is a composite material, altering the constituent materials will have direct effect on the produced concrete. As aggregates possess 65-75% of the total volume of concrete, lightweight concrete can thus be obtained by using light weight aggregates [1].

Structural lightweight concrete can be defined as a concrete having an oven-dry density of less than 2000kg/m^3. Most of the time the aggregates used may be a combination of fractions of either lightweight coarse and fine materials or lightweight coarse material with normal-weight natural fine aggregates [6]. Obviously, the primary benefit of structural lightweight concrete is reduced self weight, which allows structural designers to use reduced size of columns, footings and other load bearing elements [2, 3].

A number of researches have been conducted worldwide on different natural and artificial lightweight aggregates that can be used to manufacture mortar and concrete. Natural lightweight aggregates include pumice, scoria, sawdust, diatomite, oil palm shells, bottom ash, and starch-based aggregates. While, artificial aggregates include expanded shale, slate, perlite, sintered fly ash, bonded fly ash, solidified blast furnace slag, and vermiculite. These aggregates can be used to make structural or non structural lightweight concrete. Whenever possible, using natural lightweight aggregates will be easier and cost effective than using artificially processed aggregates [2, 3].

Studies revealed that scoria deposits can be used for producing structural lightweight concrete 25% lighter than normal-weight concrete. Such reduction in weight does have significant impact as self weight is the major load on concrete structures especially having multiple stories and larger spans [4, 6, 8]. Fortunately following Italy, Chile and Ecuador; Ethiopia is the 4th country of having abundant deposit of pumice and scoria aggregates in the world [2, 3]. Therefore, using these abundantly available natural lightweight materials in concrete making is very good. A number of studies have been done on the use of these materials as replacement of normal-weight aggregates for the production of concrete [2, 3, 4, 5]. But the use of these materials is still limited to non structural concrete like hollow concrete block.

One of the reasons, why the use of scoria aggregate concrete is not widely practiced, might be due to inadequate information on essential structural properties. Bond behavior of deformed steel bars embedded in structural lightweight concrete is among the major characteristics of reinforced concrete. In ordinary structural concrete design, it is assumed that, there is a perfect bond between the reinforcing steel and concrete. It is this bond between embedded steel bar and surrounding concrete, which makes reinforced concrete to behave as composite material. As compared to conventional concrete, there are only few researches done on bond behavior of lightweight aggregate concrete in general and scoria aggregate concrete in particular [8].

Therefore, in this thesis the bond behavior of structural concrete made with scoria aggregates is studied, by using pull-out test. In addition to the experimental study, provisions on bond property by building codes, ACI 318 and European Code-1992 (which is equivalent to the current Ethiopian code), are compared.

1.2 Significance

In our country Ethiopia, there is high deposit of natural lightweight aggregates such as scoria and pumice, which can be used as an aggregate in the production of lightweight concrete. To the best of the author's knowledge, there are only few published documents about bond behavior of scoria aggregate concrete. Thus, this thesis is intended to study about bond behavior of reinforcement bars within scoria aggregate concrete. And the finding of the research is expected to have significant use in bringing forth important information on the bond behavior of scoria aggregate concrete. In addition, the research is believed to strengthen previous related works and help in increasing the acceptance of scoria aggregate to be used in structural concrete production.

1.3 Objectives

The objectives of this research are;

- To investigate and compare the bond behavior of structural lightweight reinforced concrete made of scoria aggregates with normal-weight concrete
- To compare bond strength of scoria aggregate concrete with the provisions given by building codes (ACI-318 and Euro code-1992).
- To inspect the engineering properties (related to bond strength) of Scoria aggregate concrete

1.4 Scope and Limitations

Scoria was used as light weight aggregate for this research. And Pullout test was conducted on concrete cubes and cylinders. The reinforcements are not expected to yield as the embedment length are small. They are prepared to fail by slip or splitting at peak load.

Due to difficulty in testing and laboratory equipment limitation only pullout test was conducted. The results from the experiment are to be used for comparison purpose, so they shall not be directly taken as a basis for analytical computation of bond strength.

1.5 Methodology

The overall methodology can be described as follows:

- Literature review and assessment of building codes (ACI-318 and Euro code-1992)
- Prepare mix design for all three concrete mix types (Sc-Sc, Sc-Sa and N)
- Perform laboratory tests for basic mechanical properties of concrete and tensile capacity of steel.
- Perform Pullout test on steel bars embedded in concrete cube and cylinder.
- Analyze, discuss and compare results of the experiment and code provisions.

2. LITERATURE REVIEW

2.1 Introduction

In this chapter, basic background information regarding lightweight aggregate concrete and scoria aggregate in particular will be discussed. And the use of scoria aggregates in structural concrete will also be reviewed. Since this research is dealing with the bond behavior of structural concrete made of scoria aggregates, some literatures which have direct relation with the research will be reviewed. And National codes ACI 318/408 and European Codes (EN 1992:2004) will be assessed on their provisions on bond strength.

2.2 Lightweight Aggregate

Any aggregate with a particle density of less than 2000kg/m^3 and a dry loose bulk density less than 1200 kg/m^3 can be defined as lightweight [11]. However, this necessary dual qualification in definition is practically different from most other aggregates used in structural concrete, which have densities greater than 2000kg/m^3. In addition, these lightweight aggregate particles should not increase the density of the compacted concrete either by significant water absorption or cement paste penetration into the body of the aggregate particle when the aggregate is mixed into concrete [6].

2.2.1 Types of Lightweight Aggregates

Lightweight aggregate can be categorized in to two groups:

a. **Naturally occurring lightweight aggregates** which are ready to be used only with mechanical treatment, i.e. crushing and sieving. Important examples for this type of aggregate are volcanic aggregates, such as pumice and **scoria** aggregates [13]. Natural aggregates are preferred wherever possible as their production is simple and doesn't require much energy. However, such practice if not appropriately administered, will deplete natural resource and disturb nature eventually [14].

b. **Artificial lightweight aggregates** such as foamed slag, expanded clay, sintered PFA, blast furnace slag, expanded slate, expanded shale, silica fume etc. Mostly these aggregates are produced from waste or byproduct materials, which will help in replacing natural aggregates and get even better aggregate with improved properties [6, 14].

2.2.2 Characteristics of Lightweight Aggregates

The characteristics of chemically stable lightweight aggregate can affect the properties of the concrete made with it, the same way as normal-weight aggregate does to 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 [6]. These properties will have direct or indirect effect on the produced concrete.

Some general properties of these lightweight aggregates are explained hereafter, according to ACI 213 and ASTM standards.

a) Relative density - The relative density of lightweight aggregate particles is lower than that of normal-weight aggregates, due to their cellular structure. The fine particles do have the highest relative density compared to the coarse particles. However, the magnitude of the differences depends upon the production methods. The practical range of coarse lightweight aggregate relative densities, in dry condition, is from almost 1/3rd to 2/3rd of that of normal-weight 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 [15].

b) Bulk Density - The bulk density of lightweight aggregates is also significantly lower than that of normal-weight aggregates, due to their cellular structure. 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 maximum densities for the lightweight aggregates listed in ASTM C330 and C331 is summarized in Table 2.1 [12, 15].

Table 2.1 Bulk-density requirements of ASTM C330 and C331 for dry, loose, lightweight Aggregates [12]

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

***c) Particle Shape and Surface Texture* -** Particle shape and texture of lightweight aggregates from different sources may differ considerably. Shapes of these aggregates may be cubical and regular, 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 greatly influence proportioning of mixtures in such factors as workability, fine-to-coarse aggregate ratio, cement content, and water requirement [6, 15].

***d) 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 a concept of "strength ceiling" that is useful in indicating the maximum compressive and tensile strength attainable in concrete made with a given lightweight aggregate using a reasonable quantity of cement. Beyond the point of strength ceiling of aggregate, an increase in cement content does not produce a substantial increase in concrete strength. The strength ceiling for some lightweight aggregates may be quite high, approaching that of some normal-weight aggregates.

Apparently, the strength ceiling is influenced predominantly by the coarse aggregate. Greater strength ceiling can be achieved by reducing the maximum size of the coarse aggregate for most lightweight aggregates. This effect is more evident for the weaker and more friable aggregates. There was one case done in a laboratory that showed effect of maximum aggregate size on a specific lightweight aggregate. The result showed that strength attained for concrete containing 19 mm maximum size of that specific lightweight aggregate was 35 MPa. But 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/m3 [15].

***e) Moisture Content and Absorption* -** Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normal-weight aggregates. Based on ASTM C 127 standard, absorption test expressed at 24 h, lightweight aggregates generally absorb from 5-25% by mass of dry aggregate, depending on the aggregate pore system [12]. In contrast, most normal-weight aggregates will absorb less than 2% of moisture. The moisture content in a normal-weight 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 normal-weight aggregates, it is largely surface moisture [15].

For an individual aggregate particle the amount of water absorbed and the rate of absorption depend primarily on: the pore volume, the distribution of pores within the particle and the structure of the pores. [6]

f) Grading - Grading requirements for lightweight aggregates deviate from those of normal-weight aggregates as stated in ASTM C 33; by requiring a larger mass of the lightweight aggregates to pass through the finer sieve sizes. This modification in grading 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 normal-weight aggregates [12, 15].

2.3 Scoria and Pumice Aggregates

The use of natural lightweight aggregates, such as scoria and pumice, for building construction has been practiced since ancient times. Sumerians used these materials in building Babylon in the 3rd millennium B.C. The Greeks and the Romans also used pumice in building construction. Some of these magnificent ancient structures still exist, like St. Sofia Cathedral or Hagia Sofia, in Istanbul, Turkey, which was commissioned in the 4th century A.D. [13].

Scoria and pumice are members of the family of igneous rocks, which cool from a hot lava to form crystals. Most igneous rocks are 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. [16]

Pumice and Scoria can be defined as follows:

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/m3. 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, 4, 16].

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 [2, 4, 16].

2.3.1 Chemical Composition of Scoria and Pumice

The contents of such volcanic raw material can be established by chemical analysis. Pumice and scoria are particularly rich in SiO_2, Al_2O_3, and 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 2.2. From their chemical composition, it can be deduced that beside their use as aggregate, scoria and pumice can also be used as pozzolanic materials which could be used for partial replacement of cement.

Table 2.2 The approximate chemical composition of Pumice and Scoria [16]

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

2.3.2 Ethiopian Scoria and Pumice Aggregates

Huge amount of scoria and pumice aggregate is found 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. However, there hasn't been that much use of these aggregates for structural concrete work. There are some studies done on the use of pumice and scoria aggregates for structural concrete work. Mikyas A. (1970) investigated the concrete making properties of lightweight aggregate made with Ethiopian pumice and scoria. From the study satisfactory structural capacity has been obtained in addition to reduction of imposed dead loads on structures. [4, 17]

The use of local lightweight aggregate (scoria) as a replacement to crushed rocks has also been studied by Girma ZY. (1983). The aggregates used in the tests were a combination of gravel and scoria. The structural properties of lightweight aggregates, which were used with varying proportions to normal-weight, have been found to be structurally sound. An increase in the proportion of the lightweight aggregate has, however, shown a gradual decrease in the compressive strength. [17, 18]

Daniel A. (1999) studied on the properties of concrete and masonry blocks using pumice and scoria at different proportions. The findings indicated that structural concrete can be produced using locally available light weight aggregates provided the grading, cement content, and other parameters are considered [5,17].

Melese Y. (2010) also studied on the use of these widely available natural volcanic materials, pumice and scoria, for the construction of ribbed-slab. Based on laboratory test results and experimental investigation of ribbed-slab produced using all scoria lightweight concrete, it was found that a concrete with strength up to 30 MPa can be produced. In the same study, it was found that the use of all pumice aggregates for structural concrete production is not possible within the normal range of cement content. [2]

2.4 Lightweight Aggregate Concrete

Structural lightweight concrete is defined as a concrete having an oven-dry density of less than 2000 kg/m^3. It can be produced by combining fractions of either lightweight coarse and fine materials or lightweight coarse material with an appropriate, natural fine aggregate. According to ASTM C 330, structural lightweight 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. [6, 9, 12]

2.4.1 Properties of Structural Lightweight Aggregate Concrete

Hereafter, some important properties of lightweight aggregate concrete relevant to the study will be discussed.

a) Density **-** The density of structural lightweight aggregate concretes can range from approximately 1200 to 2000 kg/m^3 compared with normal-weight concrete which is 2300 to 2500 kg/m^3 [4]. Table 2.4 summarizes densities of different types of lightweight plain and reinforced concrete. Yasar *et al.* (2003) reported reductions of 20% in the concrete dry density of lightweight concrete produced with volcanic scoria when compared to normal-weight concrete of equal composition [22].

Table 2.3 Density classes and corresponding design densities of lightweight aggregate concrete according to Eurocode-2 [9]

Density Class		1.0	1.2	1.4	1.6	1.8	2.0
Oven-dry density ρ (kg/m3)		801-1000	1001-1200	1201-1400	1401-1600	1601-1801	1801-2000
Density (kg/m3)	Plain Concrete	1050	1250	1450	1650	1850	2050
	Reinforced Concrete	1150	1350	1550	1750	1950	2150

b) Compressive Strength **-** Compressive strength of structural concrete is specified according to design requirements of a structure. Normally, strengths of structural lightweight concrete will range from 21 to 35 MPa and sometimes 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 [15].

Reductions of 30-45% in the compression strength when normal-weight aggregate was replaced by volcanic scoria aggregates with the same cement content were reported by Hossain (2006) and Kiliç *et al.* (2009) [23,25]. Table 2.4 shows summary of characteristic compressive strength and class of lightweight aggregate concrete according to Euro Code 2.

Table 2.4 Strength classes and characteristic compressive strengths f_{lck} of lightweight aggregate concrete (in N/mm^2) according to Euro code 2 [9].

Strength Classes for lightweight concrete									
f_{lck} (MPa)	12	16	20	25	30	35	40	45	50
$f_{lck,cube}$ (MPa)	13	18	22	28	33	38	44	50	55

c) 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 mainly their fracture path and total water content. Due to their weak strength, the fracture path in lightweight concrete travels through the lightweight aggregate particles rather than around them. Total water content of lightweight aggregate concrete is higher due to the absorption capacity of the aggregates [2, 15].

The two main methods of measuring tensile strength of concrete are splitting tensile strength and flexural tensile strength test. 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 can be used for estimating the diagonal tension resistance of lightweight concrete in structures. Lightweight concrete splitting tensile strengths vary from approximately 75 to 100% of normal-weight concrete of equal compressive strength [15].

$$T = \frac{2\mathrm{P}}{\pi \mathrm{LD}} \tag{2.1}$$

Where, T = Splitting tensile strength in MPa

P = Maximum applied split load in N

L = length in mm

D = Diameter in mm

The flexural tensile strength or modulus of rupture is also used to measure the tensile strength of concrete. Standards [BS, ASTM] recommend different formulas for the calculation of flexural strength of concrete for two point loading and one point loading cases [2, 12, 11].

According to Kiliç *et al.* (2009) the introduction of volcanic scoria and pumice aggregate led to a tensile strength reduction of 7-58% when compared to normal concrete with identical cement content [25].

d) Modulus of Elasticity

The modulus of elasticity of concrete depends on the relative amounts of paste and aggregate and the modulus of each constituent. Generally, the modulus of elasticity for lightweight concrete is considered to vary between 1/2 to 3/4th 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, for values of ρ between 1440 and 2480 kg/m^3 and strength levels of 21 to 35 MPa; [9, 10, 15]

$$\mathrm{E_c} = 0.043\ \rho^{1.5}\sqrt{f_{ck}}\ \mathrm{MPa} \qquad (2.2)$$

Where, E, ρ and f_{ck} are modulus, nominal density and characteristic compressive strength respectively.

In concrete produced with scoria and pumice aggregates, reductions of 21-42% in the modulus of elasticity were documented by Hossain *et al.* (2010). The authors justify this high reduction by the low stiffness of the pumice and scoria [23, 24].

2.5 Bond Behavior of Reinforced Concrete

2.5.1 Background

Bond between reinforcing steel bars and concrete is one of the major characteristics of reinforced concrete. In most structural concrete design procedures, sufficient bond between reinforcing steel and concrete is assumed. The existence of this bond is the basic condition for concrete and steel to work together as a composite material. The reinforcement bar will not be able to resist any external load unless there is strong bond. [8]

For optimal design of reinforced concrete, efficient and reliable force transfer between reinforcement and concrete is required. As it can be seen on Fig. 2.1, the transfer of forces from the deformed bar to the surrounding concrete occurs by:

- Chemical adhesion between the bar and the concrete;
- Frictional forces arising from the roughness of the interface, forces transverse to the bar surface, and relative slip between the bar and the surrounding concrete; and
- Mechanical anchorage or bearing of the ribs against the concrete surface. [7]

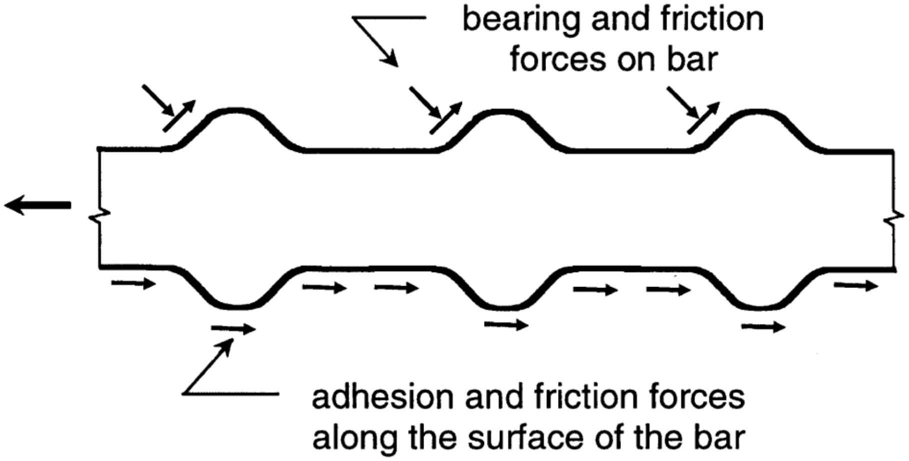

Fig. 2.1 Bond force transfer mechanism [7]

Immediately after a movement of embedded bar with respect to the surrounding concrete occur, surface adhesion is lost. Then the other forces which are the bearing forces and friction forces on the ribs of the deformed bar surface are mobilized. As slip increases, friction on the barrel of the reinforcing bar is reduced, leaving the forces at the contact faces between the ribs and the surrounding concrete as the principal mechanism of force transfer. The forces on the bar surface are balanced by compressive and shear stresses on the concrete contact surfaces, which are resolved into tensile stresses that can result in cracking in planes that are both perpendicular and parallel to the reinforcement. This will result in splitting failure.

But if the concrete cover, bar spacing, or transverse reinforcement is sufficient to prevent or delay a splitting failure, the system will fail by shearing along a surface at the top of the ribs around the bars, resulting in a “pullout” failure. It is common, for both splitting and pullout failures, to observe crushed concrete in a region adjacent to the bearing surfaces of some of the deformations. If anchorage to the concrete is adequate, the stress in the reinforcement may become high enough to yield and even strain harden the bar [7].

2.5.2 Factors Affecting Bond

There are many factors that affect the bond between reinforcing bars and concrete. The three major categories which affect bond are; structural characteristics, bar properties, and concrete properties. According to ACI 408R-03 the three major factors are discussed hereafter.

2.5.2.1 Structural Characteristics

a) Concrete cover and bar spacing - As cover and bar spacing increase, bond strength increases. The mode of failure also depends on cover and bar spacing. For large cover and bar spacing, it is possible to obtain a pullout failure. On the other hand, for smaller cover and bar spacing, a splitting tensile failure occurs due to lower bond strength [7].

b) Development and splice length - Increasing the development or splice length of a reinforcing bar will increase its bond capacity. However, the relationship between the increment in bond strength is not proportional to the increase in development length [7].

c) ***Transverse reinforcement*** - Transverse reinforcement limit the progression of splitting cracks by confining and increasing the bond force required to cause failure [7].

2.5.2.2 Bar Properties

a) Bar size - The relationship between bar size and bond strength is not always appreciated. For a given embedment length, larger bars require larger forces to cause either a splitting or pullout failure. However, longer embedment length is needed for a larger bar to fully develop a given bar stress. Whenever possible, it is better to use a larger number of small bars rather than a smaller number of large bars until the spacing between bars is not reduced to the point that bond strength is decreased [7].

b) Bar geometry - Generally, deformed bars produce higher bond resistance than plain (smooth) bars. Unlike plain bars, the ribs on deformed bars increased the bond resistance by bearing directly on the adjacent concrete. In ASTM standards for reinforcing bars (ASTM A 615; ASTM A 706; ASTM A 767; ASTM A 955; ASTM A 996), a maximum average spacing of deformations equal to 70% of the nominal diameter of the bar and a minimum height of deformations equal to 4% of the nominal diameter for bars with a nominal diameter of 1/2 in. (13 mm) or smaller, 4.5% of the nominal diameter for bars with a nominal diameter of 5/8 in. (16 mm), and 5% for larger bars is recommended [7, 12, 28].

c) *Steel stress and yield strength* - There is a common speculation about bars that yield before bond failure, producing average bond stresses significantly lower than higher strength steel in similar test specimens that did not yield. But this scenario is considerably affected by the presence of confining transverse bars [7, 29, 30].

d) Bar surface condition - The surface of a reinforcing bar plays an important role in bond because of its effect on the friction between reinforcing steel and concrete and the ability of ribs to transfer force between the two materials. Bar surface condition involves the cleanliness of reinforcement, the presence of rust on the bar surface, and the application of epoxy coatings to protect the reinforcement from corrosion [7].

2.5.2.3 Concrete Properties

a) Compressive strength - In most research works and design codes, the effect of concrete properties on bond strength is represented using the square root of the compressive strength $\sqrt{f_c'}$. This representation has proven to be adequate as long as concrete strengths remain below about 55 MPa. However, for higher strength concrete, the average bond strength at failure, normalized with respect to $\sqrt{f_c'}$, decreases with an increase in compressive strength. The reason behind is that as compressive strength increases, the bearing capacity of concrete (related to f_c) increases more rapidly than tensile strength (related to $\sqrt{f_c'}$). For high-strength concrete, the higher bearing capacity prevents crushing of the concrete in front of the bar ribs unlike normal strength concrete, which reduces local slip. Therefore due to the reduced slip, fewer ribs transfer load between the steel and the concrete, which increases the local tensile stresses and initiates a splitting failure in the concrete before achieving a uniform distribution of the bond force [7, 10, 29].

b) Aggregate type and quantity - For bars not confined by transverse reinforcement, Zuo and Darwin (2000) observed that a higher-strength coarse aggregate (basalt) increased T_c (Concrete contribution to total bond) by up to 13% compared with a weaker coarse aggregate (limestone). This observation was explained later by other studies that concrete containing basalt aggregate had only slightly higher flexural strengths, but significantly higher fracture energy than concrete of similar compressive strength containing limestone for compressive strengths between 20 and 96 MPa. For bars confined by transverse reinforcement, increases in both the strength and the quantity of coarse aggregate have been observed to increase the contribution of transverse reinforcement to bond strength [7, 29, 31].

c) Tensile strength and fracture energy - From the observed effects of aggregate strength and quantity and of concrete compressive strength on bond strength, one can deduce that the tensile properties of concrete play a significant role in determining bond strength. The concrete contribution T_c increases approximately with $f'_c{}^{1/4}$. However, from the relationship between compressive strength and tensile strength, it is generally agreed that tensile strength for normal strength concrete increases approximately with $f'_c{}^{1/2}$. If tensile strength alone were the key governing factor in bond strength, $f'_c{}^{1/2}$ should provide a good representation of the relationship between compressive strength and bond strength [7, 31].

d) Concrete slump and workability admixtures - The workability of concrete has also a substantial effect on the bond strength between concrete and reinforcing steel. Concrete with higher slump will have greater tendency to settle and bleed. Apparently, water reducers and high-range water-reducing admixtures extend the time during which settlement and bleeding occur. Even if, high slump concrete and water reducing admixtures enhance workability, it will decrease the bond between the embedded bar and concrete. On the other hand, properly consolidated, low-slump concrete usually provides the best bond with reinforcing steel [7, 10].

2.5.3 Test Methods on Bond

Various test specimen configurations have been used to study bond between reinforcing bars and concrete. Even though there are lots of specimen patterns, the most widely used for research purpose and preparation of codes are shown in Fig. 2.2. These specimen configurations do not only differ in the manner of bond strength measurement, but also in the nature of bond response [7].

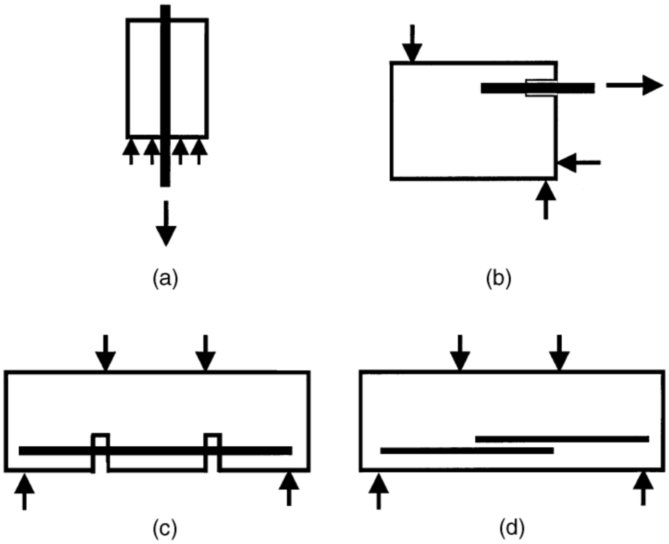

Fig. 2.2 Schematic of: (a) pullout specimen; (b) beam end specimen; (c) beam anchorage specimen; and (d) splice specimen. [7]

The pullout specimen as shown in Fig. 2.2(a) is a widely used method, mainly because of its ease of fabrication and simplicity of the test. The specimen can be done with or without transverse reinforcement depending on the desire to limit splitting when the bar is placed in tension.

On the other hand, the specimen patterns shown in Fig. 2.2 (b) through (d) are more advanced and provide more realistic measures of bond strength in actual structures. The modified cantilever beam, or beam-end specimen, shown in Fig. 2.2 (b), provides a relatively simple test that generally duplicates the stress state obtained in reinforced concrete members. In this test method the reinforcing steel and the surrounding concrete are simultaneously placed in tension.

Beam anchorage and splice specimens shown in Fig. 2.2 (c) and (d), respectively, represent larger-scale specimens designed to directly measure development and splice strengths in full-size members. The anchorage specimen simulates a member with a flexural crack and a known bonded length. Whereas, the splice specimen compared to beam anchorage method is simpler for fabrication and gives realistic results. The splice specimen has provided the bulk of the data used to establish the current design provisions for development length, as well as splice length, in ACI 318. [7, 10, 12]

2.5.4 Bond Behavior of Lightweight Concrete

It is evident that there is huge amount of information available on bond behavior between reinforcing bar and normal-weight aggregate concrete. Generally, lightweight concrete should be expected to have lower tensile strength, fracture energy, and local bearing capacity than normal-weight concrete with the same compressive strength. As a result, the bond strength of bars cast in lightweight concrete, with or without transverse reinforcement, is expected to be lower than that of bars cast in normal-weight concrete. [15, 7]

BS 8110 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. ACI 318 includes a factor for development length of 1.3 to reflect the lower tensile strength of lightweight-aggregate concrete. However, there are several researches done on various lightweight aggregate concrete, showing the modification factors to be conservative [6].

Although design provisions, in general, require longer development lengths for lightweight aggregate concrete, test results from previous researches seems to be contradictory. The first groups of researchers suggest that there is not much difference in bond behavior of lightweight concrete with that of normal-weight concrete. On the contrary, other groups assert that lightweight concrete exhibit significantly lower bond strength than normal-weight concrete. These differences among researchers come partly because of the different characteristics associated with different lightweight aggregates and mixture designs. [7]

Early research done by Lyse (1934) and Petersen (1948) on bond property of lightweight concrete, revealed that the bond strength of reinforcing steel in lightweight aggregate concrete was similar to that of normal-weight concrete. Lyse conducted pullout tests of 19 mm bars embedded in 150 x 300 mm cylinders. The mixture designs used by Lyse included natural sand for fine aggregate and gravel or slag for coarse aggregate. From his research, Lyse concluded that “the compressive, bond, flexural, and diagonal tension strengths of the concrete were very nearly the same for slag and for gravel aggregates.” Moreover, Petersen tested beams made with expanded shale and expanded slag, using diameter 25 mm bars with embedment lengths of 250, 510, and 760 mm. Similarly, he concluded that the bond strength of reinforcement in lightweight-aggregate concrete was comparable to that of reinforcement in normal-weight concrete. In addition, recent studies also showed that the bond strength of lightweight concrete have comparable bond behavior except with slightly higher values with normal-weight concrete. [7, 32, 33]

In contrast to the studies described before, there are several studies that indicate significant differences between bond strengths in lightweight aggregate and normal-weight aggregate concrete. In pullout tests done by Baldwin (1965), bond strength of lightweight concrete was found to be only 65% of those obtained for normal-weight concrete. On another research, Robins and Standish (1982) conducted a series of pullout tests to investigate the effect of lateral stresses on the bond strength of plain and deformed bars in specimens made with lightweight-aggregate (Lytag) concrete. From this study, it was concluded that bond strength increased with confining pressure for both normal-weight and lightweight concrete. For specimens that failed by splitting, bond strength was 10 to 15% higher for normal-weight concrete than for lightweight concrete. But when the lateral pressure was large enough to prevent a splitting failure, the difference in bond strength was much higher up to 45%. [7, 15, 34, 35]

Sancak et al. (2011) reported lower bond strength for deformed bars in structural lightweight concrete made of pumice as compared with that of normal-weight aggregate concrete. In the same study it was also observed that at the ultimate load, the slip of ribbed bars for both normal-weight and lightweight aggregate specimens were not very different. On another study, Hossain et al. (2008) found out that lightweight volcanic pumice concrete has lower bond strength as compared to normal-weight concrete. From this study, normal-weight concrete specimens developed normalized bond strength about 1.12 (ranging from 1.08 to 1.14) times that obtained with volcanic pumice concrete. [26, 27]

Shannag et al. (2017) studied on the bond property of reinforcing steel bars embedded in structural lightweight concrete made with locally available scoria aggregates. The test was done using pull-out tests on cubic specimens of 150x150x150 mm. Test results from the study showed that the load-slip behavior of the investigated structural lightweight concretes have reasonably comparable bond behavior with concretes reported in literatures and codes. In addition, it was reported that their bond strength is dependent on upon the compressive strength, bar size and the embedded length. Comparisons of measured bond strength of the scoria aggregate concrete was done with the ACI bond equations, and it was found for all cases the experimental bond strength values were higher than the design ones. Moreover, this study has revealed that locally available natural lightweight aggregates could be considered as a promising, and cost effective material for designing reinforced concrete members. [8]

2.6 Building Code Provisions on Bond Property (ACI and Euro-Code)

Building codes and standards provide different factors taking into account of lightweight aggregates. For this research ACI and Euro code is reviewed on their consideration on bond behavior of light weight concrete

2.6.1 Overview of Current ACI Design Code (ACI 318M-08) [10]

ACI 318 includes a modification factor λ, to account for the use of lightweight concrete. This modification factor is introduced due to the lower tensile strength of lightweight aggregate concrete. This modification factor λ is used as a multiplier in all applicable equations and sections of this Code, where $\lambda = 0.85$ for sand-lightweight (lightweight coarse and natural sand fine aggregate) concrete and $\lambda = 0.75$ for all-lightweight concrete (both lightweight fine and coarse aggregate). If average splitting tensile strength of lightweight concrete $f_{ct,sp}$ is specified, $\lambda = f_{ct,sp} / (0.56\sqrt{f_c'}) \leq 1.0$ can be used.

The code also allows linear interpolation between 0.75 and 0.85 on the basis of volumetric fractions, when a portion of the lightweight fine aggregate is replaced with normal-weight fine aggregate. And also, linear interpolation between 0.85 and 1.0 shall be permitted, on the basis of volumetric fractions, for concrete containing normal-weight fine aggregate and a blend of lightweight and normal-weight coarse aggregates. For normal-weight concrete no modification factor is used, so $\lambda = 1.0$.

Development length can be calculated by using either of the two provisions given in section 12.2.2 or section 12.2.3 of ACI 318. Section 12.2.2 is more conservative and use preselected values by considering many current practical construction cases. But equation 2.3 can also be used, as given in section 12.2.3, by including practical combinations of side cover, clear cover and confining reinforcement, so as to obtain shorter development lengths than allowed by 12.2.2. These development length (l_d) equations for deformed bars in tension according to ACI 318 are presented as follows;

i) According to ACI 318 Sec 12.2.2

Table 2.5 Development length equation according to ACI 318 Sec 12.2.2

Spacing and Cover	No. 19 and smaller bars	No. 22 and larger bars
Clear spacing of bars or wires being developed or spliced not less than d_b, clear cover not less than d_b , and stirrups or ties throughout l_d not less than the Code minimum or Clear spacing of bars being developed not less than $2d_b$ and clear cover not less than d_b	$l_d = \left(\frac{f_y \psi_t \psi_e}{2.1 \lambda \sqrt{f_c^{'}}}\right) d_b$	$l_d = \left(\frac{f_y \psi_t \psi_e}{1.7 \lambda \sqrt{f_c^{'}}}\right) d_b$
Other cases	$l_d = \left(\frac{f_y \psi_t \psi_e}{1.4 \lambda \sqrt{f_c^{'}}}\right) d_b$	$l_d = \left(\frac{f_y \psi_t \psi_e}{1.1 \lambda \sqrt{f_c^{'}}}\right) d_b$

ii) According to ACI 318 Sec 12.2.3 general development length equation

$$l_d = \left[\frac{f_y}{1.1 \lambda \sqrt{f_c^{'}}} \frac{\psi_t \psi_e \psi_s}{\left(\frac{c_b + k_{tr}}{d_b}\right)}\right] d_b \tag{2.3}$$

In which the confinement term $(c_b + K_{tr})/d_b$ shall not be taken greater than 2.5, and

$$k_{tr} = \frac{40A_{tr}}{sn} \tag{2.4}$$

Where,

l_d = development length in tension of deformed bar, mm

f_y = specified yield strength of reinforcement, MPa

λ = modification factor for the reduced mechanical properties of lightweight concrete

d_b = nominal diameter of bar, mm

f_c' = specified compressive strength of concrete, MPa

ψ_t = factor used to modify development length based on reinforcement location

ψ_e = factor used to modify development length based on reinforcement coating

ψ_s = factor used to modify development length based on reinforcement size

c_b = smaller of: (a) the distance from center of a bar to nearest concrete surface, and (b) one-half the center-to-center spacing of bars being developed, mm

k_{tr} = transverse reinforcement index

A_{tr} = total cross-sectional area of all transverse reinforcement within spacing ***s*** that crosses the potential plane of splitting through the reinforcement being developed, mm^2

s = center-to-center spacing of transverse reinforcement, mm

n = the number of bars or wires being spliced or developed along the plane of splitting.

2.6.2 Overview of Current European Code (EN 1992:2004) [9]

According to the European code (EN 1992:2004), the ultimate bond stress, f_{bd}, can be determined using the following expression:

$$f_{\mathrm{bd}} = 2{,}25\ \eta_1\ \eta_2\ f_{\mathrm{ctd}} \tag{2.5}$$

Where,

f_{ctd} = the design value of concrete tensile strength. Due to the increasing brittleness of higher strength concrete, $f_{\mathrm{ctk},0.05}$ should be limited here to the value for C60, unless it can be verified that the average bond strength increases above this limit.

η_1 = a coefficient related to the quality of the bond condition and the position of the bar during concreting:

η_1 = 1.0 when 'good' conditions are obtained and

η_1 = 0.5 for all other cases and for bars in structural elements built with slip-forms, unless it can be shown that 'good' bond conditions exist

η_2 = related to the bar diameter:

$\eta_2 = 1.0$ for $\phi \leq 32$ mm

$\eta_2 = (132 - \phi)/100$ for $\phi > 32$ mm

The value of the design tensile strength, f_{ctd}, is calculated from:

$$f_{\mathrm{ctd}} = \alpha_{\mathrm{ct}}\ f_{\mathrm{ctk},0.05} / \gamma_{\mathrm{C}} \tag{2.6}$$

Where,

$f_{\mathrm{ctk},0.05}$ = characteristic axial tensile strength of concrete (5% fractile)

γ_C = the partial safety factor for concrete, The recommended value is 1.5.

α_{ct} = a coefficient taking account of long term effects on the tensile strength and of unfavorable effects, resulting from the way the load is applied. The recommended value is 1.0 for normal-weight concrete and 0.85 for lightweight concrete.

The concrete characteristic axial tensile strength $f_{ctk,0.05}$ (5% fractile) is defined as:

$$f_{ctk,0.05} = 0.21 * f_{ck}^{(2/3)} \tag{2.7}$$

Where,

f_{ck} = Characteristic compressive cylinder strength of concrete at 28 days

The European Code restricts the diameter of bars embedded in lightweight aggregate concrete not to exceed 32 mm. Furthermore, the tensile strength of lightweight aggregate concrete may be obtained by multiplying the f_{ctk} values of normal-weight aggregate concrete by a coefficient η_1:

$$f_{lctk,0.05} = f_{ctk,0.05} * \eta_1 \tag{2.8}$$

$$\eta_1 = 0.40 + 0.60\rho/2200 \tag{2.9}$$

Where,

$f_{lctk,0.05}$ = characteristic axial tensile strength of light weight aggregate concrete

ρ = the upper limit of the oven-dry density in accordance with Table 11.1 (Euro Code 2)

2.7 Conclusion of Literature Review and Research Gap

In general, the use of lightweight concrete, such as scoria aggregate concrete, is mainly attributed to its reduction in weight. A number of researches have been conducted on structural properties of lightweight concrete and codes have included special provisions. Bond between reinforcement bar and lightweight concrete is supposed to be less than that of normal-weight concrete. ACI and Euro Codes provide certain reduction factors on bond strength to consider the effect of lightweight concrete.

The bond behavior between reinforcing steel bars and lightweight concrete is still not fully understood, because of the diversified nature of lightweight aggregates, and more research work is required. Besides, bond behavior of lightweight concrete made with locally available scoria aggregate has not been studied enough on Ethiopian scoria, to the researcher's knowledge. Therefore, this research intends to fill the gap and help in advancing the usage of locally available scoria aggregate for structural concrete.

3. EXPERIMENTAL PROGRAM

The experimental program of this thesis consists of the preparation and testing of concrete cubes (150mm x150mm x150mm) and cylinders (150mm x 300mm) with different concrete mixtures and specimen setup. Among the different tests, pullout test is the main one conducted using center-hole jack on concrete cube and cylinder specimen with embedded bars. Other tests such as, compressive strength and splitting tensile strength test were also done. All experiments were done at Addis Ababa Institute of Technology Construction Materials Laboratory. The main variable in the current study was concrete mix type, embedment length and diameter of reinforcing bars. Besides, other parameters are kept constant as much as practically possible. In the following sections, details of the specimens, their material property, test setup and instrumentation will be discussed.

3.1 Specimen Summary

Since the objective of this study is investigating on bond behavior, pullout test was used as a main test procedure. Standard cube (150x150x150mm) and cylinder (150x300mm) molds were used for the casting of concrete specimens. The Cubes were used for the diameter 14 and 16 mm embedded bars. On the other hand, cylindrical specimens were used for the diameter 20mm embedded bars.

The specimens were divided based on the concrete mixtures which are; all scoria (**Sc-Sc**), scoria sand (**Sc-Sa**) and normal (**N**) aggregate concrete. A total of eighteen cube and nine cylinder specimens were used for pullout test, which comprises of three specimens for each mix type and diameter of bar. In addition, the embedment length of rebars was also defined. For the diameter 14 and 16 mm bars which were embedded in concrete cube, the embedment length was made to be 5d (5 times the diameter). Whereas, it was 7.5d (7.5 times the diameter) for the 20mm diameter bars embedded in concrete cylinder. Schematic illustration of the three patterns of pullout specimen is shown in Fig. 3.1. To control the embedment length and interrupt the bond near loaded area of the specimen, plastic conduits were introduced. The space between the conduit and steel was sealed using silicone adhesive so as to prevent any entrance of cement grout in to the conduit. Cylindrical compressive strength (f_{ck}) and tensile strength (f_{ct}) of the concrete are computed from cube compression tests and Split cylinder tests respectively, according to European code specification. Overall information of specimens used in the experiment is summarized in Table 3.1.

Table 3.1 Summary of experimental Specimens

Concrete Mix Designation	Rebar Diameter (Embedment Length) (mm)			Cylindrical Compressive Strength, f_{ck} (MPa)	Tensile Strength of Concrete, f_{ct} (MPa)
	14 (70)	16 (80)	20 (150)		
	Number of pull-out Specimens				
Sc-Sc	3	3	3	27.167	1.968
Sc-Sa	3	3	3	27.5	2.176
N	3	3	3	31.746	3.147

Typical arrangement of pullout specimens is shown in the figure below.

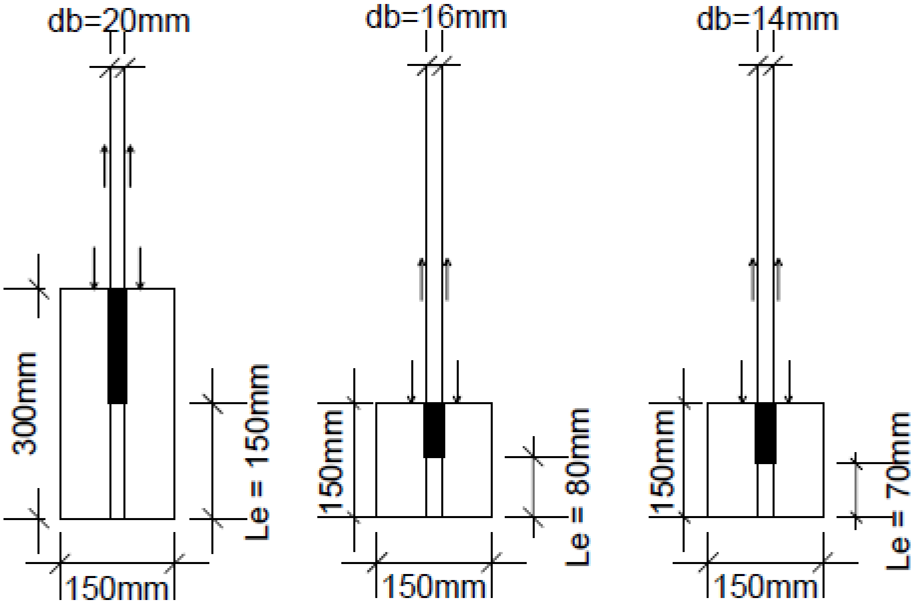

Fig. 3.1 Details of pull-out specimens

3.2 Material Properties

3.2.1 Concrete

For this research, cast in situ concrete proportioned according to ACI mix design [20, 21] was cast in a cube (150x150x150mm) and cylinder (150x300mm) formwork with embedded steel. There were three mix types; all scoria (Sc-Sc), scoria sand (Sc-Sa) and normal (N) aggregate concrete. All the specimens were mixed in the Construction Materials Laboratory of AAiT. In addition to the pullout specimens, cube samples (150 mm) and cylinder samples of diameter 150 mm and height 300mm were prepared for each mix type to determine the compressive and tensile strength of the concrete respectively.

Scoria materials, used as fine and coarse aggregate, were obtained from Tullu Dimtu quarry site, situated south east of Addis Ababa. Since the grain size distribution was very scattered, the scoria materials were sieved and put in accordance with their specific grain size as shown in Figure 3.2. In addition, the sand and gravel were washed to remove any dirt. For all the aggregates; sieve analysis, silt content, moisture content, specific gravity, and water absorption were tested accordingly and included in the mix design calculation. All the data are attached in the annex (Annex A) of this document.

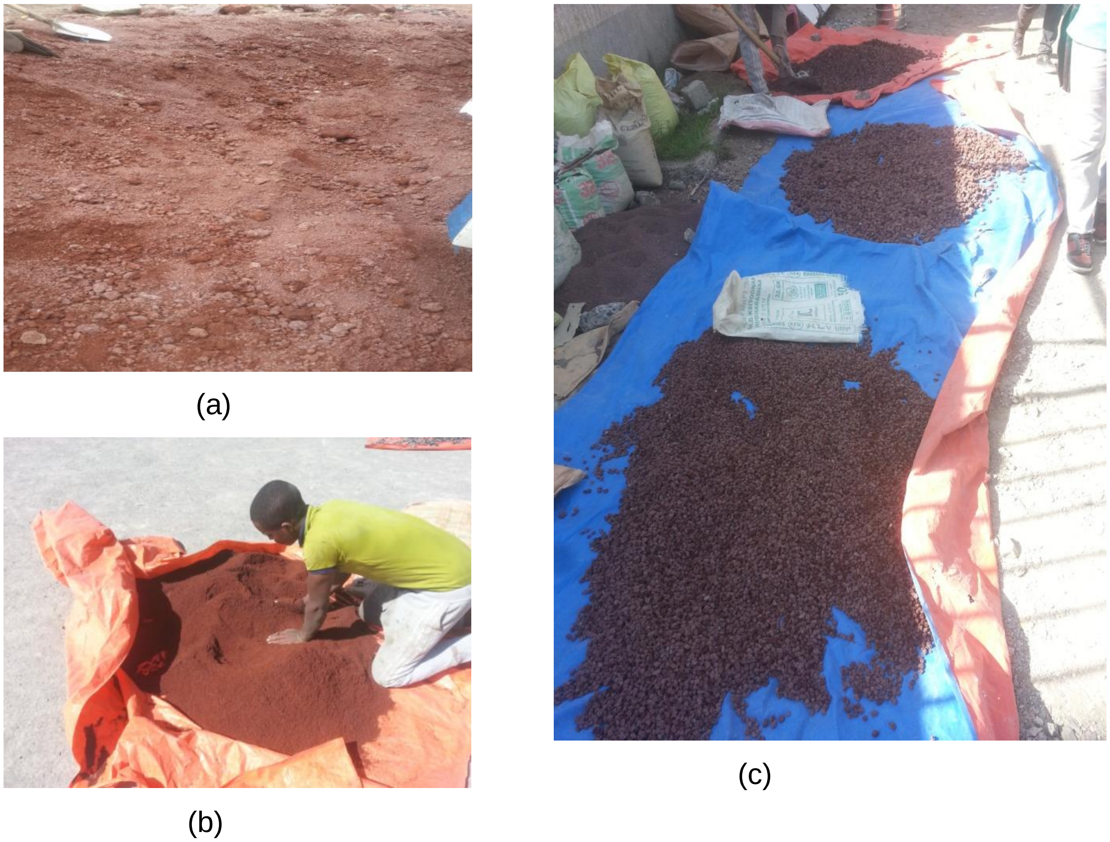

Fig. 3.2 (a) ungraded scoria aggregates from source, (b) fine scoria aggregate and (c) coarse scoria aggregate, used in the experiment

As mentioned before, the concrete was proportioned according to ACI mix design. The concrete was specified to have a slump of 25 to 50 mm with a target cubic compressive strength (f_{cu}) of 30MPa. A number of trial mixes were tested prior to the main experiment work in order to achieve the desired mix design. The mix design was done by using weight method for all mixes. Summary of mix design for the concrete mixes is shown on Table 3-2.

Table 3.2 Mix proportion of Concrete

Material	Mix-Type		
	Scoria-Scoria (Sc-Sc)	Scoria-Sand (Sc-Sa)	Normal (N)
Max. aggregate size (mm)	25	25	37.5
Free-water (kg/m^3)	253.07	248.5	197.76
Cement content (kg/m^3)	475	485	350
Coarse aggregate (kg/m^3)	644.16	619.22	1060.8
Fine aggregate (kg/m^3)	478.72	575.51	850
Water-cement ratio (w/c)	0.45	0.45	0.54

Slump test was performed on every concrete mix, as shown in Fig. 3.3, in order to check the slump is in accordance with the mix design.

Fig 3.3 Slump test

Cubes were tested in compressive testing machines as shown in Fig. 3.4, while the concrete tensile strength was measured by split cylinder tests according to ASTM standard C496-96 [12] as shown in Fig. 3.5. All samples were tested after 28 days on the same date or within a day difference with the pullout tests.

Fig. 3.4 Compressive Strength testing machine

Fig. 3.5 Cylinder splitting tensile strength testing machine

The average concrete strengths on the test day are summarized on Table 3-3 below. The splitting tensile strength of concrete was computed from the applied compressive force, P, by using equation (3.1); where L and D are the length and diameter of the concrete cylinder samples. The whole results of cube and cylinder specimens are reported in the Annex (ANNEX B).

$$f_{ct,sp} = \frac{2\mathrm{P}}{\pi \mathrm{LD}} \tag{3.1}$$

Table 3.3 Average concrete Strengths (Test day)

Mix-Type	Scoria-Scoria (Sc-Sc)	Scoria-Sand (Sc-Sa)	Normal (N)
Cubic Compressive Strength, f_{cu} (MPa)	33.033	33.500	39.793
Cylinderical Compressive Strength, f_{ck} Mpa	27.167	27.5	31.746
Split Tensile Strength, $f_{ct,sp}$ (MPa)	2.187	2.418	3.497
Tensile Strength of Concrete, f_{ct} Mpa	1.968	2.176	3.147

3.2.2 Steel

In all pullout test specimens, normal strength deformed reinforcement bars available in the local market were used. Diameter 14mm and 16mm bars were embedded in a cube specimen, while 20 mm bars were used in a cylinder pullout specimen. Tension tests were performed on all reinforcement bars as shown in the Figure 3.6. Furthermore, the mechanical properties of the tested bars are given in Table 3.4.

Fig. 3.6 Tensile Strength testing machine

Table 3.4 Mechanical properties of reinforcement bars

Specimen	Average diameter (mm)	Average Yield Load (kN)	Average Yield stress (MPa)	Average Failure Load (kN)	Average Failure stress (MPa)	Ultimate Strain (ε ‰)
φ 14	14.00	81.70	530.63	677.15	677.15	156.67
φ 16	16.00	103.40	514.05	663.37	663.37	155.00
φ 20	20.13	178.03	559.40	673.56	673.56	150.00

3.3 Specimen Fabrication

As stated earlier, standard cube (150x150x150mm) and cylinder (150x300mm) molds were used for the casting of concrete specimens. One reinforcement bar was inserted in to each form work accordingly in the center. To control the embedment length and cut the bond near the loaded area of the specimen, plastic conduits were introduced as shown in Fig. 3.7. For the diameter 14 and 16 mm bars which were embedded in concrete cube, the embedment length was made to be 5d (5 times the diameter) whereas for the 20mm diameter bars embedded in concrete cylinder was 7.5d (7.5 times the diameter). The space between the conduit and steel was sealed using silicone adhesive so as to prevent any entrance of cement grout in to the conduit. Any movement of rebar during concrete placement was prevented by firmly anchoring the rebars with steel wires. After finishing placing the reinforcements in the formworks accordingly, they were set for mixing as shown on Fig. 3.8.

Fig 3.7 Conduits to break bond between reinforcement and concrete

Fig. 3.8 Reinforcement placed in form work

Preparation of the concrete mixes was performed using tilting drum mixer of 0.05 m^3 capacity as shown in Fig. 3.9. Slump test was performed to check the workability of the concrete. After mixing, concrete was poured into the pullout specimens and into standard cube and cylinders for determining compressive strength and splitting tensile strength respectively. The concrete was filled in three layers in to the specimen being vibrated using table vibrator. The pullout specimens, cubes and cylinders were then left at room temperature for the next 24 h and then formwork removed. The steel reinforcing bars projecting out of concrete specimens were then coated with an anti-corrosion paint, as shown in Fig. 3.10, to protect them from corroding while curing. Finally, all the pull-out specimens, the concrete cubes and concrete cylinders were placed in tanks filled with water until 28 days.

Fig. 3.9 Concrete Mixer

Fig. 3.10 Application of Anti-corrosion paint

3.4 Test Setup

All pullout specimens were tested using hydraulic center-hole jack, which grips and pulls out the embedded reinforcements out of the concrete. Since the load was applied manually, the loading rate was not entirely kept constant. But the loading rate was kept below 5kN/s for all experiments. The test setup is shown on Fig. 3.11.

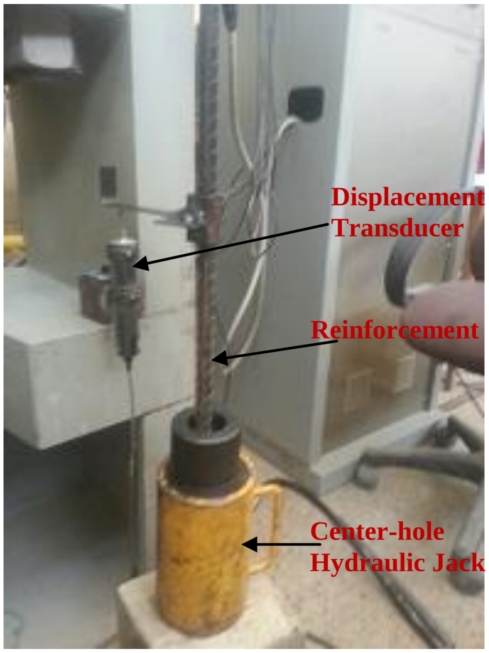

Fig. 3.11 Test Setup

3.5 Instrumentation and Data Acquisition

All pullout specimens were instrumented to measure the applied pulling loads and slip of bars. The center-hole jack had installed data logger to measure the applied load. A Linear variable displacement transducer (LVDT) was used to measure the slip of reinforcement bars throughout the experiment. Few strain gauges were attached to some representative bars just to check the elongation of embedded bars. All of the instruments used were recorded simultaneously and connected to the data logger which was obtained using a USB stick.

Fig. 3.12 Center-hole jack

Fig. 3.13 Data logger

Fig. 3.14 Linear variable displacement transducer (LVDT)

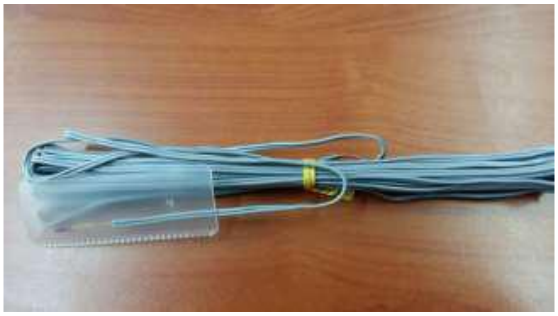

Fig. 3.15 Strain gauge

4. RESULT AND DISCUSSION

4.1 Results from Experiment

4.1.1 Result Summaries

From the pull-out tests, it was observed that all pull-out specimens have failed by splitting after pick load. If a concrete is well confined, the bond strength will be governed by a pull-out failure where the concrete between the steel ribs will be sheared off and the rebar slips in a frictional mode of failure [7]. But in this experiment there was low confinement and confining bars were not used, which made splitting failure to govern. Failures occurred suddenly at pick load with the formation of longitudinal cracks, and this causes anchorage failure resulting in splitting off of the confining concrete. Fig. 4.1 through 4.3 shows the typical failure mode and surface of pull-out specimens after testing.

Fig. 4.1 Typical failure mode and surface of Pull-out specimens (Sc-Sc mix) after testing

Fig. 4.2 Typical failure mode and surface of Pull-out specimens (Sc-Sa mix) after testing

Fig. 4.3 Typical failure mode and surface of Pull-out specimens (N mix) after testing

As it can be observed in the first two figures above (Fig. 4.1 & 4.2), which have scoria aggregate as coarse material, failure goes through the coarse aggregates. Scoria aggregates have crushed due to their weak strength and less fracture energy. On the contrary, the third figure (Fig 4.3) shows that failure goes through cement mortar not gravel aggregates. In other words, the coarse aggregate used for the normal-weight concrete mix is gravel, which is strong enough to resist the force due to the pullout load.

A quantitative summary of results for all test specimens with different concrete mixes and varying bar diameters are reported in Table 4.1. In the table the results of the pull-out tests are presented in terms of peak load and calculated bond stress. The average bond stress was calculated from the maximum applied axial load using Eq. (4.1) as shown below:

$$\tau = \frac{P}{\pi l_e d_b} \tag{4.1}$$

Where, τ = Average bond stress (MPa)
P = maximum applied axial tension force (N)
l_e = embedment length (mm)
d_b = diameter of bar (mm)

According to ACI 318-08 code provisions, one can assume a linear relationship between the bond strength and the square root of the concrete compressive strength. For the purpose of comparing bond strengths of different mixes, the concept of normalized bond strength was used in this thesis. The normalized bond strength is calculated by dividing the calculated bond strength with square root of the concrete compressive strength $\sqrt{f_{ck}}$, as expressed in the following equation (4.2).

$$\tau_{nz} = \frac{\tau}{\sqrt{f_{ck}}} \tag{4.2}$$

Table 4.1 Summary of experimental results of Pull-out test

Specimen Mix type	Cylindrical Compressive Strength, f_{ck} (MPa)	Nominal Bar diameter, d_b (mm)	Embedment Length, l_e (mm)	Max. Axial Load, P (kN)	Average Bond Stress, τ (MPa)	Normalized Bond Strength, τ_{nz}
Scoria-Scoria (Sc-Sc)	27.17	14	70	52.18	16.95	3.25
		16	80	73.14	18.19	3.49
		20	150	102.53	10.88	2.09
Scoria-Sand (Sc-Sa)	27.5	14	70	58.18	18.90	3.60
		16	80	78.66	19.56	3.73
		20	150	118.12	12.53	2.39
Normal (N)	31.75	14	70	64.44	20.93	3.71
		16	80	86.32	21.47	3.81
		20	150	138.72	14.72	2.61

4.1.2 Load-Slip Relationship

In the experiment, applied load and slip of bars were recorded together to investigate the load-slip relationship for all specimens. After acquiring the test data, the load-slip relationship for each mix type and bar diameter were analyzed. The recorded slip was a combination of movement of bar within the concrete and elongation of steel, as it was recorded above the loaded region. Therefore, strain of steel was deducted from the total slip by assuming proportional stress-strain relationship as the maximum stresses were below the yield strength of steel bars. Here after, the load-slip relationship of all tested pull-out specimens are shown in Figs. 4.4 through 4.12.

i. Scoria-Scoria (Sc-Sc) concrete Mix

In this **"Sc-Sc"** concrete mix, all fine and coarse scoria aggregates were used. The pull-out test for this mix was done on three specimens for each bar diameter (14mm, 16mm & 20mm) as shown in Figs.4.4 through 4.6. All specimens failed by splitting of concrete. For the 14mm diameter embedded bar only two specimens were plotted as shown in Fig. 4.4, because the third specimen's slip reading was not correct. The maximum load (Slip) values range from 55.2-56.5kN (1.31-1.37mm) for dia. 14mm bar, 65.3-78.2kN (1.54-1.63mm) for dia. 16mm bar and 83.1-132.7kN (2.1-2.48mm) for dia. 20mm bar.

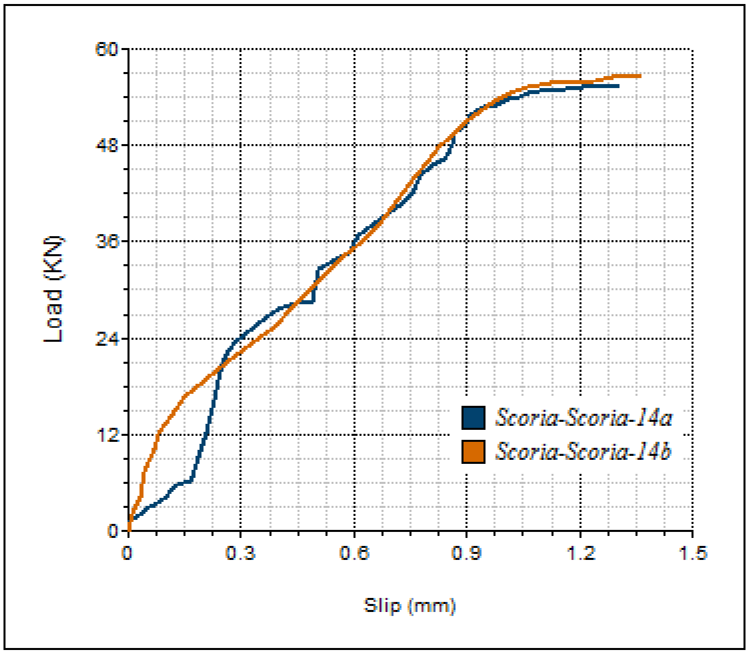

Fig. 4.4 Load-Slip relationship for 14mm rebar and scoria-scoria concrete mix $l_e = 70$mm

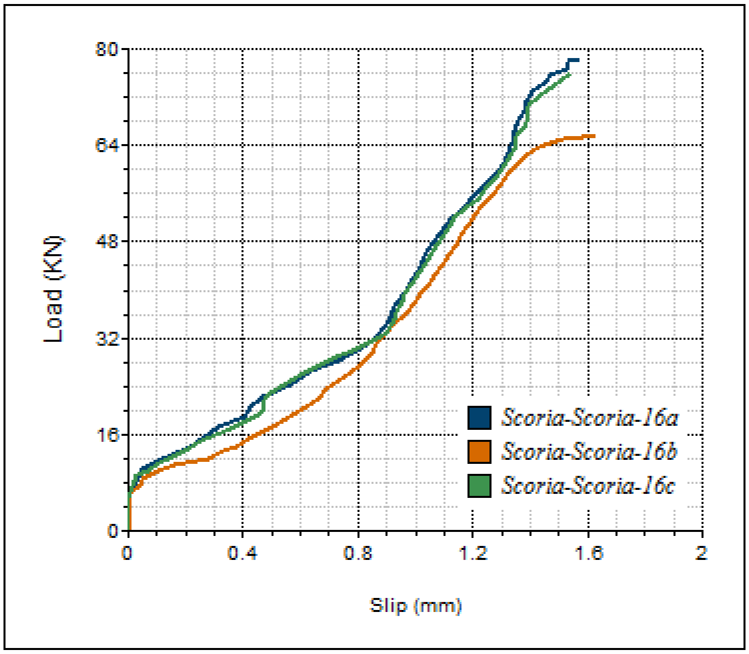

Fig. 4.5 Load-Slip relationship for 16mm rebar and scoria-scoria concrete mix $l_e = 80$mm

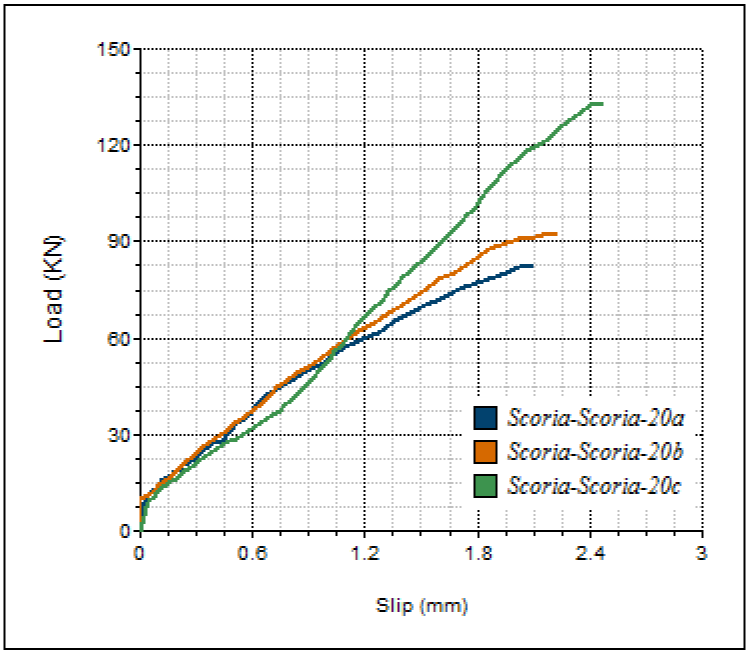

Fig. 4.6 Load-Slip relationship for 20mm rebar and scoria-scoria concrete mix l_e = 150mm

ii. Scoria-Sand (Sc-Sa) concrete Mix

In this **"Sc-Sa"** concrete mix, natural sand and coarse scoria aggregates were used. Similarly, the pull-out test was performed on three specimens for each bar diameter as shown in Figs.4.7 through 4.9. The failure mode of all specimens was by splitting of concrete. Since the third specimen's slip reading was not correct for the 14mm diameter embedded bar, only two specimens were plotted as shown in Fig. 4.7. The maximum load (Slip) values range from 65.7-66.7kN (1.57-1.93mm) for dia. 14mm bar, 68.5-85.55kN (1.71-1.77mm) for dia. 16mm bar and 97.1-136.1kN (2.53-2.71mm) for dia. 20mm bar.

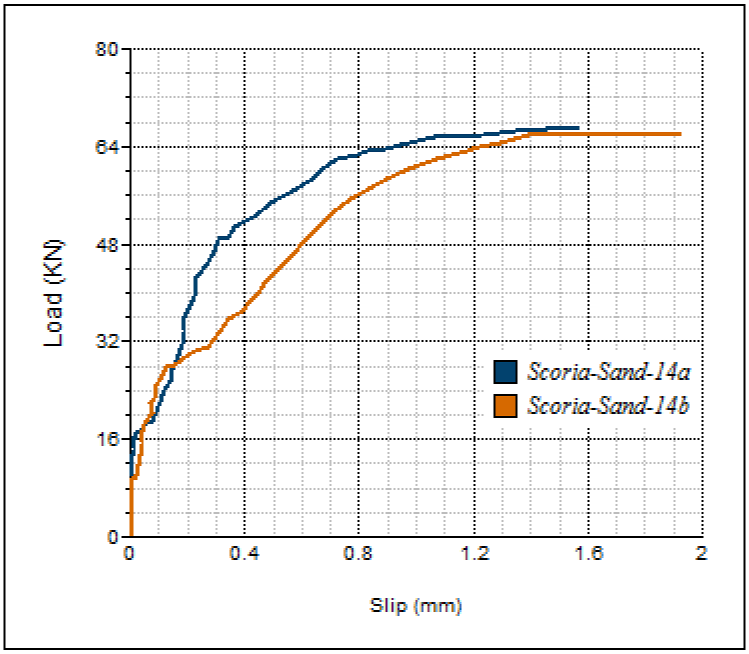

Fig. 4.7 Load-Slip relationship for 14mm rebar and scoria-sand concrete mix $l_e = 70$mm

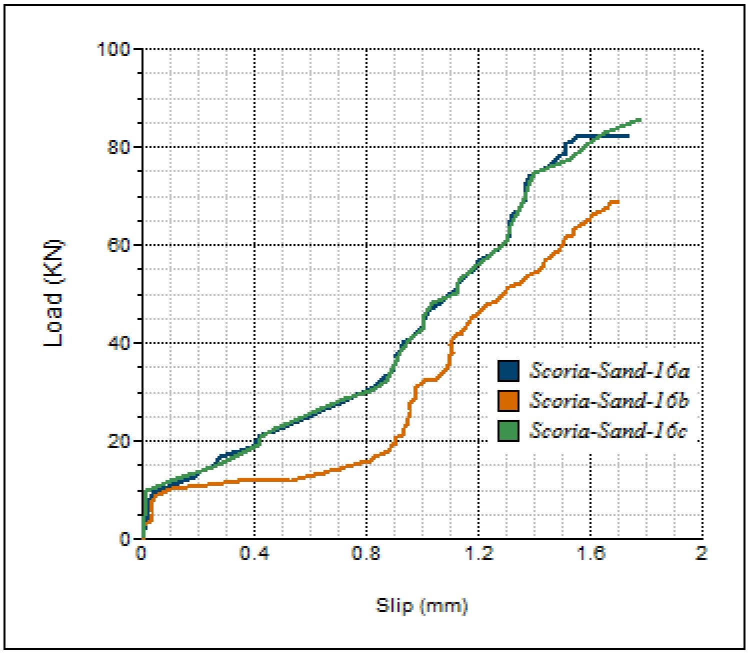

Fig. 4.8 Load-Slip relationship for 16mm rebar and scoria-sand concrete mix $l_e = 80$mm

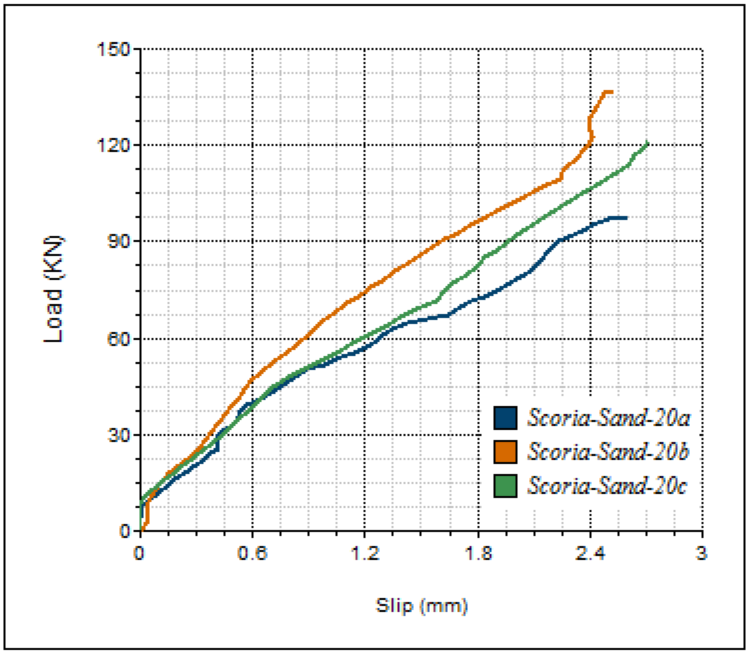

Fig. 4.9 Load-Slip relationship for 20mm rebar and scoria-sand concrete mix l_e = 150mm

iii. Normal (N) concrete Mix

For the normal **"N"** concrete mix, natural sand and normal-weight gravel aggregates were used. As the other two mixes, the pull-out test was performed on three specimens for each bar diameter as shown in Figs.4.10 through 4.12. The failure mode of all specimens was by splitting of concrete. The plots shown below exhibit uneven path compared to mixes discussed above, which might be due to the involvement of strong gravel aggregates with ribs of reinforcement. Even if the loadings of all three specimens were used for the calculation of average bond stress, only two slip reading was correct for each diameter embedded bar. As a result, only two specimens' load-slip relationships were plotted as shown in the figures below. The maximum load (Slip) values range from 57.3-70.1kN (2.01-2.3mm) for dia. 14mm bar, 78.3-93.2kN (1.43-1.98mm) for dia. 16mm bar and 134.5-141.7kN (2.95-2.21mm) for dia. 20mm bar.

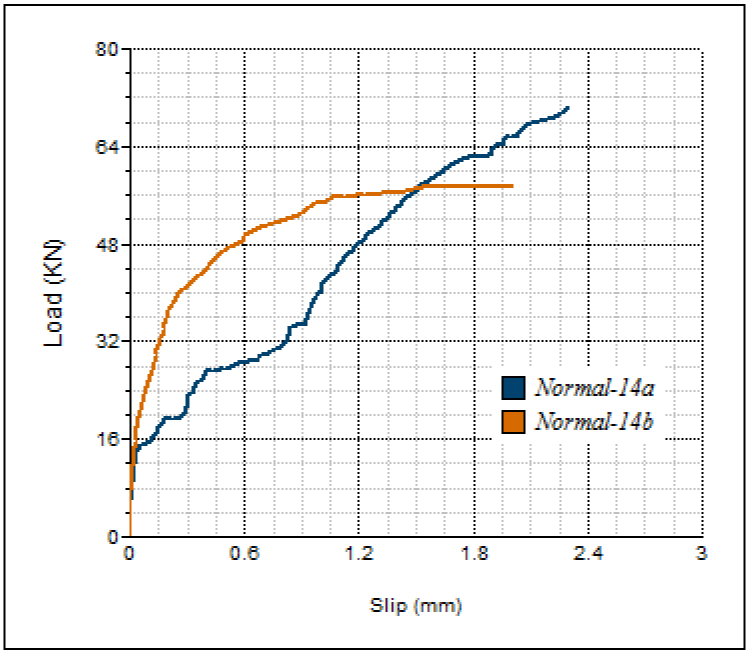

Fig. 4.10 Load-Slip relationship for 14mm rebar and normal concrete mix $l_e = 70mm$

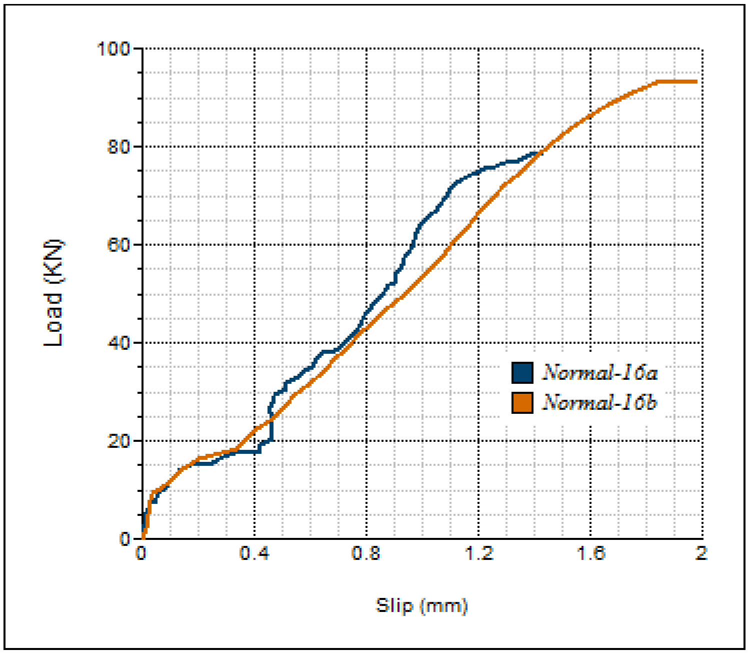

Fig. 4.11 Load-Slip relationship for 16mm rebar and normal concrete mix $l_e = 80mm$

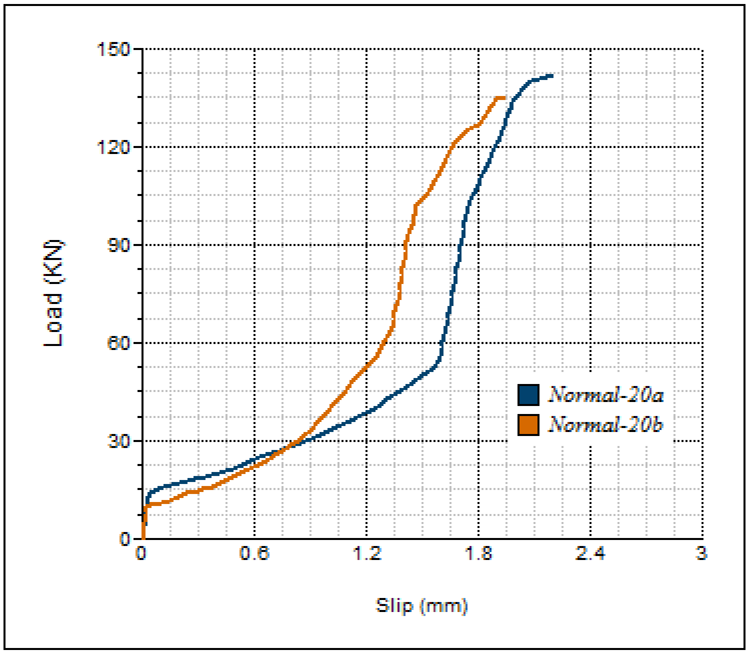

Fig. 4.12 Load-Slip relationship for 20mm rebar and normal concrete mix $l_e = 150$mm

Generally, all specimens of the experiment, with scoria aggregates (Sc-Sc & Sc-Sa) and normal aggregates (N), exhibited a load increasing up to the ultimate load followed by sudden failure. As presented in Table 4.1 the average ultimate loads were used to calculate the bond stress on concrete for each mix type and embedded bar. Apparently, the pullout load-slip curves shown in Figs. 4.4 through 4.12 seem to compare reasonably well with those reported in the literature, [7, 8, 26, 27], for normal and lightweight concretes.

4.1.3 Stress-Strain Relationship

The experiment was done with the assumption that the reinforcement steel won't have significant elongation as compared with slip of bar within concrete. This was assured by deliberately making the embedment lengths shorter which will let the embedded bars to slip out of the concrete before the yielding of steel. But in order to check the strain of bars due to axial stress applied, five strain gauges were attached on embedded bars of pullout specimens. Out of the five strain gauges, only three specimens gave reliable strain readings which are shown in Figures 4.13 through 4.15

Stress-strain curves shown in the figures below have been prepared based on the strain gauge readings attached on bars near point of load application, and calculated stress from the axial pullout load. The maximum value of stress(strain) reading for dia. 14mm, 16mm and 20mm bars were; 427.3MPa(2.13‰), 425.5MPa(2.16‰) and 385.7MPa(1.92‰) respectively. From the results it is clearly seen that the steel bars haven't reached their yield points and the strains are small. Furthermore, the stress-strain curves presented below show more or less a linear relationship, which is the expected stress-strain relationship of steel bars before yielding.

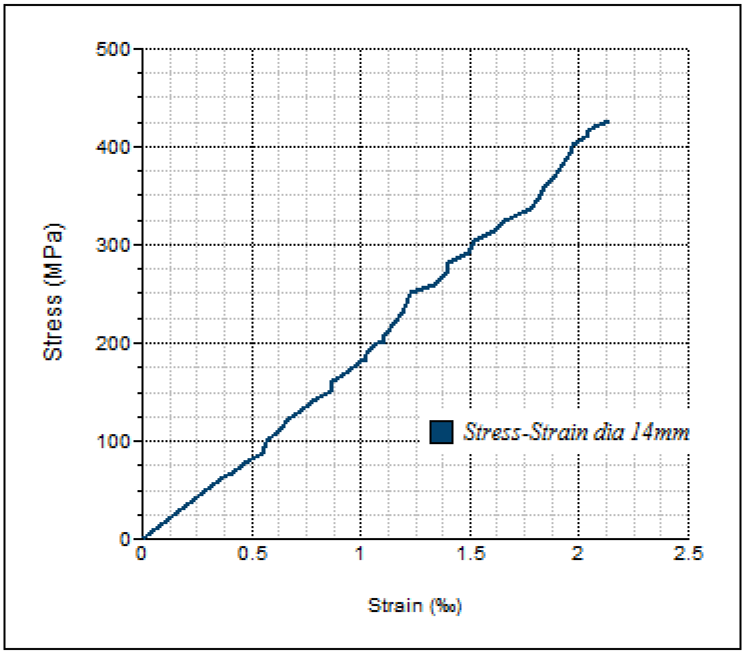

Fig. 4.13 Stress-Strain relationship for 14mm rebar l_e = 70mm

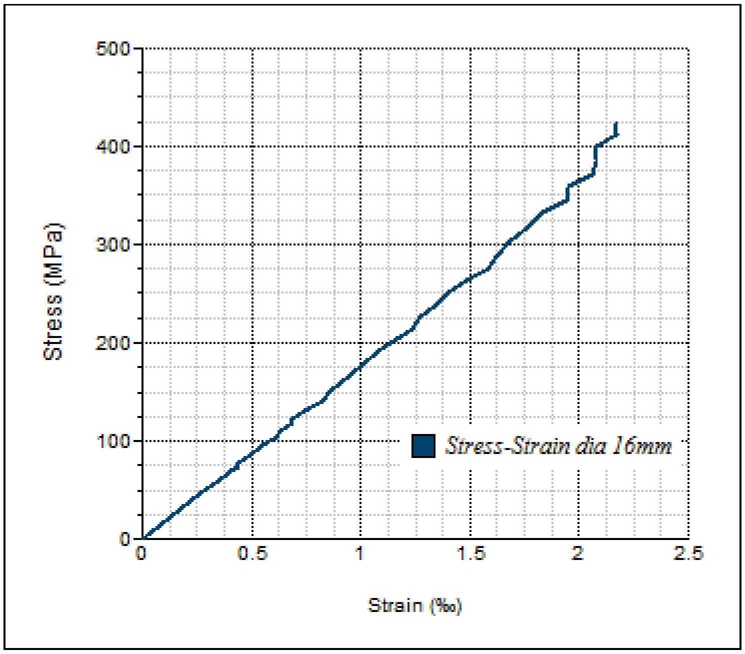

Fig. 4.14 Stress-Strain relationship for 16mm rebar l_e = 80mm

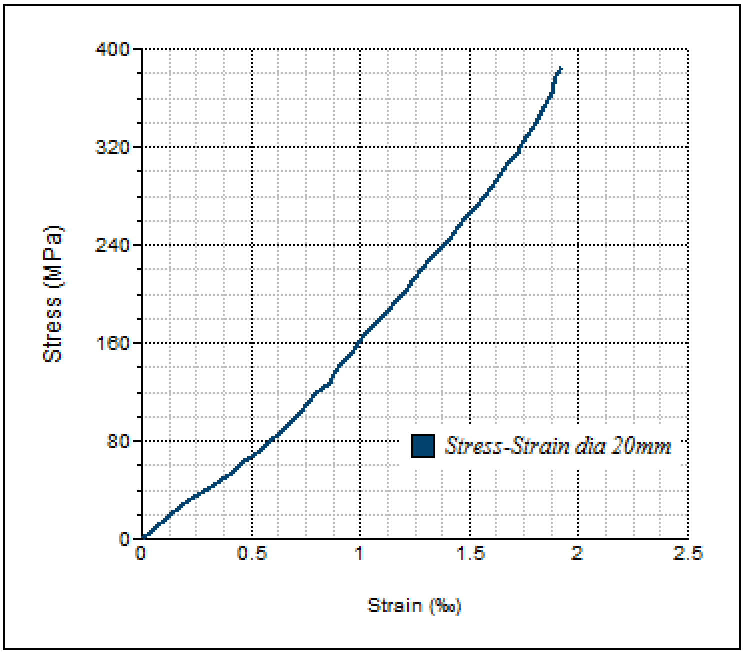

Fig. 4.15 Stress-Strain relationship for 20mm rebar $l_e = 150$mm

4.2 Comparison of Bond Strength among Different Concrete Mixes

As have been discussed before, three different concrete mixes (Sc-Sc, Sc-Sa and N) were used in this study to investigate their bond behavior using pullout test. Important results have been obtained on different properties of the mixes used in the pullout test, as can be observed in Table 4.1 and load-slip relationship discussed above. Hereafter, some comparisons related to bond strength among the three concrete mixes are discussed.

When bond stresses of specimens, with the two types of bar diameter (14 & 16mm) are compared, the bond stress of diameter 16mm bars is found to be greater than that of 14mm bars in all three mixes. Nevertheless, they had the same concrete cube specimens and proportional embedment length (5d). For Sc-Sc mix the bond stress is increased by 7.4%, which is the greatest, and Sc-Sa and N mixes increased only by 3.5% and 2.6% respectively. Therefore, it can be said that change in bar diameter and embedment length has greater influence in scoria mix than normal mix. In other words, normal-weight aggregate concrete tends to have more linear relationship with respect to change in bar diameter and embedment length than that of scoria aggregate concrete.

Cylinder specimens which have diameter 20mm embedded bars with embedment length of 150mm (7.5d), resulted in bond strength less than that of the 14mm and 16mm bars (5d). It is believed that such decrease in bond strength in all mixes happens due to the less confinement and facture energy of cylindrical specimens compared to that of the cube. This shows that, even though tensile capacity of concrete is similar other properties such as cover, confinement and fracture energy capacity of concrete plays great role.

For comparison purpose the normalized bond strength is calculated and presented in Table 4.1. As have been discussed, normalized bond strength is used with an assumption that there is a linear relationship between bond strength and the square root of the concrete compressive strength. Figure 4.16 shows plot of normalized bond strength of the three concrete mixes with their respective embedded bar types. It can be observed from the plots that Sc-Sc mix has the lowest bond strength in all three types of embedded bars (dia. 14mm, 16mm & 20mm). Whereas, the normal-weight concrete mix exhibits the largest bond strength in all embedded bars.

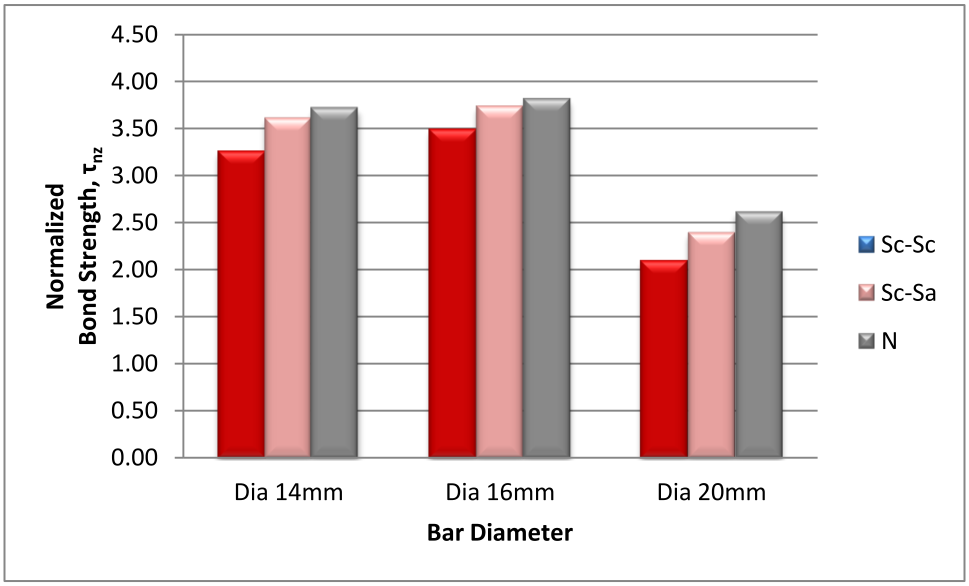

Fig. 4.16 Comparison of Normalized Bond Strength

Ratio of normalized bond stress of normal-weight aggregate concrete to scoria aggregate concrete was analyzed for comparison purpose as shown in Figure 4.17. This ratio clearly shows the effect of introducing scoria aggregates in bond strength of concrete. For Sc-Sc mix, the ratio of normalized shear stress of normal-weight concrete to all scoria concrete is between 1.09-1.25. Furthermore, the ratio for the Sc-Sa concrete mix is in a range of 1.02-1.09. In other words, the results show that Sc-Sc mix has bond strength which is 80-91% of normal-weight concrete of the same compressive strength; and Sc-Sa has bond strength 91-98% of normal-weight concrete.

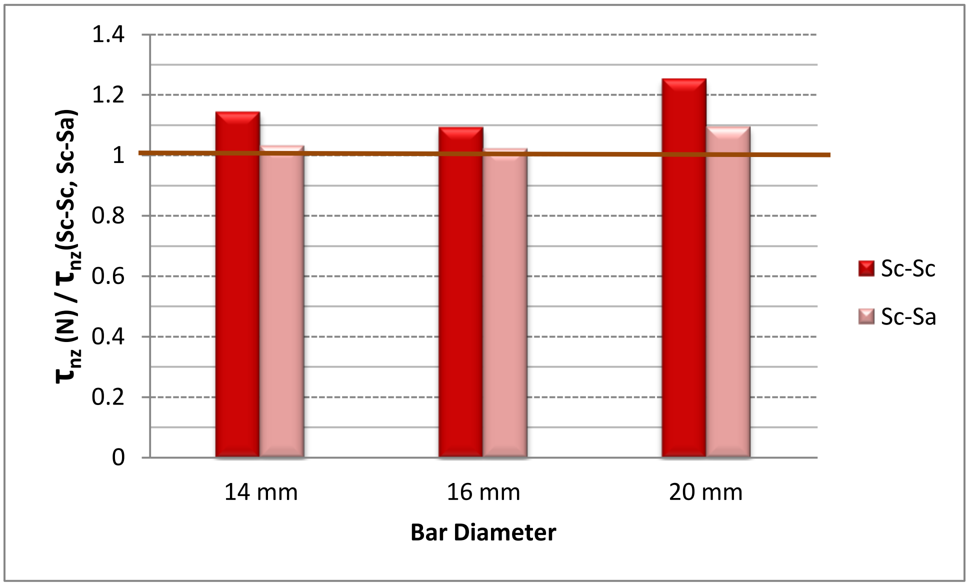

Fig. 4.17 Ratio of normalized bond stress of Normal-weight aggregate (N) to Lightweight aggregate concrete (Sc-Sc & Sc-Sa)

4.3 Comparison with Euro Code (EN 1992:2004) and ACI Code (ACI 318M-08)

The design bond strength and development length were calculated using provisions given by codes, ACI 318-08 and the European code (EN 1992:2004), and were compared with the results obtained from the experiment. As stated before, in Table 2.5 (ACI-318 (12.2.2)) and Eq. 2.3 (ACI-318 (12.2.3)) of literature review, development length can be calculated using the following expressions according to ACI 318-08 code.

$$l_d = \left(\frac{f_y \, \psi_t \, \psi_e}{2.1 \, \lambda \sqrt{f_c'}} \right) d_b \tag{4.2}$$

$$l_d = \left[\frac{f_y}{1.1 \, \lambda \sqrt{f_c'}} \, \frac{\psi_t \, \psi_e \psi_s}{\left(\frac{c_b + k_{tr}}{d_b} \right)} \right] d_b \tag{4.3}$$

The bond strength (f_b) for ultimate state condition can be calculated using the derived equation (4.4) as shown below. Then, development length (l_d) equations (4.2 & 4.3) are combined with equation (4.4) and resulted in equations (4.5 & 4.6) respectively. Therefore, bond strength of concrete with embedded bars, according to ACI 318M-08, is calculated using the following equations (4.4 & 4.5).

$$f_b = \frac{f_y\, d_b}{4\, l_d} \tag{4.4}$$

$$f_b = \frac{2.1\, \lambda \sqrt{f_c{}'}}{4\, \psi_t\, \psi_e} \tag{4.5}$$

$$f_b = \frac{1.1\, \lambda \sqrt{f_c{}'}}{4} \, \frac{\left(\frac{c_b + k_{tr}}{d_b}\right)}{\psi_t\, \psi_e \psi_s} \tag{4.6}$$

ACI code in general gives, a modification factor (**λ**) of 0.75 for all lightweight aggregate concrete and 0.85 for sand lightweight aggregate concrete. Besides, the code provides equation for **λ** (Eq. 4.6)**,** if average splitting tensile strength (**$f_{ct,sp}$**) of lightweight concrete is specified. Since average splitting tensile strength of concrete in this study was obtained from splitting tensile test, **λ** was calculated for the specific concrete mix type using equation (4.7).

$$\lambda = f_{ct,sp} \,/\, (0.56\sqrt{f_c{}'}\,) \leq 1.0 \tag{4.7}$$

On the other hand, the European code EC2-2004, specifies the following expression (eq. 4.8) for determining the ultimate bond stress. As stated in sec 2.6.1 of literature review, the coefficient η_1 is related to the quality of the bond condition and bar location during concreting and η_2 is related to the rebar size. For this study, both these coefficients are equal to unity; which means there is good bond condition and diameters are less than 32 mm. In addition, the European code limits the use of bond strength equation to a maximum strength **f_{ck}** of 60 MPa which is a similar limitation given in ACI 318-08. Furthermore, the European Code restricts diameter of bars embedded in lightweight aggregate concrete not to exceed 32 mm. Therefore, it is valid to use equation (4.8) for this study as bar diameter is less than 32mm and Characteristic compressive strength less than 60MPa.

$$f_{\mathrm{bd}} = 2{,}25\ \eta_1\ \eta_2\ f_{\mathrm{ctd}} \tag{4.8}$$

The design tensile strength (f_{ctd}) of concrete is obtained from concrete characteristic axial tensile strength ($f_{ctk,0.05}$). Moreover, this characteristic axial tensile strength of lightweight aggregate concrete (f_{lctk}) may be obtained by multiplying (f_{ctk}) with a coefficient $\boldsymbol{\eta_1}$ as shown in equation (4.9). The coefficient η_1 is calculated by using the density of lightweight aggregate concrete as shown in equation (4.10).

$$f_{lctk,0.05} = f_{ctk,0.05} * \eta_1 \tag{4.9}$$

$$\eta_1 = 0.40 + 0.60\rho/2200 \tag{4.10}$$

The values of material property and different coefficients given in the above equations are summarized in Table 4.2 as shown below. Detail definition and information on terms used in the above equations are available in sections 2.6.1 and 2.6.2 of the literature review of this document.

Table 4.2 Summary of values of material property and coefficients used in the calculation of design bond strength and development length in Codes (Euro-code and ACI-318)

		N	Sc-Sa	Sc-Sc
ACI	f'_c (f_{ck})	31.746	27.5	27.167
	$f_{ct,sp}$	3.497	2.418	2.187
	ψ_t	1	1	1
	ψ_e	1	1	1
	ψ_s	0.8	0.8	0.8
	λ	1	0.75	0.82
	$(c_b+k_{tr})/d_b$	2.5	2.5	2.5
EC-2	$f_{ctk,0.05}$	2.11	1.58	1.55
	f_{ctd}	1.40	1.05	1.03
	$\eta 1$	1	1	1
	$\eta 2$	1	1	1

Using the equations of the two codes (Euro-code and ACI-318), development length and design bond strength were calculated for the three concrete mix types and different diameter bars. The results are summarized and presented in the following Table 4.3.

Table 4.3 Summary of design bond strength and development length provisions by Codes (Eurocode-2 and ACI-318)

Mix	Bar Dia. (mm)	EC-2			ACI-318 (12.2.2)			ACI-318 (12.2.3)		
		Design Bond Strength f_b (MPa)	Norm. Design Bond Strength f_{nb}	Dev. Length, l_d (mm)	Design Bond Strength f_b (MPa)	Norm. Design Bond Strength f_{nb}	Dev. Length, l_d (mm)	Design Bond Strength f_b (MPa)	Norm. Design Bond Strength f_{nb}	Dev. Length, l_d (mm)
Sc-Sc	14	2.33	0.45	798	2.05	0.39	1359	3.36	0.64	706
	16			884			1504			791
	20			1203			2046			1003
Sc-Sa	14	2.37	0.45	783	2.27	0.43	1229	3.71	0.71	639
	16			867			1361			715
	20			1179			1851			908
N	14	3.16	0.56	588	2.96	0.53	942	4.84	0.86	489
	16			651			1043			548
	20			886			1418			696

Comparison was done on the normalized design bond strength of the three concrete mixes, the same way as was performed for the experimental bond stress results. Figure 4.18 presents a plot showing the normalized bond strength of the three concrete mixes with their respective design codes. From the plots, it can be seen that Sc-Sc mix has the lowest bond strength; and the normal-weight concrete mix has the largest bond strength in both code provisions.

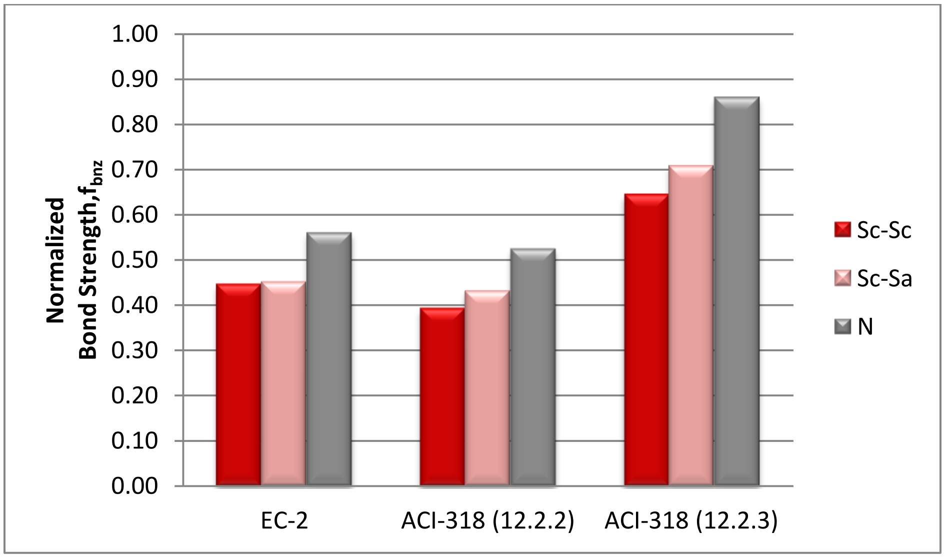

Fig. 4.18 Comparison of Normalized Design Bond Strength (Euro-code and ACI-318)

Next, ratios of normalized design bond strength of normal-weight aggregate concrete to scoria aggregate concrete were compared for the two codes as shown in Figure 4.19. For Sc-Sc mix, the ratio of normalized design bond strength of normal-weight concrete to all scoria concrete is 1.26 according to Euro Code and 1.33 for ACI Code. Likewise, the ratio for the Sc-Sa concrete mix is 1.24 for Euro Code and 1.21 for ACI Code. In other words, the results of Euro Code (ACI Code) show that Sc-Sc mix has design bond strength which is 79% (75%) of normal-weight concrete of similar compressive strength; and Sc-Sa has bond strength 81% (83%) of normal-weight concrete respectively.

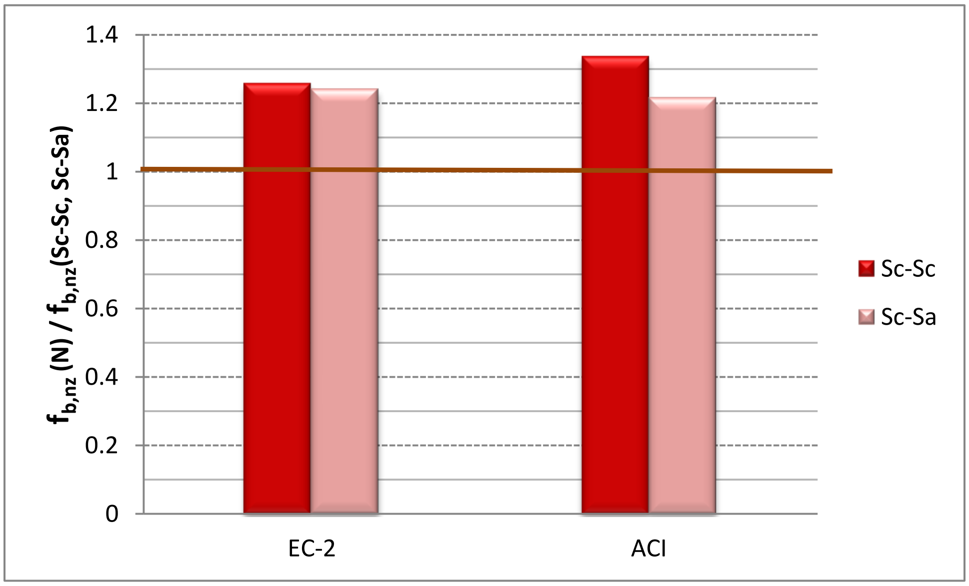

Fig. 4.19 Ratio of normalized design bond strength of Normal-weight aggregate (N) to Lightweight aggregate concrete (Sc-Sc & Sc-Sa)

Figures 4.20 - 4.21 show the experimental to design bond strength ratios of Sc-Sc and Sc-Sa concrete mixes respectively; where the design bond strength is calculated according to Euro code and ACI code as discussed before. The ratios were done indirectly by using results of ratios of scoria aggregate concrete with respect to normal-weight aggregate concrete as discussed in Fig. 4.17 and Fig. 4.19. From the plots, it is observed that experimental to design ratios were higher than 1.0 for all diameter bars using both (ACI and EC-2) design codes.

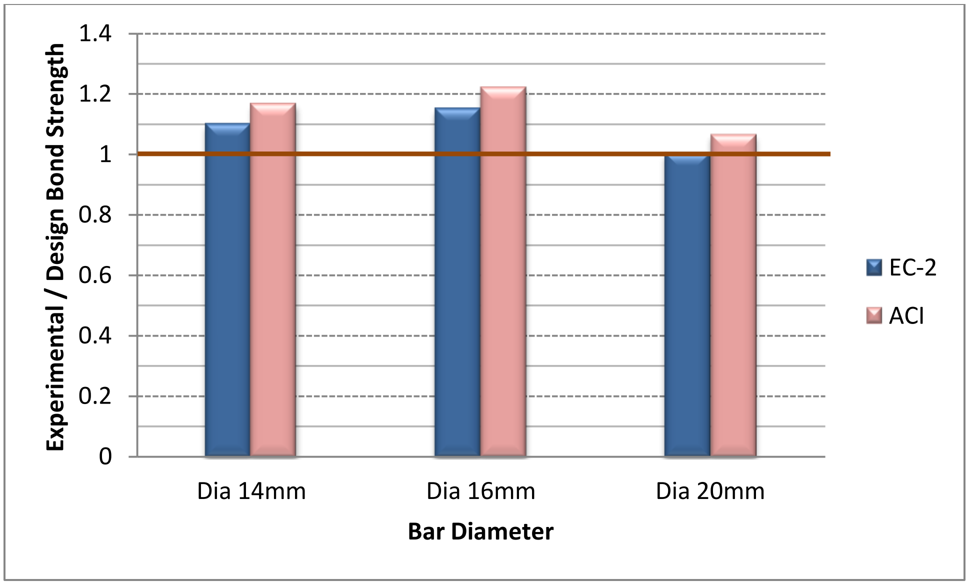

Fig. 4.20 Comparison of normalized bond stress from experiment to design bond strength from Code provisions for Scoria-Scoria (Sc-Sc) mix

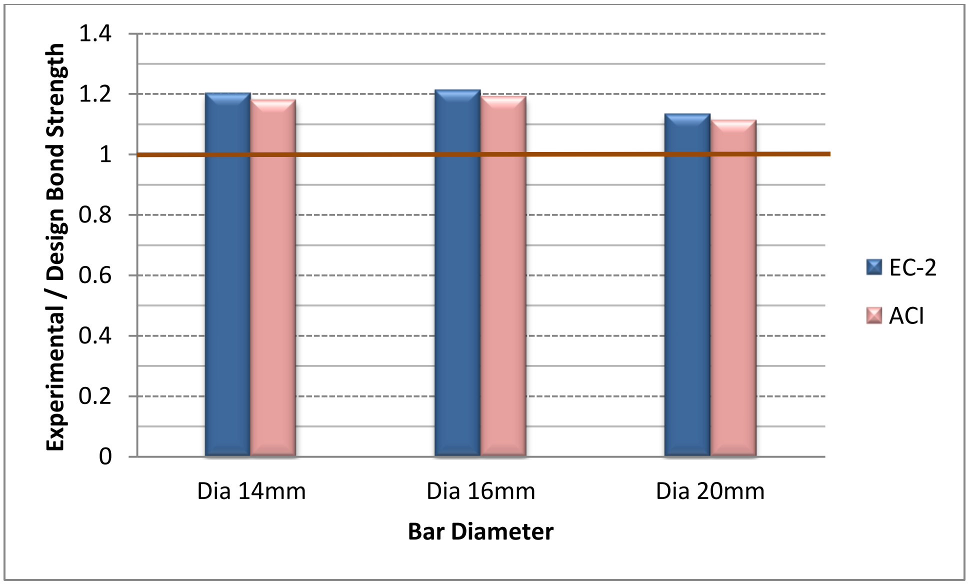

Fig. 4.21 Comparison of normalized bond stress from experiment to design bond strength from Code provisions for Scoria-Sand (Sc-Sa) mix

From the above plots (Fig. 4.20 & 4.21), it is evident that equations given by both the ACI and Euro codes are conservative enough to be used for calculating the design bond strength and anchorage length of scoria aggregate concrete.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this thesis, comparative study on bond behavior of scoria aggregate concrete was done. Pull-out test on embedded bars were tested by varying concrete mix type and diameter of embedded bars. Furthermore, analytical investigation was done using two design codes, ACI-318 and Euro code-2, so as obtain design bond strength of concrete used in the experiment. Comparison between the experimental and analytical results was also performed. Based on experimental and analytical investigation results the following conclusions have been made:

- From the pull out test, load-slip relationship of scoria aggregate concrete (Sc-Sc and Sc-Sa) exhibited comparable pattern with those reported in the literature for normal and lightweight concretes.
- Based on the experimental results, Sc-Sc mix has bond strength which is 80-91% of normal-weight concrete; and Sc-Sa has bond strength 91-98% of normal-weight concrete.
- The results, of calculations using Euro Code-2, revealed that Sc-Sc mix has design bond strength which is 79% of normal-weight concrete; and Sc-Sa has bond strength 81% of normal-weight concrete.
- According to ACI-318 equations, Sc-Sc mix has design bond strength which is 75% of normal-weight concrete; and Sc-Sa has bond strength 83% of normal-weight concrete respectively.
- Experimental results exhibit higher bond strength compared to the results of ACI and EC-2 design codes. This implies that equations given by both the ACI and Euro codes are in safe range to be used for calculating the design bond strength and anchorage length of scoria aggregate concrete.
- Beside bond strength, it was possible to produce scoria aggregate concrete with average cubic compressive strength of 33 MPa, and lighter unit weight, but higher cement content. All in all, it is believed that the findings from this study will increase the acceptance of scoria material to be used in the concrete industry.

5.2 Recommendations

The following list of recommendations is forwarded regarding bond behavior and use of scoria aggregate concrete.

- Due to limitations only pullout test was performed in this study. But further investigation using more advanced methods such as beam end specimen, beam anchorage specimen or splice specimen can be performed.
- Bond behavior of scoria aggregate concrete in post-tensioned and pre-stressed concrete can be studied.
- Better production process and standardized gradation of scoria aggregates, for the use of structural concrete, should be practiced.

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ANNEX A

Material Tests and Concrete Mix Design

Material tests on component of concrete were performed according to ASTM standards. Then, results of material property tests were used in the mix design.

A.1 Material Tests

I) Silt content

Table-A1 Silt content of fine aggregate

Sample 1		Sample 2	
A (silt content)	12 ml	A (silt content)	10 ml
B (sand)	305 ml	B (sand)	310 ml
Silt content	3.93 %	Silt content	3.22 %

II) Sieve analysis

Coarse aggregate - Scoria Aggregate

Table-A2 Sieve analysis of coarse scoria aggregate

Sieve size (mm)	Weight of Seive (gm)	Weight of Seive and Retained (gm)	Weight Retained (gm)	Percentage retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)
37.5	1225	1225	0	0.000	0.000	100.000
25	1210	1210	0	0.000	0.000	100.000
19	1195	1894	1021	20.000	20.000	80.000
12.5	1180	2141	2042	40.000	60.000	40.000
9.5	1165	1420	1276.25	25.000	85.000	15.000
4.75	1265	1319	765.75	15.000	100.000	0.000
Pan	735	735	0	0.000		
Total			5105			

Fine aggregate - Scoria

Table-A3 Sieve analysis of fine scoria aggregate

Sieve size(mm)	Weight of Seive (gm)	Weight of Seive and Retained (gm)	Weight Retained (gm)	Percentage retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)
9.5	445	445	0	0.000	0.000	100.000
4.75	430	430	0	0.000	0.000	100.000
2.36	390	475	85	16.667	16.667	83.333
1.18	355	545	190	37.255	53.922	46.078
600 µm	325	430	105	20.588	74.510	25.490
300 µm	305	375	70	13.725	88.235	11.765
150 µm	285	315	30	5.882	94.12	5.882
Pan	415	445	30	5.882		
Total			510			

Fineness Modulus = 3.27

Fine aggregate - Sand

Table-A4 Sieve analysis of fine sand aggregate

Sieve size(mm)	Weight of Seive (gm)	Weight of Seive and Retained (gm)	Weight Retained (gm)	Percentage retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)
9.5	445	445	0	0.000	0.000	100.000
4.75	430	430	0	0.000	0.000	100.000
2.36	390	427	37	7.400	7.400	92.600
1.18	355	465	110	22.000	29.400	70.600
600 µm	325	519	194	38.800	68.200	31.800
300 µm	305	405	100	20.000	88.200	11.800
150 µm	285	323	38	7.600	95.80	4.200
Pan	415	436	21	4.200		
Total			500			

Fineness Modulus = 2.89

III) Moisture content

Table-A5 Moisture content of fine and coarse aggregate used in **"Sc-Sc"** mix

Coarse aggregate			*Fine aggregate*		
A =	2000	gm	A =	500	gm
B =	1925	gm	B =	470	gm
Moisture content	3.90	%	Moisture content	6.38	%

Table-A6 Moisture content of fine and coarse aggregate used in **"Sc-Sa"** mix

Coarse aggregate			*Fine aggregate*		
A =	2000	gm	A =	500	gm
B =	1925	gm	B =	490	gm
Moisture content	3.90	%	Moisture content	2.04	%

Table-A7 Moisture content of fine and coarse aggregate used in **"N"** mix

Coarse aggregate			*Fine aggregate*		
A =	2000	gm	A =	500	gm
B =	1961	gm	B =	490	gm
Moisture content	1.989	%	Moisture content	2.04	%

IV) Unit weight

Table-A8 Unit weight of scoria coarse aggregate

Cylindrical Measure size					
H =	0.275	m	Cylinder weight	4845	g
D =	0.255	m	Cylinder with aggregate	18945	g
Volume =	0.01404439	m3	Aggregate weight	14100	g
Dry rodded density=			1003.96	Kg/m3	

Table-A9 Unit weight of gravel coarse aggregate

Cylindrical Measure size					
H =	0.28	m	Cylinder weight	4845	g
D =	0.255	m	Cylinder with aggregate	27313	g
Volume =	0.01429974	m3	Aggregate weight	22468	g
Dry rodded density=			1571.22	Kg/m3	

V) Specific gravity and absorption capacity

Table-A10 Specific gravity and absorption capacity of aggregates used in **"Sc-Sc"** mix

For Coarse aggregate					
A (oven dry) =	4746	g	Bulk Sp. gr. =	1.90	
B (SSD) =	5230	g	Bulk Sp. gr.(SSD) =	2.09	
C (water immersed) =	2730	g	Apparent Sp. gr. =	2.35	
			Absorption Capacity =	10.20	%
For Fine aggregate					
A (oven dry) =	470	g	Bulk Sp. gr. =	2.29	
B (Flask + water) =	1313	g	Bulk Sp. gr.(SSD) =	2.44	
C (water immersed) =	1608	g	Apparent Sp. gr. =	2.69	
			Absorption Capacity =	6.38	%

Table-A11 Specific gravity and absorption capacity of aggregates used in **"Sc-Sa"** mix

For Coarse aggregate					
A (oven dry) =	4746	g	Bulk Sp. gr. =	1.90	
B (SSD) =	5230	g	Bulk Sp. gr.(SSD) =	2.09	
C (water immersed) =	2730	g	Apparent Sp. gr. =	2.35	
			Absorption Capacity =	10.20	%
For Fine aggregate					
A (oven dry) =	485	g	Bulk Sp. gr. =	2.45	
B (Flask + water) =	1313	g	Bulk Sp. gr.(SSD) =	2.53	
C (water immersed) =	1615	g	Apparent Sp. gr. =	2.65	
			Absorption Capacity =	3.09	%

Table-A12 Specific gravity and absorption capacity of aggregates used in **"N"** mix

For Coarse aggregate					
A (oven dry) =	4943	g	Bulk Sp. gr. =	2.75	
B (SSD) =	5021	g	Bulk Sp. gr.(SSD) =	2.79	
C (water immersed) =	3220.5	g	Apparent Sp. gr. =	2.87	
			Absorption Capacity =	1.58	%
For Fine aggregate					
A (oven dry) =	485	g	Bulk Sp. gr. =	2.45	
B (Flask + water) =	1313	g	Bulk Sp. gr.(SSD) =	2.53	
C (water immersed) =	1615	g	Apparent Sp. gr. =	2.65	
			Absorption Capacity =	3.09	%

A.2 Concrete Mix Design according to ACI Method

Table-A13 Concrete mix design used in **"Sc-Sc"** mix

material	**Mass**	**percentage by mass**	**volume**	**percentage by volume**
Coarse aggregate	644.16	34.80	0.308	30.79
fine aggregate	478.72	25.86	0.273	27.32
cement	475.00	25.66	0.151	15.08
water	253.07	13.67	0.253	25.31
air			0.015	1.50
concrete	**1850.951**	**100.00**	1	**100**
	water cement ratio =		0.45	

Table-A14 Concrete mix design used in **"Sc-Sa"** mix

material	**Mass**	**percentage by mass**	**volume**	**percentage by volume**
Coarse aggregate	619.2208	32.11	0.296	29.6
fine aggregate	575.5102	29.85	0.292	29.15
cement	485	25.15	0.154	15.4
water	248.4928	12.89	0.248	24.85
air	0	0	0.01	1
concrete	1928.224	100	1	100
	water cement ratio =		0.45	

Table-A15 Concrete mix design used in **"N"** mix

material	**Mass**	**percentage by mass**	**volume**	**percentage by volume**
Coarse aggregate	1060.8	43.15	0.38	38.04
fine aggregate	850	34.57	0.30	30.07
cement	350	14.24	0.11	11.11
water	197.7629	8.04	0.20	19.78
air			0.01	1
concrete	2458.563	100	0	100
	water cement ratio =		0.54	

ANNEX B

Mechanical Properties of Concrete

Table-B1 Density, compressive strength and Modulus of elasticity of **"Sc-Sc"** concrete

Concrete Mix Designation	Specimen	28th day Cubic Compressive Strength, f_{cu} (MPa)	Mass (kg)	Fresh Concrete Density (Kg/m^3)	Variance=	3.521
Sc-Sc	1	30.92	7.01	2077.037	SD=	1.876
	2	32.7	6.92	2050.37	COV=	5.681 %
	3	35.48	6.905	2045.926	f_{ck}(EC2)=	27.167 Mpa
Mean		33.033	6.945	2057.778	E_{ck}(EC2)=	31.485 Gpa

Table-B2 Tensile strength of **"Sc-Sc"** concrete

Concrete Mix Designation	Specimen	Max Force, P (kN)	Split Tensile Strength, $f_{ct,sp}$ (MPa)	Tensile Strength, $f_{ct,sp}$ (MPa)	Variance=	95.247
Sc-Sc	1	142.8	2.020	1.818	SD=	9.759
	2	166.7	2.358	2.122	COV=	6.313 %
	3	154.3	2.183	1.965		
Mean		154.600	2.187	1.968		

Table-B3 Density, compressive strength and Modulus of elasticity of **"Sc-Sa"** concrete

Concrete Mix Designation	Specimen	28th day Cubic Compressive Strength, f_{cu} (MPa)	Mass (kg)	Fresh Concrete Density (Kg/m^3)	Variance=	3.286
Sc-Sa	1	31.28	6.965	2063.704	SD=	1.813
	2	35.72	7.27	2154.074	COV=	5.411 %
	3	33.5	7.005	2075.556	f_{ck}(EC2)=	27.5 Mpa
Mean		33.500	7.080	2097.778	E_{ck}(EC2)=	31.618 Gpa

Table-B4 Tensile strength of **"Sc-Sa"** concrete

Concrete Mix Designation	Specimen	Max Force, P (kN)	Split Tensile Strength, $f_{ct,sp}$ (MPa)	Tensile Strength, f_{ct} (MPa)	Variance=	135.494
Sc-Sa	1	155.5	2.20	1.98	SD=	11.640
	2	183.65	2.598	2.338	COV=	6.812 %
	3	173.5	2.455	2.209		
Mean		170.883	2.418	2.176		

Table-B5 Density, compressive strength and Modulus of elasticity of **"N"** concrete

Concrete Mix Designation	Specimen	28th day Cubic Compressive Strength, f_{cu} (MPa)	Mass (kg)	Fresh Concrete Density (Kg/m^3)	Variance=	1.544
N	1	38.23	8.14	2411.852	SD=	1.243
	2	41.27	8.045	2383.704	COV=	3.123 %
	3	39.88	8.22	2435.556	f_{ck}(EC2)=	31.746 Mpa
Mean		39.793	8.135	2410.370	E_{cm}(EC2)=	33.294 Gpa

Table-B6 Tensile strength of **"Sc-Sa"** concrete

Concrete Mix Designation	Specimen	Max Force, P (kN)	Split Tensile Strength, $f_{ct,sp}$ (MPa)	Tensile Strength, $f_{ct,sp}$ (MPa)	Variance=	153.760
N	1	234.8	3.322	2.99	SD=	12.400
	2	259.6	3.673	3.305	COV=	5.016 %
	3					
Mean		247.200	3.497	3.147		