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STRUCTURAL PERFORMANCE OF SISAL FIBERS REINFORCED LIGHTWEIGHT CONCRETE WITH WASTE PLASTIC PRE-COATED VOLCANIC SCORIA AGGREGATES.

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(Structural Engineering Option)

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DECLARATION

This research thesis is my original work and has not been submitted in this university or any other university for award of a degree.

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DEDICATION

This thesis is dedicated to my family.

For their unconditional love, prayers and support that they have always given me for the accomplishment of my studies.

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LIST OF ABBREVIATIONS AND ACCRONYMS

ACI	American Concrete Institute
ALWA	Artificial Lightweight Aggregates
ASTM	American Society for Testing and Material
BS	British Standards
LWA	Lightweight Aggregates
LWC	Lightweight Concrete
LWAC	Lightweight Aggregates Concrete
LWSA	Lightweight Scoria Aggregates
NLWA	Natural Lightweight Aggregates
NWC	Normal Weight Concrete
SFRLWC	Sisal Fibers Reinforced Lightweight Concrete
ASTM	American Standard of Testing and Materials
BS	Bristish Standard
CO_2	Carbon dioxide
W/C	Water Cement ratio
FE	Finite Element
PET	Polyethylene Terephthalate
FA	Fly Ash
SF	Silica Fume
OBBA	Overburnt Brick Aggregates
HDPE	High-Density Polyethylene

PVC	Polyvinyl Chloride
LDPE	Low Density Polyethylene
PP	Polypropylene
PS	Polystyrene
PC	Polycarbonate
PE	Polyethylene
CaO	Lime
SiO_2	Silica
Al_2O_3	Alumina
MgO	Magnesia
OPC	Ordinary Portland Cement
WP	Waste Plastic

SYMBOLS

E	Modulus of elasticity (Young's Modulus)
f_u	Compressive strength of concrete (According to BS Code)
I	Moment of inertia
Ø	Curvature
y	Compression depth of the section
S_0	Control lightweight concrete specimen made with raw uncoated scoria aggregates having no fibers in the matrix
S_1	Lightweight concrete specimen made with waste plastic pre-coated scoria aggregates at 5% containing sisal fibers at 1% in the matrix.
v	Poisson's ratio
γ	Shear strain
ε	Strain
ξ	Principal strain
σ	Stress
τ	Shear stress

ABSTRACT

Concrete is by far the most common material used for construction purposes all around the world. Structural Lightweight Concrete (SLWC) is a specific type of Lightweight Concrete (LWC) developed when there is need to produce both a strong and light concrete having other specific properties such as insulation (thermal, sound). However, instead of the use of Artificial Lightweight Aggregates (ALWA) such as expanded shales, clay and slates commonly used, this study investigated the use of Natural Lightweight Aggregates (NLWA) such as volcanic scoria for producing SLWC. ALWA are known for high carbon emission and high energy consumption in the manufacturing process which make them costly and environmentally dangerous. Previous studies on volcanic scoria aggregates used in concrete have revealed relatively weak mechanical and physical properties mainly due to its high degree of porosity leading to a high water absorption capacity in concrete and therefore low strengths. To address the issue, waste plastics (WP) were used in this study to pre-coat them in a hot mix process in order to reduce their pores before using them to produce SLWC reinforced with natural sisal fibers (NSF). The aim of this research was to produce a relatively strong SLWC, using NLWA such as volcanic scoria and NSF in the matrix, while disposing the waste plastics from the environment.

A SLWC with uncoated volcanic scoria aggregates, having no fibers in the matrix was designed as the control mix, following the specific steps prescribed by ACI 211.2 Standard, with 30 MPa as the design strength. Then, three main phases were adopted.

(i) Investigation of the effects of WP over the aggregates on the SLWC properties. Three LWC specimens were produced with waste plastic pre-coated scoria aggregates at 5%, 10% and 15% by weight replacement of aggregates in a hot mix process. It was noticed a great influence of WP over the aggregates on the LWC properties. The best WP content was found to be 5%. The 28 days compressive strength, splitting tensile strength and flexural strength were found to increase by 10.46%, 1.82% and 3.43% respectively as compared to the control.

(ii) Determination of the influence of addition of NSF in the concrete matrix on the LWC properties. Three different short discrete fibers contents (1%, 1.5%, and 2%) of length 3 to 4 cm by weight of cement, were used in the matrix of LWC mixes containing waste plastic pre-coated volcanic scoria aggregates at 5%. The results showed that the best NSF content was 1%. With comparison to the control, the 28 days compressive strength decreased by 25.49% while the 28 days splitting tensile strength and flexural strength increased by 6.20% and 40.81% respectively.

(iii) Assessment of durability performances and Comparison of the structural responses of the two main specimens under the study, the control mix named S_0 and the LWC made with waste plastic pre-coated volcanic scoria aggregates at 5%, having 1% of NSF in the matrix named S_1. The results showed a better resistance to chloride penetration of S_1 mix specimens as compared to the control mix S_0. Three steel-reinforced beams of 150 x 200 x 1000 mm of each specimen were casted and tested under bending. S_1 beam specimens were found structurally more efficient than S_0 beam specimens. S_1 beams showed better ability to sustain more loads with higher failure strains. This was due to NSF which controlled cracks and acted as cracks arresters. S_1 beam specimens was found more ductile than S_0 beam specimens.

CHAPTER ONE

INTRODUCTION

1. Introduction

1.1 Background of the Study

Concrete is by far the world's most vital, versatile and common material used in modern construction, with around 10 km^3 (equivalent to 24 billion tons) used every year. Several reasons explain this popularity; amongst them, it can be engineered to satisfy a wide range of performance specifications; it is reliable, relatively low cost and it is strong. Furthermore, it is fire resistant, sound insulating and resistant to water and environmental extremes. Concrete is plastic and malleable when newly mixed, and becomes strong and durable when hardened. Basically, the production of the concrete consists of mixing of aggregates, cement, sand, and water in appropriate proportions (Edward & Nawy 2008). The cement enters into chemical reaction with the water and other ingredients to form a hard matrix that binds the materials together into a durable stone-like material that has many uses (Zongjin Li, 2011). Most concretes used are lime-based concretes such as Portland cement concrete or concretes made with other hydraulic cements.

Sometimes, the need of specific additives (such as pozzolans or superplasticizers) can be required in the mixture, in order to improve some physical properties of the wet mix or hardened concrete. Most of the time, depending on the use of the concrete designed, it is poured with reinforcing materials (such as rebars) embedded to provide tensile strength, and the resulting material is called reinforced concrete.

However, depending on the end use of the concrete and some specific requirements and constraints, we distinguish several types of concrete, called special concrete. Those special types of concretes can be defined as those with extraordinary properties, or as those concrete produced by non-common or unusual techniques, under specific constraints for specific needs. There are about twelve types of special concrete, including architectural concrete, self-compacting concrete, lightweight concrete, fiber concrete, and many others. Concrete is important to modern society; it has a wide range of areas of application. The domain and industries where concrete is used are diverse; from the construction of buildings and infrastructure, to agriculture, architecture, energy production and much more.

Aggregates (coarse and fine) usually contribute about 70 percent of concrete production (PCA, 2014). The other 30 percent is shared between two other components, water and cement. The figure of 70 percent for fine and coarse aggregates is a significant percentage and emphasizes the importance and significance of aggregates in concrete. Sand or gravel is widely used as aggregates largely due to its availability and ease of access. But, some specific projects under specific constraints may require some specific properties of the concrete to be used and then, determine the right choice of aggregate types to choose. When the aspects of the project require a specific type of concrete with reduced dead load, whether structural or nonstructural concrete, or require some insulation properties (thermal or sound insulation), lightweight concrete is a type indicated. The use of Lightweight concrete (LWC) has been investigated in the construction industry for centuries; like other materials, nowadays, the expectations of the performance have risen, expecting a consistent, reliable material and predictable characteristics (All about lightweight concrete, 2015).

However, there are several classifications of lightweight concrete, some depending on their method of production (lightweight aggregate concrete, aerated or cellular concrete, and No-fines concrete), or also depending on the purpose for which concrete is going to be used (structural lightweight concrete, concrete used in masonry units, insulating concrete).

However, lightweight aggregates concrete is the most traditional used, amongst them. It is made by lightweight aggregates either natural or artificial. It offers an efficient strength to weight ratio, improved thermal and fire rating insulating characteristics, leading to more durable structures; Many structure types have been developed long time ago using that concrete (buildings, bridges, even for rehabilitation purposes). Reduced dead load is one of the major advantages and not only does this result in a decrease in cross section of columns, beams, walls and foundations, but also a decrease in the induced seismic loads and hence a reduction in the risk of damages due to earthquakes on the structure (Libre, et al., 2011).

As defined by the British Standard, lightweight aggregates are "aggregates of mineral origin having particle densities not exceeding 2000 kg/m^3 or loose bulk densities not exceeding 1200 kg/m^3" (British Standards Institution, 2012). Lightweight aggregates used in certain projects obviously need to be strong enough to withstand stresses in structures and meet safety standards.

The key element on lightweight aggregate concrete used being the aggregate type used, several aggregates have been long found adequate. In a broad way, we usually distinguish the natural and artificial aggregates material. Although the availability of natural lightweight aggregates like pumice or volcanic scoria, the artificial ones have been long preferred and used for structural lightweight concrete production, instead.

Nevertheless, their production process requires a great amount of energy, when polluting the environment and then costly. From that point of view, it is obvious that the solutions based on the use of natural lightweight aggregates instead of artificial ones, would lead to great economic benefits because they are naturally available and don't any transformation.

Volcanic scoria as well as pumice, for instance, are a type of natural aggregates that can be used for the purpose. Thus, investigations in that area of using volcanic scoria as main aggregates to make structural lightweight concrete, becomes relevant.

Scoria is an igneous rock usually dark-colored. The composition of scoria usually is similar to basalt, or sometimes to andesite. Scoria is produced after volcanic eruption. This material can be found in many countries in Africa such as in Kenya, or in Cameroon, in large quantities.

This material, named as volcanic scoria, has several uses in various applications. Amongst them, it has been used to produce Portland Cement.

The use of scoria as aggregates to produce lightweight concrete has attracted the interest of many researchers. For instance, the question of the effects of the use of natural lightweight aggregates such as scoria for lightweight concrete production. It has been found to lead to reduced mechanical strengths (compression, tensile, modulus of elasticity), change in physical properties such as permeability, water absorption rate, and lower durability performance as compared to the traditional concrete. Those characteristics are attributed to the porous nature of concrete made and its lower density, due to the high porosity of scoria aggregates, low crushing strength and also low density.

When replacing traditional crushed stones aggregates by natural lightweight volcanic scoria in the concrete, the density of the concrete made has been found reduced by around 20% of the initial value (Yasar et al., 2003). The same observations have been noticed regarding the compressive strength, the tensile strength as well as the modulus of elasticity; (Hossain, 2006 & 2010), and (Kiliç et al., 2009) have established the loss of 30 to 45%, 7 to 58% and 21 to 42% of the compressive, tensile strength and modulus of elasticity respectively as compared to the plain crushed aggregates concrete.

Many authors attributed these reduced mechanical properties exhibited by LWC made with volcanic scoria aggregates to the porous nature of those aggregates. Their impact on the concrete was as a result of its water absorption capability and very good water retention characteristic; this means that a higher amount of mixing water was required thus leading to lower strength and durability performance. Higher shrinkage also constituted their major disadvantage amongst others.

Methods of strengthening the lightweight aggregates concrete have been proposed so that the prime drawback of strength could be overcome. Lightweight aggregates are being considered as substitutes for normal or heavyweight aggregates in casting of concrete. One of the major reasons behind this is to ensure that the resources available (natural) are managed wisely and sustainably, and for diverse applications of concrete. A number of methods have been established to improve the performance of the LWAC; amongst them was one which steel fibers was added to the LWC mixes using pumice stones as aggregates. However, this does not improve the actual pumice aggregates (Libre, et al., 2011). There are some more recent methods that have been tried to encounter this flaw of natural LWA like pumice or volcanic scoria or any other lightweight aggregates. One of these advices was to pre-coat them with a binder (with a specific material or a mixture of two or more components) that could possibly improve certain engineering properties of lightweight concrete. However, many of those pre-coating techniques developed were in road construction, with the aim of improving either the normal aggregates or some alternatives aggregates (recycle aggregates, or bricks stones), mostly with cement mortar paste, or bitumen material and recently with waste plastic material. The pre-coating material selected in this case is waste plastic material. This is for two reasons. Firstly, the pre-coating technique with that specific material has never been investigated for lightweight concrete production, through its effect on volcanic scoria aggregates. This can lead to good results, according to similar studies carried out in road construction, using plastic as pre-coating material, applied over bricks stones for instance. And secondly, because waste plastic is an environmental disease creating several issues related to health problems, and ecosystem disturbance, through soil and ground water contamination

The 20th century is mainly characterized by use of a larger amount of plastic (Ong’unya Raphael Odhiambo et al., 2014). Till these days, we unfortunately find this material as almost an inescapable material used in our day-to-day life. This can be justified by its low cost, its durability, its lightweight, its practicability because it can have various applications carrying liquid or solid materials. Nevertheless, it is noticed that, all those factors that make it so useful, also make it so problematic after use, especially because of its non-biodegradable nature.

Some sources reported that in the African continent, problems related to the usage of those plastic bags is really more critical. This is because of the important production added to the bad usage, further make worse by the poor waste management plans throughout the continent and recycling programs that are inexistent or ineffective.

Kenya is not isolated from that fact. The monthly average amount of plastic paper bags used in the country is around 24 millions, and unfortunately there are almost no regulations for the efficient management of those plastic paper bags after their brief use when they reach the stage of solid waste. However, those waste plastic bags are very dangerous because of their non-bio degradable nature, affecting our environment stability by menacing the health of the animals when they ingest them, also by contaminating soils, then affecting also our health as human beings (Ong'unya Raphael Odhiambo et al., 2014). Amongst the several causes facilitating the evolution of the problem, we can target some factors contributing to worsen the problem; the populations, the industries, companies, stores, supermarkets, and the weak government politics in dealing with the issue. Plastics are just released to the consumers, without any management plan to address the issue of the after use.

In that way, the use of those waste plastic as a pre-coating material to improve the physical and mechanical properties of scoria aggregates could make them a good alternative solution to common artificial lightweight aggregates for producing lightweight concrete. It shall also assist in the waste plastic disposal, contributing to the government's policies in the management of those waste through various recycling industries. In that sense, the investigation on the use of this waste plastic will be of a great importance and innovative. In fact, the investigations will clarify whether the waste plastic as pre-coating material on scoria, will have positive effects. Also, the required proportions or content of plastics to be used on aggregates so as to give improved results in concrete shall be established. Cost benefits and environment safety will be the direct outputs. This is through the valorization of those almost waste volcanic scoria, available, renewable and cheaper than commonly used artificial ones for lightweight concrete production purposes, when helping in the waste plastic disposal management.

The waste plastic can be used to pre-coat the scoria aggregates in a hot mix process, where the aggregates will be first heated at around 190°C. Thereafter, shredded plastic added. They will form a shell on aggregates, when filling up the pores.

The fibers has long been used to improve some properties of the normal concrete. Modern life is usually characterized by constructions where the Portland cement concrete is commonly used. However, this material is brittle. That means amongst other characteristics, it exhibits brittle failure (failure is sudden, and no plastic deformations are observed before it). It shows a very low tensile strength, a limited ductility and low resistance to cracking. In general, its low tensile strength is due the existence of internal micro cracks which when propagate leading to brittle fracture of the concrete. In brittle materials like plain concrete, there are existence of structural cracks, which evolve even when loadings are not yet applied; this is due to several causes amongst drying shrinkage. More internal cracks occur, develop, open up and propagate when the plain concrete is then subjected to loadings due to resulting internal stresses.

We attribute the inelastic deformations in concrete to the development of these cracks. From that point of view, some researchers propose addition of small closely spaced and uniformly dispersed fibers in the concrete to act as crack arresters and improves its static and dynamic properties, and that has been proved. This has resulted to what is called fiber reinforced concrete, or concrete containing fibrous materials which increases its structural performance (Saandeepani Vajje & N.R.Krishna murthy (2013). It is made by concrete constituted with short discrete fibers that are uniformly distributed in the mix and randomly oriented. In general, we distinguish five types of fibers used in concrete, steel, glass, polymeric (polypropylene, polyethylene, polyester, amarid), natural (Sisal, bamboo, jute) and mineral fibers (asbestos, carbon). It is recognized that addition of fibers in general, can increase strength (increase in the toughness, tensile strength, Compressive strength, Flexural strength, impact strength); an improvement in the cracking and deformation characteristics of the resultant concrete is also noticed, since there is plastic shrinkage and drying shrinkage reduction, due to the fact that cracks cannot propagate more.

The problem of low tensile strength of concrete, has led to the development of steel reinforcement, but, unfortunately, it doesn’t constitute the ultimate solution to the problem of micro cracks due to drying and plastic shrinkage, owing to weathering conditions (Saandeepani Vajje, Dr. N.R.Krishna murthy, 2013). In a real-life structures, the tensile load is transferred from the concrete to the steel. Then, one can state that an alternative to increase the load carrying capacity of concrete in tension is by addition of fibers (Saandeepani Vajje & N.R.Krishna murthy (2013).

This led to the importance of carrying out researches on various fibers as reinforcement in concrete production. Addition of steel fibers has been investigated and has shown reduction of the micro cracks. However, over a long period, steel gets corroded due to various actions. It resulted in the need to investigate also the usage of various available natural fibers which are more eco-friendly and economic. It is in that context that the use of sisal fibers finds its application as natural organic fibers also called vegetable fibers, with the advantages that they are very much renewable, available, eco-friendly, economical and the production cost is also very low such as in Kenya.

Hence study on the effects of vegetable fibers as reinforcements on the pre-coated volcanic scoria aggregates lightweight concrete, was carried out in this work. The objectives are to come out with the effects of both natural sisal fibers and wasted plastic pre-coated volcanic scoria aggregates on the scoria lightweight concrete properties.

1.2 Statement of the Problem

The engineering properties of concrete produced mostly depends on the quality of the aggregates and cement paste which is also related to water cement ratio. The selection of aggregates is thus critical since it constitutes one of the major criteria that can be used to differentiate types of concrete, due to their qualities, strengths, characteristics and properties. It is in that way that lined lightweight concrete, mainly according to the properties of aggregates used which are of low density. It can offer a good strength to weight ratio, and costs savings due to smaller sizes of structural elements, and facilitations during the construction process, amongst many other advantages discussed earlier.

Despite the availability of natural lightweight aggregates like volcanic scoria in our environment, most of people define structural lightweight concrete as the one made using artificial lightweight aggregates like expanded clays and shales, for which, porous structure has been obtained through heating them in a rotary kiln at high temperatures in order for them to be light. However, the production of those aggregates has several negative repercussions on the environment due to the high CO_2 produced. It is also associated to large amounts of natural resources expenditures, high energy consumptions during the manufacturing process and high costs. From the above, it is obvious that the use of natural lightweight aggregates for lightweight concrete production instead of artificial ones, will be more economic, and environmentally friendly. This explains the need to investigate the use of natural volcanic scoria aggregates for lightweight concrete manufacturing. Natural volcanic scoria is available in our environment, and can be suitable as aggregates for LWC production due to its porous nature and low density.

However, some studies reported their non-suitability to produce structural lightweight concrete with strengths comparable to the ones made with artificial aggregates or with normal weight aggregates. They attributed that weakness to their high porosity. Those strengths reductions have been discussed previously in the background of the study, when the normal weight aggregates were replaced by volcanic scoria. Therefore, since their high degree of porosity constitute their major drawback, responsible for the weaknesses of the lightweight scoria concrete, an attempt to reduce that porosity should be addressed. Thus, applying a pre-coating material on those aggregates can lead us to the point, in order to finally make them as real competitive alternative aggregates to artificial ones for structural lightweight concrete production. This investigation should be done.

This idea of pre-coating of aggregates have been long investigated mostly in the area of road construction, using different special pre-coating materials for the purpose. Most of those materials of interest were cementitious materials like Portland cement or mortar paste, and asphalt for the purpose. The main aim was usually to either deal with dust or any other organic material on the aggregates before using them in the bituminous concrete. The objective was to increase the bonding of those aggregates with the bitumen, or sometimes to reduce the porosity of alternative aggregates such as recycle aggregates, aiming to improve the physical and mechanical properties of bituminous concrete made.

Only very few investigations have been done on the use of waste plastic as pre-coating material in the area of road construction and never in the area of lightweight aggregates concrete production (Sarkar, Pal, & Sarkar, 2016). Investigations for instance on the influence of waste plastic as pre-coating material over natural scoria lightweight aggregates in order to reduce their pores, their absorption capability in concrete with the aim to check whether they are suitable as aggregates to produce improved structural lightweight concrete, have never been done. In that line, applying waste plastic to pre-coat the volcanic aggregates has two benefits. Firstly, plastic can improve their physical performances in terms of water absorption, apparent density and crushing strength value. This will make them suitable alternative aggregates to artificial ones for producing stronger structural lightweight aggregates concrete. Secondly, the environment safety guaranteed through waste plastic disposal has an economic benefit. The basic objective here is to utilize the "waste" volcanic scoria as well as the waste plastic in an ecofriendly way. The use of plastic in the concrete will really contribute to the waste plastic's management strategy politics of the country as an alternative of recycling it.

The demand curve of concrete is rising at an increasing rate all around the world. This is due to the development of infrastructures and construction activities. However, it cannot be without consequences. Amongst them, we can cite some relevant, like extensive extraction of aggregates from natural resources, leading to its depletion every more again, and cause ecological imbalance. The basic ideas or objectives of researchers in that sense, is to use agricultural and industrial waste to investigate whether they can be used to improve the strength properties of concrete, and save the environment, leading to sustainable development. This environmental issue has generated a lot of concerns in the construction world. In that context, the use of natural fibers, as reinforcements of concrete has recently captivated the curiosity of several researchers, mainly because of their advantages over other traditional established materials. Natural fibers are environmentally friendly, biodegradable, sufficiently available, with low cost and relatively high strength, renewable, and are of low density. They are found lighter than glass and carbon fibers. Many researchers have found that the addition of these fibers in normal plain concrete, can increase strengths (tensile strength, flexural strength, toughness, impact resistance), also reduce plastic and drying shrinkage by arresting the propagation of cracks, and improve the durability performance through stabilization of those micro cracks, and thus reduce the permeability.

From that observation, with the availability of sisal fibers in Africa and particularly in Kenya, and knowing the lower strengths, lower durability performance, brittle nature and higher shrinkage exhibited by natural scoria lightweight aggregates concrete as compared to plain normal weight concrete, we had the right to think that the addition of natural sisal fibers as reinforcements of the matrix could really be useful in improving those performances in the resulting lightweight concrete produced. Again, added to the pre-coating technique developed with waste plastic over the aggregates, both the effects can lead to a competitive structural lightweight concrete. This investigation should be carried out.

Finally, it will be of great importance to analyze the structural responses of the new lightweight concrete material developed and compare to that of the traditional lightweight aggregates concrete made with uncoated scoria aggregates and without fibers in the matrix. Several important parameters should be analyzed such as the first crack and failure load, the failure mode and crack patterns, the mid-span deflections, the ultimate moments and curvatures, the flexural stress-strain behaviors, the concrete stress-strain distributions (compressive stress-stain distributions, principal stress-strain distributions, shear stress-strains distributions) and steel strains distribution (load-tensile steel strain distribution, load-steel compressive strain distribution).

1.3 Objectives

1.3.1 General Objective

The main objective of this research is to study the structural performance of the SLWC made with waste plastic pre-coated volcanic scoria aggregates having sisal fibers as reinforcements of the matrix and compare to the performance of the traditional LWC with natural uncoated volcanic scoria aggregates and without fibers in the matrix.

1.3.2 Specific Objectives

1- To investigate the effects of waste plastic as surface texture over the volcanic scoria aggregates, on the physical and mechanical properties of LWC.

2- To determine the influence of natural sisal fibers as additive on the physical and strength properties of LWC made with waste plastic pre-coated volcanic scoria aggregates.

3- To assess the durability performance of the lightweight concrete specimens.

4- To compare the structural responses of two categories of steel reinforced concrete beams each made with each LWC specimen; the LWC specimen made with waste plastic pre-coated volcanic scoria aggregates containing sisal fibers as reinforcements of the matrix, and the control specimen made with traditional LWC with raw uncoated volcanic scoria aggregates, having no fibers.

1.4 Research Questions

1. What are the effects of the use of waste plastic as pre-coating material over the volcanic scoria aggregates, on the physical and mechanical properties of LWC made?
2. What is the influence of natural sisal fibers on the physical and strength properties of LWC made with waste plastic pre-coated volcanic scoria aggregates?
3. What is the durability performance of the new concrete material developed?
4. How are the structural responses of the new lightweight concrete, as compared to the control concrete?

1.5 Justification

The investigation finds its sense and its great importance in several points. Firstly, the study will be about how to use natural lightweight aggregates for instance volcanic scoria, for structural concrete making purposes instead of artificial lightweight aggregates commonly used, like expanded slag and shale, known to be related to environmental issues with the emission of CO_2 , and to large energy consuming during the manufacturing process, then costly. The use of volcanic scoria which are available, will be an economical alternative to lightweight aggregates for structural lightweight concrete production. Secondly, waste plastic is the selected material used to pre-coat those aggregates. We know the negatives effects of those waste plastics in our environment which are related to health problems and ecosystem disturbance, through soil and ground water contamination. So, if ever the investigation justifies its use as good pre-coating material, it will be a great advancement as a positive contribution to the waste plastic recycling politics and waste plastic disposal from the environment.

Thirdly, the use of natural sisal fibers, would lead to costs benefits and sustainable development, because of the low cost of available fibers and they are renewable; it will result also a lower consumption of energy, and lower emission rate of CO_2, one of the several causes of ecosystem disturbance. Added to this, fibers would be benefic to be used as reinforcements in concrete to overcome some of its drawbacks as low tensile strength, limited ductility, low resistance to cracking as it is established in ordinary concrete, and higher shrinkage value usually exhibited by lightweight concrete. The study is an attempt to investigate the effects of these natural fibers on the waste plastic pre-coated volcanic scoria lightweight concrete properties regarding the strengths (tensile strength, compressive strength, flexural strength), the cracking and deformation characteristics, the ductility of the resultant lightweight concrete. It is in that context that the use of sisal fibers finds its application as natural organic fibers, with the advantages that they are very much renewable, available, eco-friendly, economic and their production cost is also very low in Kenya, compared to others like steel fibers.

Finally, the analysis of the structural responses of both the LWC made with waste plastic pre-coated scoria aggregates with sisal fibers in the matrix, and the LWC made with uncoated scoria aggregates having no fibers (control), is of great importance to understand deeply the behaviors of the materials in real life situations when used in constructions. For the purpose models beams will be casted and tested under four-point load bending.

1.6 Scope

The main scope of this study is to emphasize the use of natural volcanic scoria as aggregates to make structural lightweight concrete, with the use sisal fibers as reinforcement of the matrix. This will be achieved through the pre-coating of those aggregates with waste plastic material, as an attempt to overcome its major drawback of the high degree of porosity and high water absorption and make them suitable as good competitive alternative aggregates to artificial aggregates such as expanded clay and shales, commonly used for the purpose. This will contribute to waste plastic disposal from our environment, which is leading to several problems, attaining our health and ecosystem disturbance. Various tests will be conducted throughout the study, regarding physical and mechanical properties, as well as durability performance. Finally, construction of model beams made with the material specimens under study in the laboratory, and tested under four point loads bending, is one of our important targets. It will help to analyze deeply the structural responses of the materials.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical Review

Depending on the end use of the concrete and some specific requirements and constraints, various types of concrete called special concrete can be distinguished. Those special types of concretes can be defined as those with special properties, produced using unusual techniques, under specific constraints for specific needs. There are about twelve types of special concrete, including lightweight concrete as discussed deeply earlier. The use of lightweight concrete finds its importance when one seeks to have a good strength to weight ratio, amongst many other characteristics, including insulating properties. Lightweight concrete has a wide range of applications areas.

2.1.1 Lightweight concrete

Various types of lightweight concrete, depending on the use or the purpose of the concrete, and also depending on the method of production are classified as follows:

- *<u>Depending on the purpose of the concrete made, we have</u>*:

i. *Low density concrete*, with low unit weight, at no more than 800 kg/m³, for insulation purposes, heat insulation value is high. Whereas Compressive strength are low, from about 0.69 to 6.89 N/mm2.

ii. *Moderate strength concrete*, this class of concrete, is defined by a fair degree of compressive strength, and thus are situated about midway between the structural and low density concrete. Their Compressive strength are approximately 6.89 to 17.24 N/mm² and insulation values are intermediate.

iii. *Structural concrete*; this concrete with full structural efficiency are made generally with expanded shales, clay, slates materials, for which the pores have been created through heating them in a rotary kiln at higher temperatures, slag and fly-ash. The minimum compressive strength of these concrete is generally about more than 17.24 N/mm². The have insulation efficiency lower than those of low density concrete, since their unit weight are considerably greater. However, thermal insulation values for structural LWC are substantially better than Normal weight concrete (NWC).

- *Depending on the method of production:*

i. *Aerated, cellular, foamed or gas concrete;* this can be defined as a lightweight, cellular material consisting of cement or lime or both together, and sand or other siliceous material. This type has the lowest density, thermal conductivity and strength. It is manufactured trough processes which can be either physical or chemical during which either air or gas is introduced into a slurry, which currently doesn't contain coarse material. Generally, for in situ works, the usual methods of aeration are by mixing in stabilized foam or by whipping air in with the help of an air entraining agent.

ii. *No-fines concrete;* No-fines concretes are concrete composed of cement and a coarse (9-19mm) aggregate only (at least 95 percent should pass the 20 mm BS sieve, not more than 10 percent should pass the 10 mm BS sieve and nothing should pass the 5 mm BS sieve), that results many voids distributed randomly inside the concrete mass. The density is about two-third to three quarters that of normal weight concrete produced with the same type of aggregates. Because of those large pores within the body of the mass concrete, it exhibits low strength, but because they are large in size, there is no capillary movement of water that can take place.

iii. *Lightweight aggregate concrete;* This class of lightweight concrete is usually obtained by using porous lightweight aggregate i.e. characterized with low apparent specific gravity (lower than 2.6). This is mainly produced through the development and production of new types of artificial lightweight aggregates (LWA), then made it possible to introduce structural lightweight concrete of high strength, suitable for structural work.

However, there are also several types of lightweight Aggregates (LWA) suitable for the production:

i. *Pumice, or volcanic scoria*; generally used for reinforced concrete roof slab, mainly for industrial roofs~~.~~

ii. *Foamed Slag*; was the first LWA suitable for reinforced concrete that was produced in large quantity in UK.

iii. *Expanded Clays and Shales*; capable of achieving sufficiently high strength for prestressed concrete. Well established under the trade names of Aglite and Leca (UK), Haydite, Rocklite, Gravelite and Aglite (USA).

iv. *Sintered Pulverised*, also known as *fuel ash aggregate*, it is being used in the UK for a variety of structural purposes and is being marketed under the trade name Lytag.

2.1.2 Waste plastics

According to a research conducted by the Environmental Protection Agency, between five hundred billion and one trillion disposable bags are used each year around the world (Ong'unya Raphael Odhiambo et al., 2014). Plastic bags, which are normally used for an average of about twelve minutes, remain in landfills, oceans and other places for thousands of years. The problem with plastic bag usage on the African continent is further aggravated by inexistent or ineffective waste management plans. Modern life in our societies nowadays is unthinkable without the use of plastic. Since the beginning of the 20th century, the use of plastic has turned to be inescapable material. Unfortunately, because of the drawbacks of those plastic on the environment, plastic is supposed to be seen as a critical disease for the environment. It is then recognized that what makes plastic so useful, and so popular such as its durability, lightweight and low cost, also makes it problematic when it comes to its end of life phase, due to its non-biodegradable nature. All around the African continent, as well in Kenya, the issue of waste plastic pollution is one of the biggest environmental concern to deal with, as explained earlier. To some extent, the issues of climate change, are related to waste plastic bags, in a variety of ways. It affects air quality, responsible for ocean toxicity; plastic bags contribute to eco-system disruption. It is also proved that, plastic is poisonous, which is even the worse side of its use. Plastic is made with some dangerous ingredients such as biosphenol-A and Phthalates, that have been proved to cause cancer, birth defects, impaired immunity, endocrine disruption and other ailments. Wildlife cannot be forgotten, for which the equilibrium is threatened by plastic; and also, plastic is a great pollutant of groundwater (Ong'unya Raphael Odhiambo et al., 2014). According to the International Association of Hydrological Sciences, cases of groundwater pollution due to landfills have been reported worldwide, and toxic leachates from landfills are among the major groundwater quality risks. Some few years ago, many comprehensive plastic waste management strategies for Nairobi the capital city of Kenya have been developed. Nothing much has been done and now, plastic waste is no longer an urban issue, it is an environmental problem throughout the country.

There are globally 7 classes of plastic depending on their chemical components and contents, and their use. They are ranged from class one to class seven. They are most of them synthetic and usually issued from petrochemicals processes.

i. *Class 1*: constitute plastics mainly made of Polyethylene Terephthalate (PET). This class of plastic is ordinarily used in current life in the form of medicine jars, combs, and beverage bottles.
ii. *Class 2*: constitute plastics mainly made of High-density Polyethylene (HDPE). This class of plastic is the one used in our day to day life in the form of some package for milk, containers of motor oil.
iii. *Class 3*: this class of plastic constitute the one mainly made of polyvinyl chloride (PVC). In our day to day life, we use them as pipes in plumbing for instance.
iv. *Class 4*: constitute plastics mainly made of Low density polyethylene (LDPE). They are using in current life mostly in the form of pastry bags, plastic cling package, water bottles.
v. *Class 5*: constitute the class of plastic mainly made of polypropylene (PP); they usually used in the form of some specific medicine bottles, or cups.
vi. *Class 6*: for this class, the main component is polystyrene (PS). They are generally in the form of disposable containers or packaging.
vii. *Class 7*: is the class of plastic mainly made of polycarbonate (PC) and polylactide.

However, the one that we used in this study was waste plastic carry bags type; it is basically the type of plastic belonging to class 1 and 5. Polyethylene (PE) and Polypropylene (PP) are the dominant components of this type of plastic and it is the most common used around the world. This type of plastic is known for some good specific properties as, good wear resistance as well as fatigue and impact resistance, high tensile strength, and low moisture absorption characteristic.

2.1.3 Characterization of sisal fibers

- ***General***

There are several types of natural fibers used for a wide range of applications. In this study, sisal fibers originated from a plant called Agave Sisalana was used. These natural fibers which are yellow in nature, after extracting, exhibit very interesting properties regarding its use as reinforcement in a cementitious composite. Amongst those properties are, relatively high strength, stretch and durability capabilities (Ali, 2012). Length of sisal fibers naturally range between 45 cm to 160 cm. Sisal fibers are locally available in Kenya, in a clean and dried state, in the various forms: cords, strips, rolls and wires. Basically, lignin and hemicelluloses are the two main components of sisal fibers.

According to (Sen & Reddy, 2011), some properties of fibers are as below:

Table 2.1: Some properties of sisal fibers

Specific gravity (Kg/m^3)	1370
Elasticity modulus (Mpa)	15x10^3
Water absorption capability (%)	110
Strength (in tension) (Gpa)	0.347-0.378

- ***Various properties of sisal fibers***

According to (Sathish & Murugesh, 2016) fibers have the following properties;

i. Sisal fibers lie in the category of strong and durable natural fibers
ii. Do not require much maintenance when used in various applications.
iii. Exhibit good wear resistance
iv. Are naturally occurring, available and then recyclable.
v. Have low water absorption capability.
vi. Have low moisture absorption and less moisture content.
vii. Are defined as Anti-static; they do not retain dust particles.
viii. Sound insulating properties
ix. Show good impact resistance when used in composite materials.
x. Can be treated by special chemicals to have better fire resistance.

- ***Chemical composition***

The basic chemical components of sisal fibers according to the (Sathish & Murugesh, 2016) are shown in Table 2.2

Table 2.2: basic chemical components of sisal fibers

Chemical components	**Content (%)**
Lignin	9.9
Cellulose	65
Waxes	2
Hemicellulose	12

Plate 2.1: Sisal fibers

2.1.4 Characterization of volcanic scoria

Scoria is an igneous rock usually dark-colored, obtained after volcanic eruption. The small pieces or particles of scoria basically look like the ash yielded in a coal furnace. The composition of scoria is usually similar to basalt, or sometimes to andesite. This material can be found in large quantities in many countries in Africa such as Kenya and Cameroon. Volcanic scoria lightweight aggregate concrete is expected to show a better strength to weight ratio due to the reduced dead load as compared to normal weight aggregates concrete. It is also expected to have less thermal conductivity as well as better sound and fire rating insulation characteristics due to its porous nature and lower density.

2.2 Experimental Background

2.2.1 Use of volcanic scoria for Lightweight concrete

Several studies have investigated on the use of volcanic scoria, mainly for its suitability to be used as lightweight aggregates for structural lightweight concrete production. According to (Hossain, 2006), apart from its suitability that was established to be used as lightweight aggregates for lightweight concrete production, it can also be used as a cement additive, in the form of ground scoria. The same study also shows that volcanic scoria is a good material for heat insulation according to ASTM requirements. Due to its good heat insulation characteristic, saving energy can be obtained through its use in building construction. For the purpose of assessing the potential use of volcanic scoria as both fine and coarse aggregates in lightweight concrete, several tests have been performed regarding the strength, air content, the density, water absorption, workability, drying shrinkage. The oven dry density found in the range of 560 to 1120 Kg/m^3, made volcanic scoria a suitable lightweight aggregate for structural lightweight concrete production (Hossain, 2006). Pertaining the properties of fresh lightweight concrete, the study found that the increase of volcanic scoria content as percentage replacement of Crushed gravel aggregates by volume while maintaining the same water cement ratio at 0.45, the slump values decrease from 82 mm to 64 mm. This is due to the low weight of the aggregates and then of the concrete, that reduced the slump value as compared to the normal aggregates. The particles don't settle as much as normal aggregates according to the gravity law. So even with the same workability, the normal weight aggregates exhibits higher values of slump as compared to the lightweight concrete (Hossain, 2006). According to the author, regarding the strength of concrete, it is noticed that when increasing volcanic scoria aggregates content as replacements of normal weight aggregates by volume, the strength decreases. For instance, the replacement of crushed gravel from 0% to 100% with volcanic scoria, the cube strength decreases from 40 to 28 MPa. The same observation was done regarding the density of the concrete made which decreases when increasing the volcanic scoria content. (Hossain, 2006) found that the resulting lightweight concrete made was 25% lighter than the control (made with normal weight aggregates) at 100% of replacement of the crushed aggregates gravel by volcanic scoria. The dry density was found less than 1842 kg/m^3, satisfying the criteria density for structural lightweight concrete according to ASTM C330 (maximum air dry density of concrete 1842 kg/m^3, and 17.2 MPa as minimum cylinder compressive strength at 28 days).

The study also explained that high water absorption of scoria was linked to its high porosity which finally led to the low strength of volcanic scoria aggregates concrete.

According to (Hossain, 2006), drying shrinkage is also of a great of importance to check, when it comes to the use of Lightweight aggregates in concrete. The study found that, the drying shrinkage increases with the content of volcanic scoria and with the time. The research study came out with an increase of drying shrinkage when using 100% of volcanic scoria aggregates in concrete, of about approximately 27% higher than the control made without volcanic scoria (with Normal Crushed gravel aggregates), after a period of 3 months. It exhibited around 578 micro strains in comparison to that of 450 for the control concrete. However, it was still satisfying the criteria of less than 700 microstrains according to the ASTM C330 Standard. That finding was in line with (Neville, 1995) who stated that higher drying shrinkage was related to higher absorption rate of the aggregates which depends on its degree of porosity. The drying shrinkage strongly depending on the water cement ratio, increases in the presence of volcanic scoria because of their porous nature requiring more mixing water in the mix. The study has also investigated the permeability performance of the concrete made. It has been found that samples with 100% of volcanic scoria as aggregates showed a higher permeability than the control mixes with only crushed gravel aggregates, at around 3.5 times higher (Hossain, 2010). This high permeability is one of the major drawback of lightweight concrete made with volcanic scoria. In fact, in long term, it can be associated to several problems in structures as corrosion of reinforcements affecting the durability of the structure.

From a critical point of view made from this study, it is clearly established that the use of volcanic scoria as aggregates in concrete has some drawbacks or limits. This includes, the high porosity of those aggregates linked to their high potential to absorb higher amount of water in the mix, the higher permeability with corrosion risks of reinforcements during the life of the structure and the problems of drying shrinkage that leads to strength's reduction of the concrete. So, it will be beneficial to develop a proper coating technique for those aggregates to overcome the problem of high absorption and permeability, and establish an internal reinforcement of the matrix by using fibers to reduce the shrinkage so as to improve the strength of LWC.

According to (Moufti et al., 2000), volcanic scoria has been assessed for their potential industrial utilization. For the authors when using them in concrete as coarse and fine aggregates, the lightweight concrete satisfied the ASTM requirements as structural lightweight concrete (strength and density). In the study, silica fume was added to the mixes, to increase the strength while reducing the permeability. The study also assessed their potential as a cement additive and as a heat insulating material. The results were found to be acceptable, according to ASTM standard (1995). The study suggested their used for producing building blocks.

According to Bogas & Gomes (2015), who worked on mechanical and durability behavior of structural lightweight concrete made with volcanic scoria aggregates, it was established that as compared to the concrete made with Normal weight aggregates (NWA), all the mechanical and physical properties grow worse with the use of natural lightweight aggregates (LWSA) (compressive and tensile strengths, shrinkage, capillarity absorption). It was established that when using natural lightweight scoria aggregates, the lightweight concrete made can only attain strength up to 35 MPa Bogas & Gomes (2015). The study established that the shrinkage was higher when using the scoria aggregates as compared to the normal weight aggregates. Shrinkage was also greater when coarse and fine aggregates used were scoria aggregates. The chloride and carbonization resistance, as well as the capillarity absorption of lightweight concrete made with volcanic scoria were greatly affected by their high porosity. As an attempt to explain those lower performances of the lightweight concrete made with scoria, the authors said it was because of the absence of an outer shell on volcanic scoria aggregates and the surface effects when using them in concrete.

Chandra & Berntsson (2003) established that, using volcanic scoria as aggregates in concrete, led to higher shrinkage than normal weight aggregates concrete, and this can be the result of higher deformability and high absorption capacity of volcanic scoria aggregates. Similar studies which with pumice aggregates stated that concrete made with lightweight aggregates exhibits an increase of the permeability to up to 136%, as compared to the normal weight aggregates concrete even in the case of similar concrete in terms of strength.

According to Bogas & J.A, (2011), the durability of lightweight concrete is more affected by the lightweight aggregates types, and enhanced with higher porous nature of paste and also less dense outer shell of lightweight aggregates. According to Al-Khaiat & Haque (1999), higher porosity of concrete made with lightweight aggregates like scoria or pumice, contributes to lower the resistance to carbonation, especially when lightweight fine aggregates replace natural sand in the concrete for instance. (Assas, 2012) also reported that using pumice fine aggregates exhibit higher chloride penetration. When using 75% of natural and 25% of pumice in the concrete, the author found the reduction of 81% of chloride penetration for instance.

(Abubakar et al., 2017) were interested in determination of effects of using coarse volcanic scoria aggregates as partial replacement of normal coarse weight aggregates, on the mechanical and physical properties of concrete made, especially in terms of water absorption, splitting tensile strength, flexural strength and dry density. It has been shown that using coarse volcanic scoria at 100% replacement of normal coarse aggregates in concrete is in line with ASTM C330 and ACI 211.2 requirements for structural lightweight concrete. Authors reported an increase of water absorption with a peak value of about 10.20%, at 100% of replacement. Also, when replacing the normal weight coarse aggregates from 0% to 100% with lightweight coarse scoria, the density was found to reduce from 2584 Kg/m^3 to 1870.9 Kg/m^3. Splitting tensile strength also was found to reduce from 2.32 N/mm^2 to 0.74 N/mm^2 after 28 days. The same trend was observed regarding the flexural strength but with a peak value of 4.55 N/mm^2 at 10% of replacement.

2.2.2 Pre-coating techniques on aggregates

A proper analysis from all those studies, led us to one main point. Structural lightweight concrete can be obtained through the use of volcanic scoria. However, the high porosity of those aggregates is one of their major drawback or limitation in concrete. It leads to higher water absorption in the concrete, which is linked to higher drying shrinkage, reduced strength of the concrete, and higher permeability of the lightweight concrete with corrosion risks of reinforcements in real life structures. Finally it led to lower durability performance (shown through lower carbonation and chloride penetration resistance carried out in some studies).

(Sarkar et al., 2016) tried to explain the reason behind this lower performance of the lightweight concrete made with scoria. For them, it is because of the absence of an outer shell in volcanic scoria aggregates and the surface effects when using them in concrete.

Considering the situation, there is need to develop a proper coating technique for those aggregates to overcome the problem of high water absorption and permeability. It will be beneficial to improve the strength, the shrinkage and the durability performance.

Studies have been done previously on pre-coating techniques over recycles aggregates, or over many alternative aggregate's materials used in road construction, for instance Over burnt Brick Aggregates. Most of the studies done in pre-coating techniques, are in that area of road construction, with the use of plastic paper, cementitious materials as asphalt, Portland cement with different water cement ratios, sulfoaluminate cement, combined with other available cement such as fly ash (FA), silica fume (SF) or ground granulated blast slag (GGBS). In general, it was found that pre-coating techniques exhibit good results, through improvement of the physical properties of the aggregates and then leading to improve the matrix made (either bituminous and Portland cement concrete), in terms of strength and durability performance.

Plastic as pre-coating material has never been investigated to improve the properties of natural lightweight volcanic scoria, for reducing its high porosity and water absorption capability. However, plastic has been used in the area bituminous concrete road construction with various applications. One of the recent study was to pre-coat over burnt bricks aggregates (OBBA) with waste plastic in order to reduce its porosity, and therefore improve the physical and mechanical properties of the bituminous concrete made.

(Sarkar et al., 2016) investigated the use of waste plastic bags to pre-coat Over Burnt Brick Aggregates (OBBA) in order to make them a real alternative aggregates to natural stones aggregates becoming scarce for Bituminous Road Construction. It has been found that plastic coated OBBA is suitable as aggregates in the area of bituminous concrete for road construction. The properties of plain Over Burnt Brick Aggregate (OBBA) are weaker as compared to natural stone aggregates. It has lower specific gravity, lower impact and crushing resistance, with high pore rate, thus exhibiting high water absorption. This explains why the mechanical properties of bituminous concrete with plain OBBA are usually less than those of bituminous concrete with natural stone aggregate (Sarkar et al., 2016). So, for them to be as efficient as usual stones aggregates, the authors thought of pre-coating them by waste plastic in order to improve their properties before using them in concrete. For the purpose of the investigation, Shredded waste plastics were mixed with OBBA in different ratio of the weight of brick aggregates, in a hot mix process. The results showed great improvement in various mechanical properties (stability, stiffness, moisture damage, indirect tensile strength, fatigue) of the bituminous concrete mix as compared to the plain OBBA bituminous concrete mix. The best result was obtained at 0.54% of waste plastic pre-coated over burnt bricks. The basic idea behind the process that explained the improvement was that, when a thin plastic comes in contact with a hot aggregate, it filled up the pores in the aggregate and forms a thin film of plastic coating or a sort of shell or coating cover on the surface of the aggregate. Plastic coated OBBA becomes less porous and thus reduces water absorption to a great extent.

Another recent similar study has been conducted as regards to how to improve the properties of these OBBA to produce improved bituminous concrete, but this time by pre-coating them with a cement paste. D. Sarkar & M. Pal (2016) showed that at 4% of cement paste as coating material on OBBA, the resulting bituminous concrete was better as regard to various mechanical properties of the resulting bituminous concrete made

Similarly, (Lee et al., 2012) carried out a research to assess the effects of pre-coated recycled aggregates, on the properties of hot mix asphalt, and got improved properties. (Zhihui et al., 2013), performed on recycled aggregate (RA) and showed that RA had poor characteristics due to its porous structure, thus high water absorption and low crush resistance attributed to the presence of porous mortar, as well as the tiny seams derived from crushing process resulting in a decline of workability, strength and durability of recycled aggregates concrete. In that study, the surface structure of recycled aggregate was modified with several kinds of paste used to pre-coat the recycled aggregates (Portland cement paste at different percentages of water cement ratio, Sulfoaluminate cement paste with and without mineral additives such as Silica Fume (SF), Fly Ash (FA) and ground granulated blast slag (GGBS) at different percentages of water cement ratio). The study globally showed that this technique improves the physical performance of recycled aggregates in terms of water absorption, apparent density, crushing value. Also, exhibits improved recycled aggregates concrete as regards to the strengths and the durability resistance. It has been concluded that higher physical performance is achieved at 0.8 of water to cement ratio of the cement paste, corresponding to 0.035 mm of paste thickness. Durability performance has been found also enhanced.

Punith & Veeragaran (2004) and Awwad & Shbeeb (2007) have carried out several experimental works aiming to improve the bitumen properties using plastic, and through applying them as coating material on stone aggregates in the area of road pavement. Positive results as regards to mechanical properties (stability, indirect tensile strength, moisture damage, improved by the plastic) were obtained.

There are other similar pre-coating techniques developed aiming to coat aggregates using different coating material, like slag cement paste. (Lee et al.,2012) have investigated the use of slag cement paste to pre-coat the recycle concrete aggregates (PRCA), for pavement construction. Since the recycle concrete aggregates (RCA) are more porous by nature and have lower specific gravity than the common crushed aggregates, the ideas was to reduce their porosity, contributing in the increase of their crushing resistance and friction, in order to finally improve the physical and mechanical properties of the hot mix asphalt made with RCA. The target was to make them a competitive alternative to common crushed aggregates. The peak (highest value) coating paste volume, was found corresponding to the coating thickness of 0.25 mm. It has been also found that, the hot mix asphalt with 100% of PCRCA was within the range of the specifications requirements as regard to the mechanical properties assessed, such as indirect tensile strength (ITS), moisture sensitivity and wheel-track. Also, even if PCRCA still exhibited higher water and asphalt absorption rate than the common crushed aggregates, they were in accordance with the specifications requirements (Lee et al., 2012).

Ajdukiewicz & Kliszczewicz (2002) reported that the weak properties of concrete made with recycle aggregates regarding various strengths, durability performance, as well as workability were mainly attributed to the main drawback of the recycle aggregates which is the high porosity leading to high water absorption rate and low crush resistance. Those weaknesses were due to the porous mortar formed with the aggregates Poon CS & Chan D (2006).

Nevertheless, pre-coating techniques find more its application in road pavement construction, mostly when using bituminous binder, in order to either increase the bonding characteristics between aggregates and the binder or to improve the physical properties of alternative aggregates to be used for the purpose. This is because the bonding or the adhesion between the bituminous binder and the aggregates is most of the time affected by the dust or any other organic material on the surface of the aggregates. It is usually the cause of seat coat failures. That is the reason why pre-coating techniques on the aggregates have been developed, providing them a sort of shell or film of bituminous binder in order to increase the initial adhesion between them and the binder (Zealand et al., 2015).

The technique finds less applications with porous aggregates used in Portland concrete commonly made for superstructures such as buildings. One would think also of its application in that area which can also be beneficial, with the aim to deal with the high porosity of some aggregates for producing better lightweight aggregates concrete in terms of strengths and durability performances.

2.2.3 Use of fibers as reinforcements of concrete matrix

The fibers used as reinforcements of concrete matrix are usually of 5 types; steel, glass, mineral, polymeric (polypropylene, polyethylene, polyester, amarid) and natural fibers (sisal, coir, jute, bamboo). However, since artificial fibers are costly and sometimes scarce, the use of natural fibers has increased. In Africa we have a lot of natural fibers. Some previous studies proved that they have good physical and mechanical properties and can be used to reinforce concrete. The basic idea is to provide some reinforcements in the concrete matrix which is weak in tension, and therefore improve the concrete tensile strength as well as other properties such as flexural strength, toughness, and impact resistance. Reduction of shrinkage and cracks, improvement of durability performance through stabilization of micro cracks and permeability's reduction are also amongst the expectations. In Kenya, sisal fibers is a kind of natural fibers from a plant called Agave Sisalana. Because of its high content of lignin, sisal is much more advantageous than other natural fibers.

(Neville, 1995) also showed that lightweight concrete usually exhibited higher shrinkage due to their high porosity and absorption capability. Therefore, the use of sisal fibers finds its importance in order to overcome those drawbacks regarding not only the high shrinkage but also some weak mechanical properties as reported earlier. In fact, we expect a lightweight concrete exhibiting a high permeability, high shrinkage, weak durability performances and strengths. This is because of the volcanic scoria aggregates which are highly porous and therefore exhibiting a high water absorption capability. It results a higher amount of water required for the mix and a higher water cement ratio, responsible of the drawbacks discussed above. (Carlson, 1938) has shown that an increase of 1% of the amount of mixing water in the mix, led to an increase of **2**% of shrinkage.

- ***Fibers reinforced concrete (Using of fibers as reinforcement in cement based composite)***

According to Rahuman & Yeshika (2015), the sisal fibers in the concrete increases its strength and workability properties. In that study, the influence of adding discrete sisal fibers of length of 4 cm was investigated at different percentages addition of 0.5%, 1% and 1.5% by weight replacement of cement. The investigation was done on two different mix designs named M20 (design strength: 20 MPa) and M25 (design strength: 25 MPa). The mechanical properties were of interest in the study. They found optimum results at 1.5% of fibers addition with compressive strength increasing by 50.53% and tensile strength increasing by 3.416% with M20 mix design. Similarly, with M25 mix design, compressive strength was found to increase by 52.51% and tensile strength to increase by 3.904%, both as compared to the control mix (without fibers). The workability was also found suitable, exhibiting a value of 53 mm as the slump and 0.88 as the compaction factor, at 0.45 of water cement ratio with 0.2% of super plasticizer in the mix.

(Joseph et al., 1999) have carried out investigations on the performance (physical and mechanical properties) of cement based matrices, incorporating sisal fibers at different percentages content and length. The results showed that sisal fibers reinforcing composites, exhibited improvement in various strengths and physical properties and could be used to build structural elements in constructions. The study added that the composite material with fibers could be a real alternative to asbestos-cement composite which negatively affect the health of people and animals, and would lead to social and economic gains.

Chandrashekaran & Selvan (2015) investigated also the contribution of natural sisal fiber as reinforcements of the concrete as regard to strengths. Various percentage fibers content (0.5%, 1%, 1.5%, and 2%) were used at 4 different aspects ratio 100, 200, 300, and 400. The results showed an increase of compressive strength with aspect of 300 at 1.5% of addition of fibers as compared to the control mix. The same observation was done as regard to the splitting tensile strength, which was found to increase with aspect ratio of 300 at 0.5 % of addition of fibers. Also, an increase of flexural strength with aspect ratio of 300 at 1% of fibers addition was recorded, as compared to the control mix.

The same tests were conducted to assess the performance of blended concrete reinforced with sisal fibers Sathish & Murugesh (2016). The blended cement was made by partial replacement of Ordinary Portland Cement by Ground Granulated Blast Furnace Slag (GGBS) at different percentages of 10%, 20%, and 30%, with 1% sisal fibers in the matrix, both by the weight of cement. It has been concluded that the replacement of Ordinary Portland Cement by 20% of GGBS, with 1% of sisal fibers exhibited the optimum performance (compressive, splitting tensile and flexural strength) of the resulting slag blended fiber reinforced concrete as compared to the conventional concrete.

Torgal & Jalali (2014) investigated the use of natural fibers as reinforcements of concrete. Their main concern was about the durability performance of the reinforced concrete made and some treatments that can be applied either on the natural fibers or in the matrix to improve their long term quality.

(Li et al., 2006) stated that one of the inconvenient of the use of natural fibers in concrete is their ability to change in properties depending of the surroundings, which can affect concrete properties during its life. In the study, treatments have been found to be useful to improve the bonding between fibers and the matrix, and to increase their efficiency against the chemical reactions with the cement, through resisting to alkaline attack for instance (Savastano et al., 2003).

Plastic shrinkage reduction has been found by adding 0.2% of sisal fibers content of 25 mm length by volume replacement of cement in the mix (Filho et al., 2005).

Mechanical properties were found to increase as well as impact resistance, as compared to conventional concrete and also concrete with synthetic fibers.

The investigation on the hardness and strength properties of sisal fibers reinforced concrete was also done by (Aruna, 2014). He conducted experimental tests on slabs at different percentage of fibers content at 6%, 12%, 18%, and 24% of cement replacement by weight. The results showed higher tensile and toughness properties when long sisal fibers (400 mm) were used and enhanced post cracking behaviors when the density decrease.

(Edgington et al., 1974) recognized as the contributions of steel fibers in the fiber reinforced systems, the enhancement of the flexural capacity, the higher ductility, as well as the cracks reduction (width and number of cracks). Some authors have demonstrated that an addition of steel fibers into concrete in the range of 1-1.5% by volume replacement of the binder, resulted of an increase of the compressive strength till about the percentages of 10 to 25%, also the flexural strength of about 150 to 200% and the tensile strength till 100% (Dvorkin L & Dvorkin O., 2011).

- ***Fibers reinforced Lightweight concrete***

(Hassanpour et al., 2012) carried out investigations on the influence of steel fibers in lightweight concrete as regard to the physical and mechanical properties (compressive strength, tensile strength, flexural strength, modulus of elasticity, toughness, stress-strain behavior, and workability). According to the authors, the use of steel fibers is an indicated solution to deal with the problems of higher brittleness and lower mechanical properties which characterized the LWAC. The study showed that steel fibers really enhanced the toughness and the ductility behavior when used in LWAC, and advised the use of superplasticizer to improve the workability, which was found reducing with the presence of steel fibers. The study recognized a significant improvement in the splitting tensile and flexural strengths by far higher than for plain NWC due to the presence of steel fibers.

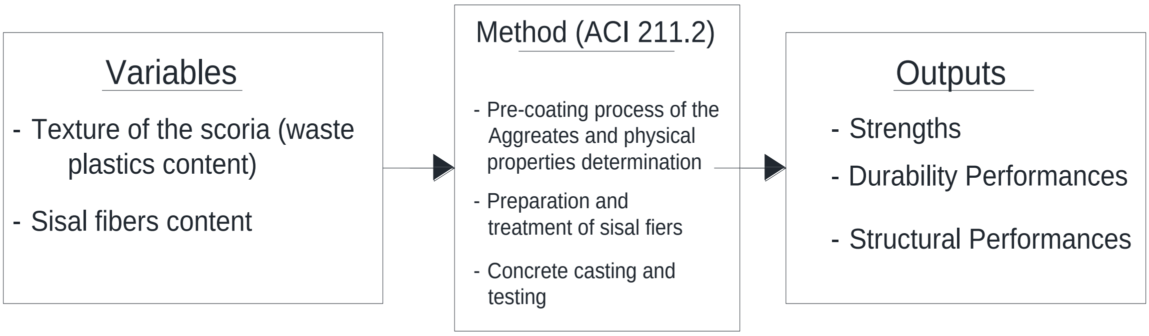
(Balendran et al., 2002) reported that LWC was more brittle than NWC of the same characteristics (mix proportion and design compressive strength). Therefore, with other similar reasons, the expectations regarding the LWC properties are to be weaker than that for NWC (Arisoy B & Wu HC., 2008). To deal with that brittle nature and lower mechanical properties, the incorporation of fibers such as steel has been seen as the solution.

However there are almost no works on the structural lightweight aggregates concrete reinforced with natural sisal fibers.

A similar study has been conducted, using coconut fibers to reinforce lightweight concrete (Noor et al., 2012). The aim for the authors was to investigate the influence of incorporating different percentages (1%, 3%, and 7%) by volume replacement of coarse aggregates of short discrete coconut fibers of length of 15 to 35 mm, on the physical and mechanical properties of lightweight concrete. It was recorded a decrease regarding the compressive strength of the resulting concrete when increasing coconut fibers content, and better behaviors vis-à-vis of cracks occurring. Actually, with the addition of 3% of coconut fibers by volume replacement of coarse aggregates, the resulting lightweight concrete exhibited its optimum mechanical properties. The compressive strength was found about 18.85 N/mm^2 as compared to 31.57 N/mm^2 for the plain concrete after 28 days curing. Toughness also was found improved. The specimens with 1 to 3% of fibers were still able to sustain loads without crashing as compared to the plain concrete. The authors concluded on the suitability of coconut fibers for structural lightweight concrete production. The coconut fibers were used in this case as replacement of coarse aggregates.

2.3 Conceptual Framework

For the investigation, two main variables were defined for several outputs regarding the strengths, the durability of the structural performances. The conceptual framework below gives a clear explanation of the research process.



2.4 Literature Review Summary

(Hossain, 2006) found that Volcanic scoria aggregates were suitable as lightweight aggregates for lightweight concrete production. He also reported that the resulting LWC was relatively weaker in terms of strengths, durability performances, ductility and with higher drying shrinkage as compared to NWC with crushed gravel. He attributed those lower properties to the high porosity of volcanic scoria aggregates conferring them a high water absorption capability. According to Bogas & J.A, (2011), the durability of lightweight concrete is more affected by the lightweight aggregates types, and enhanced with higher porous nature of paste and also less dense outer shell of lightweight aggregates.

(Sarkar et al., 2016) found useful the use of waste plastic bags to pre-coat Over Burnt Brick Aggregates (OBBA) in order to reduce their high porosity and finally improve the physical and mechanical properties of the resulting bituminous concrete produced. They found that plastic coated OBBA were suitable as aggregates in the area of bituminous concrete for road construction.

Chandrashekaran & Selvan (2015) found that the addition of natural sisal fiber as reinforcements of the concrete matrix, could improve its physical and mechanical performances. (Hassanpour et al., 2012) also found that incorporating of steel fibers in lightweight concrete matrix enhanced the toughness and the ductility behavior. A significant improvement was also found regarding the splitting tensile and the flexural strength.

2.5 Research Gap

Pre-coating technique has been long used in the area of bituminous concrete on either normal or alternative aggregates for road construction. The aim has been mainly to reduce the pores or to deal with dust in order to increase the bonding between aggregates and asphalt and thus, increase the physical and mechanical properties of the resulting bituminous concrete made. From that point of view, dealing with high porosity of natural volcanic scoria aggregates, which is the cause of lower strengths and durability performance and higher shrinkage of LWC made, by pre-coating them with waste plastic can be beneficial and has to be investigated for structural LWC production. The benefits will be improved structural performance of the resulting LWC, while contributing to the waste plastic disposal from the environment. Unfortunately, there are very few or limited researches in that direction.

Added to that, LWC made by natural aggregates are usually not strong enough, more brittle, with higher shrinkage and lower durability performances as compared to NWC or LWC made with artificial aggregates. Investigation on the influence of natural sisal fibers in scoria lightweight concrete should be investigated as regard to the strengths, the durability and the structural performances as well as the ductility behavior. Almost no works have been done in that area.

And then, the combined effects of the waste plastic pre-coated scoria aggregates and sisal fibers as reinforcements of the matrix should be investigated to check whether this can lead us to a better structural lightweight concrete.

CHAPTER THREE

MATERIALS AND RESEARCH METHODS

3.1 Introduction to the research methodology

This chapter deals with the methodology that was used in the research to carry out the investigations on the structural performance of sisal fibers reinforced lightweight concrete made with waste plastic pre-coated volcanic scoria aggregates. This research focused on the strengths, the durability aspects and the structural performance of the lightweight aggregates concrete incorporating different plastic contents over the aggregates and different contents of sisal fibers in the matrix. Based on ACI 211.2-98 “Standard practice for selecting proportion for structural lightweight concrete”, concrete mix design has been carried out using the three different approaches proposed by the standard, with the purpose of retaining the best approach giving us better expected results. However, prior to that process, the constituent materials have been subjected to several experimental tests for their physical properties determination which are relevant for the mix design process. Different tests on both wet and hardened concrete have been carried out according to the standard. The research was conducted at the Structural and Materials Laboratory of Jomo Kenyatta University of agriculture and Technology (JKUAT).

3.2 Raw Material

The raw material for this research included:

i. Ordinary Portland cement (OPC) class 42.5,

ii. Aggregates (Fine : Ordinary river Sand, Coarse: Natural volcanic scoria)

iii. Waste plastic (plastic papers, plastic paper bags)

iv. Sisal fibers

v. Potable water

3.3 Material properties and preparation

Lightweight concrete is a composite material made globally with two components; the binder which is the Ordinary Portland Cement in this case and the aggregates (natural river sand as fine and natural volcanic scoria as coarse aggregates). The determination process of the appropriate proportions of these composite materials is called *mix design* (Kong & Evens, 1840). Some physical and mechanical properties are required for their use in various application. The composite material in the wet state or fresh concrete had to provide a good workability, while in the hardened state must make available the sustainability, the serviceability, and the economy benefits (Edward G. Nawy, 1905). Each of the raw materials used had to follow some specific requirements in order to be used as constituents' materials for the structural lightweight aggregates concrete production.

3.3.1 Ordinary Portland Cement (OPC)

This investigation was carried out using Portland Cement (PC) as the binder. It is an hydraulic binder type made up of raw materials such as; Lime (CaO) from Limestone (60 – 65 %), Silica (SiO_2) (18 – 25%) and alumina (Al_2O_3) (3 – 6%) both from clay, with a little quantity of magnesia (MgO) and sometimes alkalis, and Iron oxides (0.5 – 5%) added for composition control (Edward G. Nawy, 1905).

Varying the different proportions of these constituents allow to distinguish the two main type of Portland Cement, the *ordinary Portland cement* (OPC) and *rapid hardened Portland cement* Knog & Evens (1840). Portland cement shall contain not less than two-third by mass of calcium silicates $(CaO)_3 \cdot SiO_2$ and $(CaO)_2 \cdot SiO_2$) (BS 12:1996).

Ordinary Portland Cement has been used for the study. It is an Ordinary Portland Cement Type I (CEM I 42.5 N) called “Bamburi Power Plus”. It is made locally in Kenya, by the manufacturer “Bamburi Cement Ltd Company”. This cement is safely kept in dry place condition. Its chemical composition has been given by the supplier and some other important physical properties were determined in the Laboratory, such as bulk density (loose and compacted) and the specific gravity.

3.3.2 Aggregates

- ***Fine aggregates: Natural sand***

The natural fine aggregates used in this study was the ordinary river sand with the nominal size 4.76 mm according to ACI standard. This river sand is obtained from the location of Meru in Eastern Kenya. As regard to the standard requirements, it was clean enough, without any organic contamination, like dust or others coatings like clay that can prevent proper bonding of the material with the cement paste, leading to poor characteristics of concrete. This requirement is relevant, to ensure that the aggregates would not react in the matrix, and hard enough and durable as preconized by the standards. Also, the Alkali-Silica Reaction (ASR) is an important parameter that should be avoided as well as much as possible. For the purpose, the aggregates should not contain silica; when we have silica on the aggregates in the concrete, it reacts with the alkali presents in the cement, leading to some extend to concrete disintegration. Corrosion of steel bars in reinforced concrete, can also be due to the presence of Chlorides on the aggregates, so aggregates should not contain chlorides as well. Added to all those requirements, the sample sand used should have an allowable particles sizes distribution which is called grading as prescribed by the standard (ASTM C330-05). Thus, Sieve analysis was carried out on the sand with the aim to have the particles size distribution, then the grading curve chart of the aggregates was plotted, to check the limits in accordance with the standard which should be within the acceptable specified ranges. Grading of aggregates is as important as it affects the concrete properties both in the fresh state (workability), and in the hardened state (strengths and durability). Some other basic physical properties were carried out such as the Bulk density, the specific gravities, the fineness modulus, the water absorption and moisture content.

- ***Coarse aggregates: Natural Volcanic Scoria***

In general, there are several types of aggregates usually used depending on the purpose of the concrete made. When it comes to lightweight aggregates, we have artificial lightweight aggregates and natural lightweight aggregates. Volcanic scoria is one of the naturally occurring lightweight aggregates that was used in this study. However, there are some specific requirements dictated by standards that those aggregates had to follow, in order to be used as lightweight aggregates for structural lightweight concrete production. Knowing the large percentage occupation of aggregates in the concrete, at around 70%, which greatly affect the mechanical and physical properties of the concrete produced, we have thus started by carrying out some important physical properties on those scoria aggregates such as the unit weight, the specific gravities, the absorption capacity, as well as the grading, firstly in order to check their suitability as aggregates for structural lightweight concrete production as regard to the standard, and then used those properties relevant for concrete design process. The tests were carried out in accordance with BS EN 932-2:1999. It is important to note that here we had 4 different scoria aggregates samples, the uncoated sample for the control mix, and the three different pre-coated aggregates samples with waste plastic at respectively 5%, 10% and 15%, and those properties were determined for each. Plate 3.1 and 3.2 show the physical appearance of raw natural scoria aggregates and pre-coated scoria aggregates respectively. Table 3.1 gives some requirements for the range of their unit weight depending on the purpose of the concrete, with the resultant unit weight of those specific types of concrete, according to ASTM standard C330-05, and the Table 3.2 give us the grading requirements according to the same Standard as well. The grading or the particle size distribution of volcanic scoria aggregates should fall within the required ranges, for them to be used properly as lightweight aggregates for structural concrete as per ASTM C330-05.

The volcanic scoria used for this study was obtained from the location of lukenya around Mombasa Road in Kenya. The specific parameters for their characterization like their particle dry density (ρp), their 24 hours' water absorption (w_{abs}, 24h), and their specific gravities were determined. As the lightweight scoria aggregates have a great potential to absorb water, it was easier to use all the different sample aggregates in saturated surface dried (SSD) condition as recommended, so as to reduce the bias due to environment changes which modify their moisture content all the time, thus ensure the reliability of all the experiments.

Also, to carry out better understanding of the volcanic scoria aggregates, the different chemical components were determined, in the Laboratory of the Ministry of mining in Kenya, and the other physical properties at the Structural and Materials Laboratory of Jomo Kenyatta University of Agriculture and Technology (JKUAT).

Table 3.1: Range of Unit Weight of Aggregates and concrete given by ASTM C330-05.

Type	**Unit Weight of Dry-rodded Aggregates (Kg/m^3)**	**Unit Weight of Concrete (Kg/m^3)**
Insulating concretes (perlite, vermiculite, etc.)	240.3 – 801	320.4 – 1441.8
Structural lightweight	640.8 – 1121.4	1441.8 – 1762.2
Normal weight	1121.4 – 1762.2	2082.6 – 2563.2
Heavyweight	> 2162.7	2883.6 – 6087.6

Table 3.2: Grading Requirements for Lightweight Aggregates for structural concrete given by ASTM C330-05.

Size Designation	**Percentage (by weight) Passing Sieves Having Square Openings**									
	1 in. (25 mm)	**¾ in. (19 mm)**	**½ in. (12.5 mm)**	**⅜ in. (9.5 mm)**	**No. 4 (4.75 mm)**	**No. 8 (2.36 mm)**	**No. 16 (1.18 mm)**	**No. 50 (300 µm)**	**No.100 (150 µm)**	**No.200 (75 µm)**
Fine Aggregates No. 4 to 100	–	–	–	100	85 – 100	–	40 – 80	10 – 35	5 – 25	0-10
Coarse Aggregates										
1 in. to No. 4	95 – 100	–	25 - 60	–	0 – 10	–	–	–	–	0-10
¾ in. to No. 4	100	90 – 100	–	10 – 50	0 – 15	–	–	–	–	0-10
½ in. to No. 4	–	100	90 – 100	40 – 80	0 – 20	0 – 10	–	–	–	0-10
⅜ in. to No. 8	–	–	100	80 – 100	5 – 40	0 – 20	0 – 10	–	–	0-10

Plate 3.1: Raw natural volcanic scoria aggregates.

Plate 3.2: Pre-coated volcanic scoria aggregates at different percentages of waste plastics on scoria aggregates (0%, 5%, 10%, and 15%)

3.3.3 Sisal fibers

Sisal is a natural fiber (Scientific name is Agave sisalana) from Agavaceae family which yields a stiff fiber traditionally used in making twine and rope. Sisal is fully biodegradable and highly renewable resource of energy. Sisal fiber is exceptionally durable with a low maintenance with minimal wear and tear. Sisal fiber is extracted by a process known as decortication, where leaves are crushed and beaten by a rotating wheel set with blunt knives, so that only fibers will remain.

Sisal fibers were chopped into relatively small length (3 to 4 cm) to avoid balling when mixing, before applying them in the mixes as shown on plate 3.3. In the first objective of the work, the best waste plastic's percentage over the aggregates was found, giving the best results in the lightweight concrete produced. In the second phase, investigation on the effects of sisal fibers in the lightweight concrete matrix was done. For that purpose, different percentages of fibers content by weight of cement (0%, 1%, 1.5% and 2%) were tested in the resulting lightweight concrete developed in the first objective. The control concrete was the lightweight concrete made with raw uncoated scoria aggregates, having no fibers. The best fibers content was the target, giving the optimum results with the mix, as regard to the physical and mechanical properties of the lightweight concrete made both in the wet and hardened state.

However, the high alkaline environment in a concrete due to Portland Cement used, affects the durability performance of the natural sisal fibers with the time, by dissolving its lignin and hemicellulose phase. To avoid the fibers to disintegrate in this alkaline reaction and loss its strength after some time in a concrete, the fibers were coated by a solution of sodium silicate trough impregnating them into the solution for 10 hours prior to use them ,as it is recommended by Torgal & Jalali (2012). That process is called fiber surface treatment. Washed, cut and dried sisal fibers were put in trays and the solution of sodium silicate was added. The fibers remained soaked into the solution for a duration of about 10 hours, then were removed and washed thoroughly with water to remove the excess of sodium silicate sticking to the fibers. Thereafter they were dried in a room temperature for around 2 hours, before the use in the mixes. Plate 3.3 shows the cutting process of the fibers. For better understanding of the sisal fibers, chemical analysis was carried out to determine their different chemical components and concentrations. The analysis was done in the Laboratory of the Ministry of Mining.

Plate 3.3: cutting process of Sisal fibers

3.3.4 Waste plastic as pre-coating material

In the process of pre-coating, plastics papers were cleaned, dried, then shredded and applied on aggregates in a hot process as shown on plates 3.4, 3.5 and 3.6. The process was involving heating the aggregates at 190°C in the oven, before applying the shredded waste plastic at different percentages by the weight replacement of the scoria aggregates, respectively at 5%, 10% and 15%. The plastic formed a sort of shell or thin film over the surface of the aggregates contributing in the reduction of their porosity by filling up their pores, and finally led to the reduction of their water absorption capability. Improved physical and mechanical properties of the aggregates and the resulting lightweight concrete made were the expectations. Plates 3.4, 3.5 and 3.6 show the washing process of waste plastics, the shredded waste plastics in a tray and the pre-coating process respectively.

Pre-coating process of the aggregates

Well graded volcanic scoria aggregates were heated at 190°C in oven. A known quantity of sample aggregates was put in trays and left in an oven. A thermometer was used to check whether the aggregates have reached the required temperature. Two hours was needed for this step for the aggregates to reach 190°C. Then, the trays were taken out from the oven and the required percentage of shredded plastics was poured on the hot aggregates while mixing. 15 minutes was required for that second step. Thereafter, the trays were put back in the oven for another duration of one hour at the same temperature of 190°C. After that, the aggregates were removed from the oven and mix again for a duration of 15 minutes before leaving them to cool in a room temperature.

Plate 3.4: washing process of waste plastics

Plate 3.5: waste plastics washed and shredded

Plate 3.6: Pre-coating process of volcanic scoria aggregates with waste plastics (mixing).

3.3.5 Water

Water and cement consists of the only two active ingredients that we have in a proper concrete. Water allows the cement to get into a chemical reaction leading to a fluid paste that bind the aggregates together and fill the voids between them. This process is called hydration *Gibbons & Jack (2012*).

Two types of water in the concrete is distinguished in general; the essential water which is the exact amount of water needed by the cementitious material for its hydration process (the required mixing water), and the free water which is the extra water, and does not contribute to the reaction according to Wilson & Kosmatka (2002). However, this free water should be controlled enough because the amount of water in the concrete in general, affects directly the strength of the hardened concrete. The more is the water in the concrete, the more is the water cement ratio and then the less is the strength of the hardened concrete. The water used should also be of a good quality, and the amount should be controlled. The water should be without any harmful agent which can affect the chemical reaction with the cement. It should be clean, drinkable, if not concrete can be subjected to premature failure, in its hardened state according to Wilson & Kosmatka (2002).

The water used in the study, was drinkable water obtained from the general supplier of water of the region. As drinkable water, it was found good enough to be used as mixing water. That water was also useful for curing the concrete after casting. This allow the concrete to reach the desirable strength at the required ages 7, 14, 28, and 45 days.

3.4 Concrete mix design

The methods of mix design applied here are the method prescribed by ACI 211.2-98 (Standard practice for selecting proportion for structural lightweight concrete). This standard prescribes three different methods for designing structural lightweight concrete, namely:

- The weight method: specific gravity pycnometer,
- The absolute volume method,
- The volumetric method (damp or loose volume method).

The design was carried out using the three different approaches, with the purpose to find the one giving the best results mostly in terms of the expected design strength, workability, and dry density. Basically each approach involves some specific steps that we have followed.

3.4.1 The weight Method: Specific Gravity Pycnometer

There are basically 9 main steps to follow with this method according to the standard ACI 211.2-98.

Step 1: Choice of slump.

Table 3.3 give us the recommended slump for various types of constructions according to the standard ACI 211.2-98.

Table 3.3: Recommended slumps for various types of constructions (ACI 211.2-98.

Types of construction	Slump, in (mm)	
	Maximum	Minimum
Beams and reinforced walls	4(100)	1(25)
Building columns	4(100)	1(25)
Floor slabs	3(75)	1(25)

The slump ranges recommended are applied when vibration is used to consolidate the concrete. A slump range of 1-2 in (25-50 mm) was chosen here as for general construction.

Step 2: Choice of nominal maximum size of lightweight coarse aggregate.

Volcanic scoria lightweight aggregates available, graded from ¾ in to No 4 (4.76 mm) were found suitable according to the standard requirements ASTM C330 and ASTM C33.

Step 3: Estimation of mixing water and air content.

The quantity of water per unit volume of concrete required to produce a given slump is dependent on the nominal maximum size, the particle shape and grading of the aggregates, the amount of entrained air, and inclusion of chemical admixtures. Table 3.4 provides estimates of required mixing water for concrete made with various nominal maximum sizes of aggregate, with and without air entrainment.

Table 3.4: Approximate mixing water and air content requirements for different slumps and nominal maximum sizes of aggregates.

Aggregate size	***3/8 in. (9.5 mm)***	***½ in.(12.7 mm)***	***¾ in. (19.0 mm)***
Air-entrained concrete			
	Water, (kg/m^3) of concrete.		
Slump, 1 to 2 in. (25 to 50 mm)	181	175	166
Slump, 3 to 4 in. (75 to 100 mm)	202	193	181
Slump, 5 to 6 in. (125 to 150 mm)	211	199	187
	Recommended average total air content, %, for level of exposure.		
Mild exposure	4.5	4.0	4.0
Moderate exposure	6.0	5.5	5.0
Extreme exposure	7.5	7.0	6.0
Non air-entrained concrete			
	Water, (kg/m^3) of concrete.		
Slump, 1 to 2 in (25 to 50 mm)	350 (208)	335 (199)	315 (187)
Slump, 3 to 4 in. (75 to 100 mm)	228	217	202

Slump, 5 to 6 in. (125 to 150 mm)	237	222	208
	Approximate amount of entrapped air in non-air-entrained concrete, %		
	3	2.5	2

No severe weathering condition for the study was expected, so non-air entrained concrete was appropriate with the slump between 1–2 inches, and max nominal size of aggregates ¾ in (19 mm). Thus the amount of mixing water from Table 3.4 is 187 kg/m3, and the approximate amount of entrapped air is 2%.

Step 4: Selection of approximate W/C ratio

The design compressive strength at 28 days was 30 MPa (4351.132 Psi). Table 3.5 gave the relationship between w/c and compressive strength of concrete.

Table 3.5: Relationships between w/c and compressive strength of concrete

Compressive strength at 28 days, psi (Mpa)	***Approximate water-cement ratio, by weight***	
	Non air-entrained concrete	*Air-entrained concrete*
6000 (41.4)	0.41	-
5000 (34.5)	0.48	0.40
4000 (27.6)	0.57	0.48
3000 (20.7)	0.68	0.59
2000 (13.8)	0.82	0.74

From that table, in the case of non-entrained air concrete with that compressive strength, the W/C by weight is around **0.54.** However, there is another constraint giving us the maximum permissible w/c for durability requirement consideration. Table 3.6 gave those values.

Table 3.6: Maximum permissible water-cement ratios for concrete in severe exposures based on ACI 201.2R.

Type of structure	Structure wet continuously or frequently; exposed to freezing and thawing	Structure exposed to sea water or sulfates
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 in. (25 mm) cover over steel	0.45	0.40
All other structures	0.50	0.45

From the table, the maximum permissible water cement ratio for durability requirements is 0.45. So, W/C is taken as 0.45.

Step 5: Calculation of cement content

With the amount of mixing water (step 3) and the value of w/c (step 4), the amount of cement is just deduced as C=W/0.45

W/C= 0.45, W= 187kg/m^3, this means that C=187/0.45= 415.6 kg

Step 6: Estimation of lightweight coarse aggregates content.

The fineness modulus of the fine aggregates used was found 2.4 and the nominal maximum size of aggregates is ¾ in. (19 mm). Table 3.7 allows us to estimate the volume of oven-dry loose coarse aggregates per unit volume of concrete, in function of the fineness modulus of the sand used and the maximum size of aggregate.

Table 3.7: Volume of coarse aggregate per unit of volume of concrete.

Maximum size of aggregate, in. (mm)	***Volume of oven-dry loose coarse aggregates per unit volume of concrete for different fineness modulus of sand***			
	2.40	*2.60*	*2.80*	*3.00*
3/8 (9.5)	0.58	0.56	0.54	0.52
½ (12.7)	0.67	0.65	0.63	0.61
¾ (19.0)	0.74	0.72	0.70	0.68

This table indicates that 0.74 m^3 of coarse aggregates, on a dry loose basis may be used in each m^3 of concrete. The oven dry loose weight of aggregates being 1013.6 kg/m3, thus the dry weight of the coarse aggregates for an m^3 of concrete is 0.74 x 1 x 1013.6 = 750.064 kg.

Because the coarse aggregates have an absorption of 13.06%, the saturated weight is 1.1306 x 750.064= 848.022 kg

Step 7: Estimation of fine aggregates content

At the completion of step 6, all ingredients of the concrete were estimated except the fine aggregate. Its quantity is determined by difference. Table 3.8 gave the first estimate of the unit weight of the fresh concrete based on the specific gravity factor of the lightweight coarse aggregate and the air content of the concrete.

Table 3.8: First estimate of weight of the fresh lightweight concrete comprised of lightweight coarse aggregate and normal weight fine aggregate.

Specific gravity factor	***First estimate of lightweight concrete weight, lb/yd^3 (kg/m^3)***		
	Air-entrained concrete		
	4%	*6%*	*8%*
1.00	2690 (1596)	2630 (1561)	2560 (1519)
1.20	2830 (1680)	2770 (1644)	2710 (1608)
1.40	2980 (1769)	2910 (1727)	2850 (1691)
1.60	3120 (1852)	3050 (1810)	2990 (1775)
1.80	3260 (1935)	3200 (1899)	3130 (1858)
2.00	3410 (2024)	3340 (1982)	3270 (1941)

The ingredients weights already known are (per m3 of concrete):

Water (net mixing):	187 kg
Cement:	415.6 kg
Coarse Aggregates (saturated)	848.03 kg
Total	1450.63 kg

Unfortunately, the table is drawn only for air-entrained concrete. The amount of air was approximated at 2% for non-air-entrained concrete in the study. The closer value of 4% as the amount of air entrained from the table 3.8 was taken. The lightweight specific gravity factor was found 1.45. The first estimate of weight of lightweight concrete is 1789.75 kg (for a m^3 of concrete).

The SSD weight of sand is therefore equal to 1789.75 – 1450.63 = 339.12 kg

The Oven dried weight of sand is 339.12/1.047 = 323.90 kg (The absorption capacity being 4.70%)

Step 8: Adjustment for aggregates moisture

Weight already known are (per m3 of concrete) SSD

Water (net mixing):	187 kg
Cement:	415.6 kg
Coarse Aggregates (saturated)	848.03 kg
Fine Aggregates (Saturated)	339.12 kg
Total	1789.75 kg

Step 9: Adjustment of trial batch

For trial batch, the weights already known are (per 0.028 m3 of concrete)

Water (net mixing):	187x0.028 m3= 5.236 kg
Cement:	415.6 x0.028 m3= 11.637 kg
Coarse Aggregates (saturated)	848.03 x0.028 m3= 23.745 kg
Fine Aggregates (Saturated)	339.12 x0.028 m3= 9.5 kg
Total	50.12 kg

The moisture content of the sand in stock is 3.4% and the absorption is 4.7 %, so the adjustment in sand is:

9.5/1.047 x1.034 = 9.38

The Adjustment of added water is: 9.5-9.38 = 0.117 kg

The added water is: 5.236 +0.117 = 5.353 kg

For trial batch, the adjusted weights are (as they are) (per 0.028 m3 of concrete)

Water (net mixing):	5.353 kg
Cement:	11.637 kg

Coarse Aggregates (saturated)	23.745 kg
Fine Aggregates (moist)	9.38 kg
Total	50.115 kg

3.4.2 Absolute Volume Method

Proportioning design with this method is articulated broadly on 8 main steps as follows:

Step 1: Selection of appropriate W/C ratio

Compressive strength at 28 days: 30 MPa (4351.132 Psi)

From Table 3.5, with an non-entrained air concrete with that compressive strength, the W/C by weight is around **0.54**

Or the maximum permissible water cement ratio for durability requirements is 0.45 from table 3.6. So, W/C has been taken as **0.45**.

Step 2: Estimation of the amount of Mixing Water

Non-air-entrained concrete (no severe weathering condition expected), with the slump between 1–2 inches (25-50 mm), and max nominal size of aggregates ¾ in (20 mm), the amount of mixing water from Table 3.4 is 187 kg/m3 and approximate air content is 2%.

Step 3: Estimation of Cement content

W/C= 0.45, W= 187kg/m^3, this means that C=187/0.45= 415.6 kg

Step 4: Estimation of approximate Air content 2% = 0.02 m^3

Step 5: Estimation of the lightweight aggregates absolute volume

516 /(1.45 x 1000)= 0.356 m^3 (516 kg/m^3: coarse aggregates factor at a 13.06% moisture content)

Step 6: Estimation of the absolute volume of sand

Item A: Cement absolute volume

415.6 /(3.14 x 1000)= 0.132 m^3

Item B: Water absolute volume

187 /(1 x 1000)= 0.187 m^3

Item C: Air absolute volume 0.02 m^3

Item D: Lightweight aggregates absolute volume = 0.356 m^3

Total absolute volume + volume of air = 0.695 m^3

Item E: Sand absolute volume 1-0.695 = 0.305 m^3

Sand weight = 0.305x2.507x1000 = 764.64 Kg

Step 7: Estimation of the theoretical unit weight (per m^3 of concrete)

Cement	415.6 kg
LWA	516 kg
Sand	764.64 kg
Water	187 kg
Total	1883.24 kg/m^3

Step 8: Adjustment for aggregates moisture and trial batch (Per 0.0371 m^3 of concrete)

Cement	15.42 kg
LWA (ssd)	19.14 kg
Sand (ssd)	28.37 kg
Water	6.94 kg
Total	69.87 kg/m3

As they are on site

Cement	15.42 kg
LWA (ssd)	19.14 kg
Sand (moist)	28.02 kg
Water	7.29 kg
Total	69.87 kg/m^3

3.4.3 Volumetric Method (damp, loose volume)

Step 1: Estimate 1 m^3 trial batch weights on an oven dry basis

- Cement 374.86 Kg from Appendix 1 (for the compressive strength of 4351.123 psi=30 MPa)
- Weight of Lightweight coarse aggregates: 0.55 (1.127)x 1013.6 = 628.3 Kg
- Weight of Sand: 0.45(1.127)x1461.25= 741.10 kg
- Water: 187 Kg+(13.06%x628.3)+(4.7%)741.10= 303.9 kg

In the case of non-air entrained concrete used (we assume no severe weathering condition), with the slump between 1–2 inches, and max nominal size of aggregates ¾ in (20 mm), the amount of mixing water from table 3.2 is 315 lb/yd^3 (187 kg/m^3), and air content is 2%.

Total (Plastic Unit weight**)** 2048.16 kg/m^3

Step 2: Approximation of air dry weight

Oven dry hydrated weight = 1.20 x374.86 + 628.3 + 741.10 = 1819.23 kg/m^3

The Plastic Unit weight minus the Oven-dry hydrated weight is 2048.16-1819.23 = 229 kg

75% retained moisture factor per ASTM 567, Section 9.7 = 171.70 kg/m^3

And 171.7 (retained moisture) + 1819.23 (oven dry weight) = 1990.93 kg/m^3 (Approximate Air dry weight**)**

Step 3: Estimate 1 m^3 trial batch weights on an oven dry basis

Cement	374.86 Kg
LWA (dry)	628.30 kg
Sand (dry)	741.10 Kg
Water	303.90 Kg
Total	2048.16 kg/m^3

Step 4: Adjustments (SSD basis)

Cement	374.86 Kg
LWA (SSD)	710.36 kg
Sand (SSD)	775.93 Kg
Water	187 Kg
Total	2048.16 kg/m3

<u>Estimate trial batch weights on an SSD Basis (per 0.0371 m^3 of concrete)</u>

Cement	13.91 Kg
LWA (SSD)	26.35 kg
Sand (moist)	28.43 Kg
Water	7.30 Kg
Total	75.99 kg

The objective here was to pick the best mix design approach, whichever method gave us the expected design strength at 28 days, the expected workability (slump) and dry density. The mix design selected is the best mix design approach that we have followed throughout the study. The control specimen has been designed following the best approach, and the other lightweight concrete specimens were made according to that. Tables 3.9, 3.10 and 3.11 show respectively the recapitulation of the mix proportions from the three approaches, the mix proportion adopted for the control mix and the specimens having different percentage of waste plastic on aggregates, and finally the mix proportions of mixes having different fibers contents.

Table 3.9: Different mix proportions from the 3 different approaches.

Mix design Method	***Lightweight Coarse aggregate content (SSD), kg/m3***	***Sand content (SSD), kg/m3***	***Water cement ratio (W/C)***	***Water content (kg/m^3)***	***Cement content (kg/m^3)***
Method 1: *Weight method*	848.03	339.12	0.45	187	415.6
Method 2:*Absolute volume method*	516	764.64	0.45	187	415.6
Method 3:D*amp loose method*	710.36	775.93	0.45	187	374.86

The second approach or the absolute volume method was found to be the best mix design approach, regarding the slump, the density and the compressive strength obtained.

Then, the same mix design with the pre-coated aggregates at respectively 5%, 10% and 15% of plastics over the aggregates by weight replacement, was carried out with the mix proportions as shown in Table 3.10.

Table 3.10: Mix proportions of the different mixes with different plastic contents on aggregates.

Mix design	***Lightweight Coarse aggregate content (SSD) kg/m3***	***Sand content (SSD) kg/m3***	***Water cement ratio (W/C)***	***Water content kg/m3***	***Cement content kg/m3***	***Waste plastic content %, by weight of scoria (Kg/m3)***
So *(Control)*	516	764.64	0.45	187	415.6	0%
S1 *(95% Scoria+5% plastics)*	490.2	764.64	0.45	187	415.6	5% (25.8)
S2 *(90% Scoria+10% plastics)*	464.4	764.64	0.45	187	415.6	10% (51.6)
S3 *(85% Scoria+15% plastics)*	438.6	764.64	0.45	187	415.6	15% (77.4)

And finally, three different sisal fiber contents by weight of cement was added to the mixture (1%, 1.5%, and 2%), and physical and mechanical characteristics of the resulting lightweight concrete were under interests. Table 3.11 shows the path as it has been done.

Table 3.11: Mix proportions of the different mixes containing different sisal fibers percentage.

Mix design	***Lightweight Coarse aggregate content (SSD) kg/m3***	***Sand content (SSD) kg/m3***	***Water cement ratio (W/C)***	***Water content kg/m3***	***Cement content kg/m3***	***Fiber content (%) Added***
So *(Control)*	516	764.64	0.45	187	415.6	0%
S1 *(95% Scoria+5% plastics) +* ***0% Fiber***	516	764.64	0.45	187	415.6	0%
S1 *(95% Scoria+5% plastics) +* ***1% Fiber***	516	764.64	0.45	187	415.6	1%
S1 *(95% Scoria+5% plastics) +* ***1.5% Fiber***	516	764.64	0.45	187	415.6	1.5%
S1 *(95% Scoria+5% plastics) +* ***2% Fiber***	516	764.64	0.45	187	415.6	2%

3.5 Mixing process

The batching was carried out by weight, with manual mixing and the mix was compacted using an electric vibrator. In the mixing process, the aggregates were soaked 24 hours earlier to make them in Saturated Surface Dry Condition (SSD), in order to avoid them to absorb a certain amount of the mixing water required for the hydration of the cement. The mixing was done in a tray where water was the last component to be added.

For the mixes having fibers, the fibers were added in portions at the final stage after all the concrete ingredients were mixed. The fibers were treated earlier with sodium silicate. This method of mixing gave uniform dispersed fiber in the concrete mix.

3.6 Method of curing

Demoulding was done 24 hours later after casting. The specimens were water cured in curing tanks until the dates of testing. This process was applied for cylinders and cubes specimens. Beams specimens were covered with thick bags capable of retaining water for long period, and water was poured on them 3 times a day as shown on plate 3.7.

. Plates 3.7: Curing process of beams under membranes.

. Plates 3.8: Curing process of cylinders and cubes in tanks.

3.7 Tests on aggregates and lightweight concrete

Tests were carried out on aggregates, fresh and hardened concrete. Three main phases of testing were carried out in the laboratory in order to assess the strengths, the durability and structural behavior of the materials under investigation.

Phase one: Pre-coating of the volcanic scoria aggregates with waste plastics.

Pre-coating of the aggregates was carried out in the hot mix process with waste plastics. For the purpose of this activity, waste plastics were collected, washed and shredded prior to pre-coating and three different percentages of plastics as weight replacement of aggregates at 5%, 10% and 15%, were used to pre-coat the aggregates. The plastics were mixed with scoria aggregates previously heated at 190°C using an oven.

After the process of pre-coating, the pre-coated scoria aggregates were kept for 24 hours, in a room temperature to cool them prior to the physical tests and using them in concrete making.

Suitability requirements of the natural uncoated scoria aggregates as well as the pre-coated scoria as lightweight aggregates for structural lightweight concrete making, had to be clarified as regard to the standards (grading, density, specific gravities). Then, four different mixes of LWC corresponding to one control and three others mixes with waste plastics pre-coated aggregates at 5%, 10% and 15% were carried out, and physical and mechanical properties were of interest (compressive, splitting tensile, flexural strengths, dry density, workability). The aim here was to find the optimum mix (optimum percentage of waste plastic on the aggregates which would exhibit best results on the produced lightweight concrete). The control mix was the ordinary LWC made with natural uncoated scoria aggregates.

Phase two: Use of sisal fibers as reinforcement of the matrix of the LWC made with waste plastic pre-coated volcanic scoria aggregates.

The phase one helped to investigate the use of waste plastic as coating material over the aggregates to produce a structural LWC using the pre-coated volcanic scoria as aggregates and to find the best mix, as compared to the control (the uncoated scoria lightweight concrete). In the second phase, the intention was to investigate the effects of the addition of natural sisal fibers as reinforcements of the matrix of the lightweight concrete made with waste plastic pre-coated volcanic scoria aggregates. The aim was to find if ever the addition of natural sisal fibers in the concrete would improve its properties (physical and mechanical). For that reason, short discrete natural sisal fibers with lengths of 3 to 4 cm were cut and treated through impregnation into a solution of sodium silicate to avoid their deterioration with the time in the concrete matrix caused by the alkali reaction due to contact with cement as described earlier, then 3 different percentages of them by the weight of cement (1%, 1.5%, and 2%) were added and investigated as regards to the physical and mechanical properties of the concrete. So, as explained earlier, similar physical and mechanical tests cited previously were to be done.

<u>Phase three:</u> Assessment of the durability performances and structural performance analysis

The main control mix which is the ordinary uncoated scoria lightweight concrete without fibers in the matrix, as well as the new concrete developed, the sisal fibers reinforced lightweight concrete with pre-coated scoria aggregates (the best mix: made with the best plastic content over the aggregates having the best sisal fibers content in the matrix) were under investigation to find out their durability performances and to analyze their structural responses. For the purpose, durability tests (Acid attack and chloride penetration resistance) were carried out as well as the structural performances analysis through steel reinforced beams casted with the material specimens and tested accordingly (with a look at the ductility, post cracking behavior and other useful mechanical parameters).

The tests results helped in the classification the type of lightweight concrete developed. As per ASTM C 330 and ACI 211.2-98, the main requirements to check to clarify whether a lightweight concrete is in the range of structural use is the minimum 28-days cylinder compressive strength which is 17.2 MPa and the maximum dry density which is about 1842 kg/m^3.

3.7.1 Physical Properties

i. Physical properties of materials

- ***Cement***

Physical properties of cement was determined in the laboratory such as the specific gravity and the bulk density. The supplier provided the chemical composition.

- ***Sand***

Physical Properties of the sand used such as bulk density, specific gravities, water absorption and moisture content were determined and confirmed suitable in accordance with BS EN 932-2:1999. Sieve analysis was done as well and grading curve was drawn and checked in accordance with the limits prescribed in ASTM C330-05.

- ***Uncoated and pre-coated volcanic scoria aggregates***

Physical parameters like bulk density, specific gravities, water absorption and moisture content were determined and confirmed suitable in accordance with BS EN 932-2:1999, for both the uncoated and pre-coated aggregates. Grading curve was also determined and the suitability checked as for ASTM C330-05.

ii. Physical properties of Fresh concrete: Workability

Workability is a physical properties of concrete, measured in its wet stage. It describes the ease with which, the concrete can be transported, placed, compacted and finished. It is the combination of various factors namely: compatibility, mobility and stability.

i. Compactibility is the ease with which the entrapped air in the concrete can be expelled.

ii. Mobility describe the ease with which concrete can be made to flow around reinforcements, inside the mould.

iii. Stability describes, the ability of the concrete to resist internal and external segregation, by staying a stable homogeneous and coherent mass in the handling phase.

The workability property was performed through the slump test conducted on the lightweight concrete as regard to BSEN 12350 (2009) as shown on Plate 3.9. This test, was carried out in the two first phases described above. In the first phase, it helped to understand the effects of waste plastic pre-coating the volcanic scoria aggregates on the workability of the lightweight concrete; and in the second phase, it gave us an explanation on the effects of both waste plastic as pre-coating material over volcanic scoria aggregates and sisal fibers reinforcement on the produced lightweight aggregates concrete in terms of workability.

Plate 3.9 Slump test

iii. Physical properties of hardened concrete

- ***Dry Density***

Dry density test was performed on lightweight concrete with uncoated scoria (control) and with pre-coated scoria aggregates. Then, on the final product the lightweight concrete made with pre-coated scoria and with sisal fibers as reinforcements of the matrix.

The aim was to understand step by step the effects of the 2 different variables in the concrete mix in terms of density, and then be able to check its classification as structural lightweight aggregates concrete, as regard to the standard specifications.

3.7.2 Mechanical Properties

- ***Compressive Strength***

The compressive test was carried out in order to characterize the concrete obtained. The test was conducted according to BSEN 12390 (2000) as shown on plate 3.10. This experiment was performed in the two first phases. The first phase is the pre-coating step, where a control mix was designed (concrete with initial uncoated natural volcanic scoria aggregates) and three other concrete samples made with pre-coated scoria aggregates at respectively 5%, 10%, and 15% of waste plastic pre-coating them by their weight replacement. The aim in this phase was to find the best waste plastic content as pre-coating material over the volcanic scoria aggregates. The result of the compressive strength guided on the optimum waste plastic content on the aggregates.

In the second phase, the main concern was also to determine the optimum content of natural sisal fibers in the waste plastic pre-coated volcanic scoria aggregates concrete matrix that would yield best strengths. For that purpose, three new concrete samples corresponding to 3 different percentages of sisal fibers addition by weight of cement, were designed, casted and tested. The sisal fibers content leading us to the highest compressive strength, gave us the best mix (result of the combined effects of waste plastic pre-coated volcanic scoria aggregates and sisal fibers) of our final concrete material, *‘‘sisal fibers reinforced waste plastic pre-coated volcanic scoria lightweight aggregates concrete’’.* According to the ACI 211.2-98 and ASTM C31&C330 standards, the concrete was casted in the cylinder moulds of internal dimensions of diameter 150 mm and height of 300 mm; the compressive strength was tested at 2 different ages, 7 and 28 days. And for each date and each design mix, 3 cylinder samples were casted and tested, and the average of 3 strengths was taken as mean strengths to avoid bias as much as possible. So, a total of 24 cylinders were casted for the first phase and 18 cylinders for the second phase.

Plate 3.10: Compression test

- ***Splitting Tensile Strength***

The splitting tensile strength is the indirect mechanical test to characterize tensile strength of the concrete as shown on Plate 3.11. The test was carried out on concrete through casting samples on a standard test cylinder of diameter of 100 mm with height of 200 mm. BSEN 1239(2009) standard requires 3 cylinders to carry out the test for each mix and each age. So, for the two ages 7 and 28 days, a total of 24 cylinder samples and 18 cylinder samples respectively were required for the first and second phase.

Plate 3.11: Splitting tensile test

- ***Flexural Strength***

According to BSEN 12390(2009), this test was performed through casting beam samples of dimensions 150x150x560 mm. The aim of the test was to determine the flexural strength of the sample of concrete. Plate 3.12 shows the setting of the test. The samples of different mixes were to be casted and tested after 28 days of curing. 3 beams samples were casted for each mix. This means a total of 12 samples and 9 samples were required for the first and the second phase respectively.

Plate 3.12: Flexural test

3.7.3 Durability Performance

For the purpose of durability performance study, chloride penetration resistance and resistance to acid attack were used.

i. Chloride Penetration Resistance.

The objective of this test was to assess the capability of the sisal fiber reinforced lightweight concrete with waste plastic pre-coated scoria aggregates to resist to chloride penetration. The test was performed on cylinders specimen of the diameter of 100 mm and the height of 200 mm of the casted concrete mixture. The test was calibrated to be performed at different ages of the concrete specimens, at 7, 28, and 45 days. For that purpose, after the required 28 days curing period was over, samples were put into a solution of 3% of sodium chloride. Up to the required age, the specimens were removed and tested for the chloride penetration, by breaking each of them into two parts in their longitudinal direction, and by spraying a solution of silver nitrate over the exposed interior broken surface. The presence of this solution on the concrete specimens, caused reactions and a change of colour to white precipitate was noticed, and the depth of penetration was measured accordingly.

ii. Acid Attack

This test was carried out by exposing the cylinder's specimens of Ø150 mm x 300 mm, and cubes specimen of 150 mm x150 mm into a 1% hydrochloric acid solution. Prior to that, the samples were cured for 28 days in water. The target here was to assess the weight loss of cubes specimens and the compressive strength loss through crushing the cylinders at the specific ages of 14 and 45 days.

3.8 Structural performance of sisal fibers reinforced lightweight concrete with waste plastic pre-coated volcanic scoria aggregates

The control mix was designed for a class 30 MPa concrete. Two different types of concrete beams were casted at this stage of work. The first beam type made with the control concrete (with uncoated scoria aggregates and without sisal fibers) was the control beam, and the second beam type was made with the new lightweight concrete developed, "sisal fibers reinforced lightweight concrete with waste plastic pre-coated volcanic scoria aggregates" (the mix one exhibiting the optimum values).

After the mixing stage of the concrete was over, the concrete was placed into a formwork previously made ready at the desired dimensions of 150x200x1000 mm. The curing process started after 24 hours, when the formwork had been removed, and for the period of 28 days. During that period, a membrane was used to cover the specimens allowing water to remain, and preventing effects of temperature changes. Table 3.12 shows the different beam specimen with sizes.

Table 3.12: Beam types with dimensions

Beam type	Control: lightweight concrete with uncoated scoria aggregates	Sisal fibers reinforced lightweight concrete with waste plastic pre-coated scoria aggregates
Dimensions	150x200x1000	150x200x1000
Number	03	03

The structural performance on the different beams was done using a set of equipment and materials for specific needs:

i. A load cell, which is an electronic device (Transducer), was used for recording of loadings applied.

ii. The electrical device for precision measurement of displacements named LVDT (Linear Variable Displacement Transducer), was placed at the middle of beams, for measuring deflections.

iii. Two main types of electrical strain gauges were used, for measuring strains on the concrete and on the steel bars reinforcements. The can be used in various ways as follows:

- Shear stress strain gauges; these were bonded on the shear reinforcements in order to measure the corresponding strains in shear, and also on the surface of the concrete within the shear region of the beams, in order to carry out the corresponding strains on the concrete beams.
- Flexural strain gauges; Flexural strains were measured on reinforcements and on the beam surface where the flexural stresses are higher (at the mid span), For the purpose, the strain gauges were bonded at the mid span on both the longitudinal reinforcements inside the concrete before casting, and on the lateral sides surface of the concrete beam.

iv. The data logger or strain meter is the instrument used to read, translate and record the outputs data measured by those equipments cited above. For that purpose, those equipments were connected properly to its channels.

The beams were casted and tested with reinforcement (shear and longitudinal reinforcements).

The longitudinal reinforcements were 2Y10 at the bottom and 2Y8 at the top of the beams, and R6 for stirrups.

3.8.1 Specimens Preparation

Different types of specimen were cast for hardened concrete tests. Cubes of sizes 150x150x150 mm were prepared for dry density tests. Two cylinders size types of diameter 150 mm and height 300 mm, and of diameter 100 mm and height 200 mm were used respectively for compressive strength tests and splitting tensile strength tests. Beams of size 150x200x1000 mm were cast as well, for structural performance analysis through four point loads flexural tests. The lightweight concrete specimens were made by pouring the concrete into the moulds and compacted using an electric vibrator. The demoulding were carried out after 24 hours later after casting, and the specimens were water cured until the date of testing. Figure 3.1 shows the typical reinforcement arrangement and geometry of the beam specimens tested. The Plates 3.13 and 3.14((a), (b), (c), (d)) show the basic steps of the realization of the steel reinforced beams.

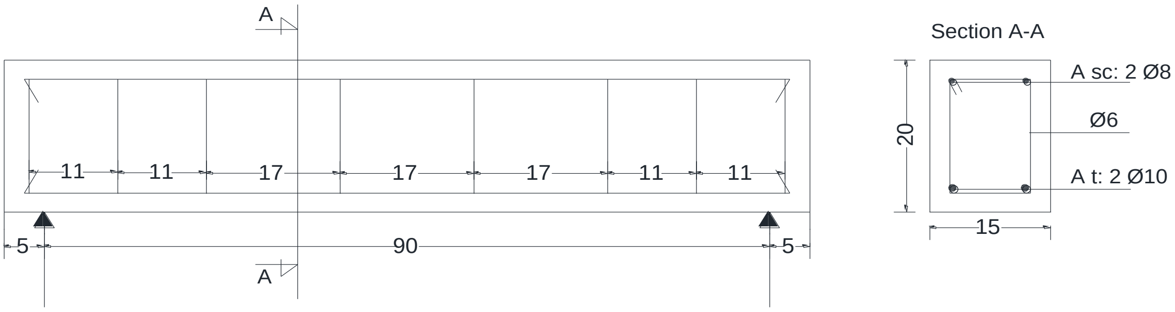
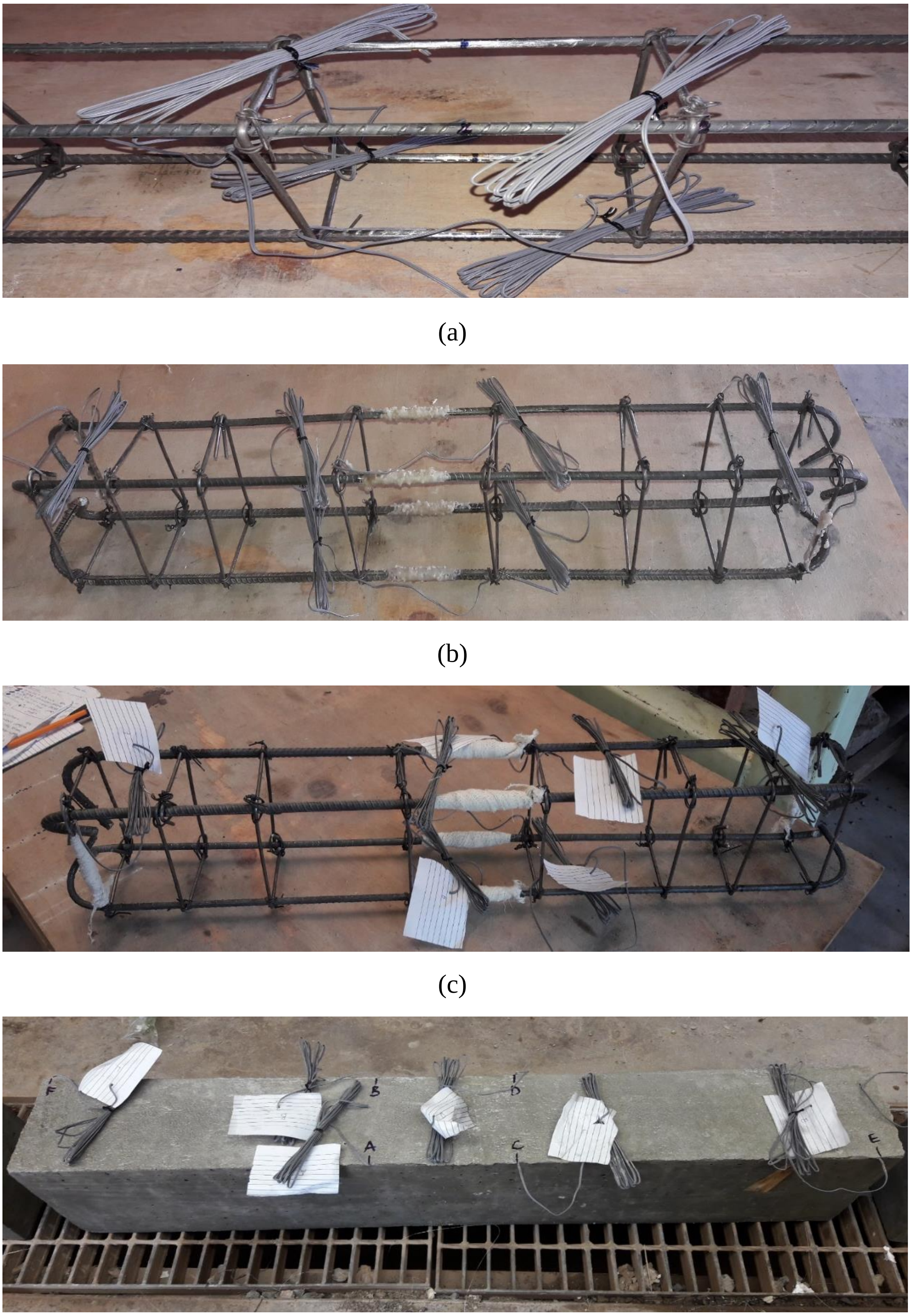


Figure 3.1: Typical reinforcement arrangement and geometry of the beam specimens tested

Plates 3.13: Strain gauges mounted on reinforcements.



(a)

(b)

(c)

(d)

Plates 3.14: realization process of reinforced beams

3.8.2 Four point Flexural test

Two sets of three beams each were tested under four point bending test. The first set was made up of lightweight concrete specimens with uncoated scoria aggregates and without sisal fibers in the matrix denoted as S_0, and the second set with waste plastic pre-coated scoria aggregates and with fibers in the concrete matrix, denoted S_1. Each beam was water cured for 28 days before testing. The tests were carried out by placing the beams on two supporting pins, set at a particular distance apart as shown in Figures 3.2 and 3.3. Each beam was instrumented with 9 concrete strain gauges, 6 steel strain gauges, an LVDT and a load cell, all connected to a data logger. The compressive and tensile strains of beams specimens were measured through 2 concrete strain gauges placed longitudinally along the axis of the beam, respectively on top and at the bottom. The remaining 7 strain gauges were placed at the sides of the beams as shown in Figure 3.3. The data logger was then recording all the specific data transmitted by those censors during the test until failure. The main parameters of interest recorded for analysis, were:

- The first crack and ultimate load
- The mid-span deflection
- The mode of failure and crack patterns
- The concrete and steel stress-strain characteristics (tensile, compressive and shear)

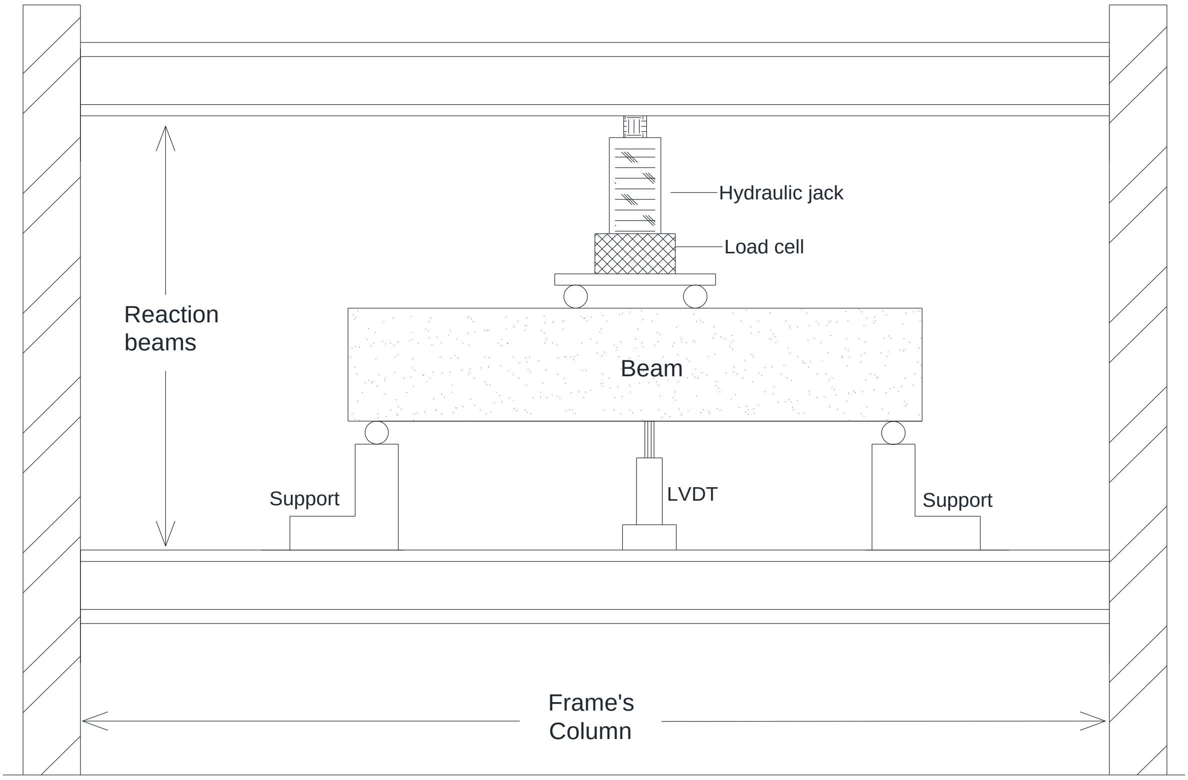


Figure 3.2: Set up of the four-point bending test.

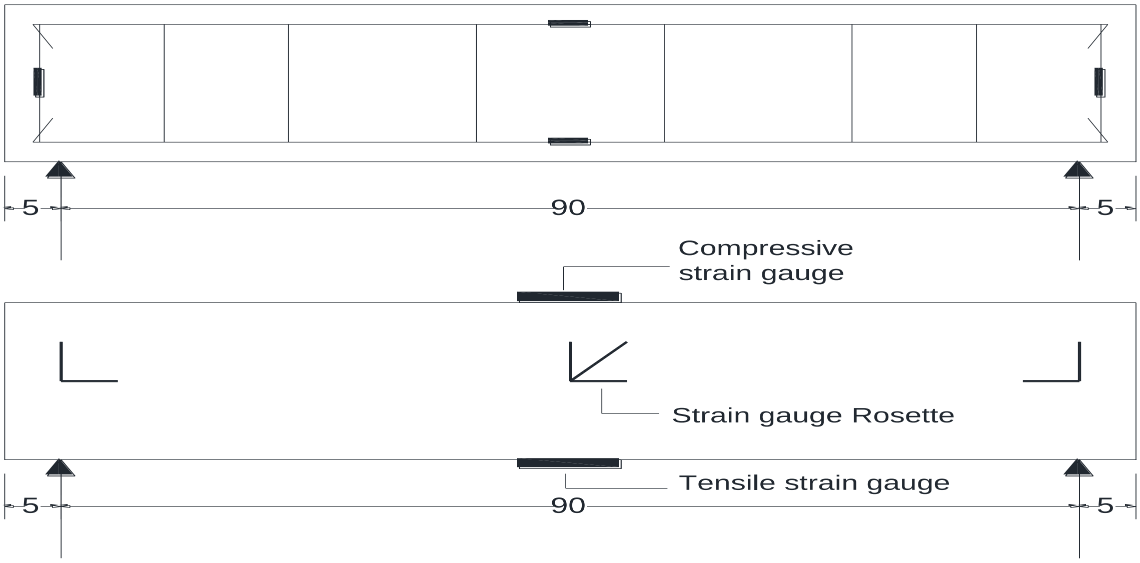


Figure 3.3: Disposition of the concrete and steel strain gauges.

All the results from the different tests performed are stated, analyzed and discussed in chapter four of the thesis. Some results are found in appendix as well.

CHAPTER FOUR

RESULTS, ANALYSIS AND DISCUSSION

4.1 General

In order to attain the objectives of this research, the following activities were undertaken:

- A survey of the related literatures was carried out. The properties of the constituent materials of concrete, methods of investigation of materials, methods of proportioning of lightweight concrete mixes and properties of hardened concrete were covered in the literature review.
- Investigations of the materials were done and relevant material characteristics were evaluated.
- Mix designs were performed using scoria as coarse aggregate and sand as fine aggregate. Batches were prepared according to the ACI method of Mix Design.

Casting of Concrete was done according to the absolute volume method of mix design results retained out the three methods of mix design evaluated, achieved in accordance with the ACI 211.2-98 standard.

Results analysis and discussion are presented in the next sections of this chapter.

4.2 Material Investigation

4.2.1 Cement

The chemical composition of the Ordinary Portland Cement type I (CEM 42.5) used for this study as given by the supplier Bamburi Cement Ltd Company, and some physical properties respectively are presented in appendix 2.

4.2.2 Aggregates

i. Fine aggregates: Sand

- **Specific gravity and water absorption of sand**

Table 4.1 gives presented in the specific gravity and water absorption of sand aggregates used. The sample sand was found suitable. The apparent specific gravity was found to be 2.75 as the most of the natural aggregates (about 2.7) as for ASTM C29 (2003).

Table 4.1: specific gravity and water absorption of sand

Specific Gravity and water absorption of Sand				
Tests	1	2	3	
Weight of bottle + Sample + Water (**A**) g	1641	1655	1655	
Weight of bottle + Water (**B**) g	1343	1351	1351	
Weight of SSD Sample (**C**) g	500	500	500	
Weight of Oven Dried Sample (**D**) g	468	475.5	475.5	
				Mean
1) Specific. gravity on oven dried basis = D/ (C-(A-B))	*2.31*	*2.42*	*2.42*	**2.365**
2) Specific. gravity on a SSD basis = C/ (C-(A-B))	*2.46*	*2.54*	*2.54*	**2.507**
3) Apparent Specific. Gravity = D/ (D-(A-B))	*2.74*	*2.76*	*2.76*	**2.755**
4) Water absorption (% of dry mass) = 100 (C-D)/D	*4.75*	*4.90*	*4.45*	**4.70**

Bulk unit weight of sand (Loose and compacted)

Table 4.2 gives the bulk density of sand aggregates. The density of the sample sand was found suitable. The ratio of the loose and compacted bulk density (which here is 0.91), lies conventionally between the limits of 0.87 and 0.96 as prescribed by the standard ASTM C29 (2003).

Table 4.2: Bulk density of sand

Bulk Density of Sand			
Loose Bulk Density of Sand			
Tests	1	2	3
Weight of Tare M1 (g)	1540	1542	1541.5
Weight of Tare + Sand M2 (g)	4523.5	4450.5	4417
Weight of Sand M3 = M2-M1 (g)	2983.5	2908.5	2875.5
Volume of the Tare (V=2000 cm3)	2000	2000	2000
Loose Bulk Density of Sand ϕs = M3/V (g/cm3)	1.491	1.454	1.43
Mean of Loose Bulk Density of Sand (g/cm3)		1.461	
Mean of Loose Bulk Density of Sand (kg/m3)		**1461**	
Rodded Bulk Density of Sand			
Tests	**1**	**2**	**3**
Weight of Tare M1 (g)	1539.5	1540.5	1540.5
Weight of Tare + Sand M2 (g)	4802	4716	4720

Weight of Sand M3 = M2-M1 (g)	3262.5	3175.5	3179.5
Volume of the Tare (V=2000 cm3)	2000	2000	2000
Rodded Bulk Density of Sand ϕs = M3/V (g/cm3)	1.63125	1.58775	1.5898
Mean of Rodded Bulk Density of Sand (g/cm3)		1.60292	
Mean of Rodded Bulk Density of Sand (kg/m3)		**1.602.92**	

- **Particle size distribution of the aggregates**

The Particle size distribution was determined as shown in Table 4.3. The initial weight of sample was 1000 g. The sand was found well graded according to ASTM C33-05. The graving curve was as shown in Figure 4.1

Table 4.3: Particles size distribution of sand aggregates

Sieve size	***Mass retained***	***percentage retained***	***Cumulative percentage by weight passing***	***Cumulative percentage retained***	***Limits (Upper-Lower) as prescribed by the standard ASTM C33-05***
4.75	0	0	***100***	0	***95-100***
2.36	28.83	2.883	***97.117***	2.883	***80-100***
1.18	79	7.9	***84.217***	10.783	***50-85***
0.6	393.17	39.317	***49.9***	50.1	***25-60***
0.3	218.5	21.85	***28.05***	71.95	***10-30***
0.150	248.5	24.85	***3.2***	96.8	***2-10***
Fine (Pan)	32	3.2			
Total	1000	100		232.516	

Fineness modulus = 232.516/100 = **2.32**

The Fineness Modulus of the Sample Sand ranged within the typical values of 2.3 to 3.0 as for ASTM C330-05.

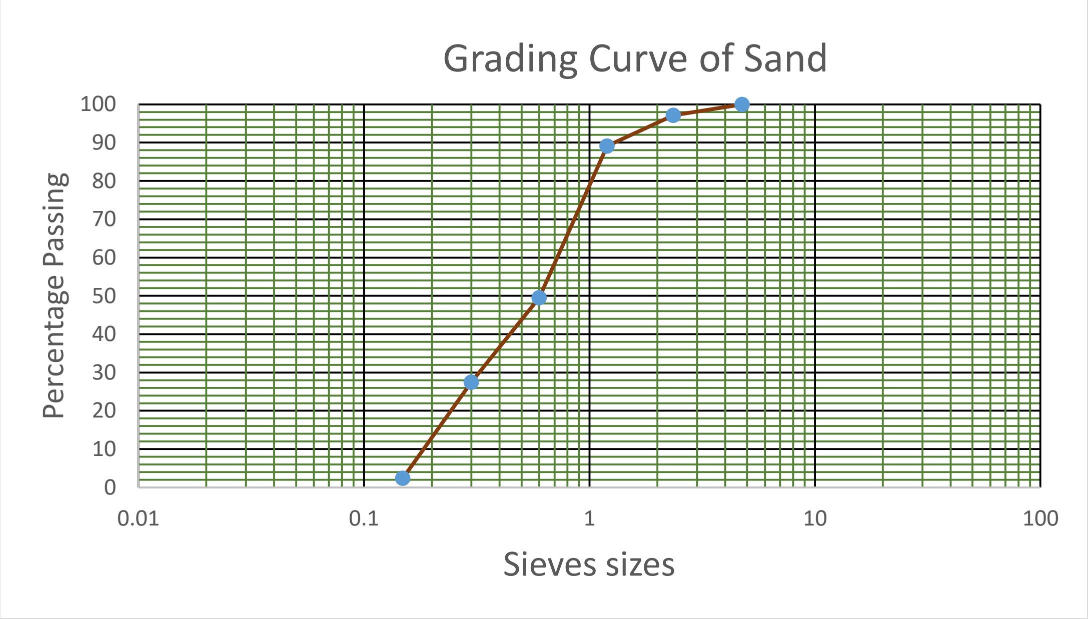


Figure 4.1 grading curve of sand

ii. Coarse aggregates: uncoated and pre-coated volcanic scoria aggregates

- **Chemical composition of the volcanic scoria aggregates used in the study**

The chemical composition of the volcanic scoria aggregates used in the study is presented in appendix 3.

- **Specific gravity and water absorption of uncoated volcanic scoria aggregates**

Table 4.4 gives the specific gravity and water absorption of uncoated volcanic scoria aggregates obtained. This scoria aggregates have an apparent specific gravity of 2.54 which is lower than 2.60, and the Oven dry Particles density was found to be about 1907 kg/m3 less than 2000 kg/m3, making them acceptable as LWA according to ASTM C330 Standard.

Table 4.4: specific gravity and water absorption of uncoated volcanic scoria aggregates

Specific Gravity and water absorption of uncoated volcanic scoria aggregates				
Tests	**1**	**2**	**3**	
Weight of bottle + Sample + Water (**A**) g	1569.5	1570	1569.5	
Weight of bottle + Water (**B**) g	1301.5	1301.5	1302	
Weight of SSD Sample (**C**) g	500	500	500	
Weight of Oven Dried Sample (**D**) g	441.5	443	442	
				Mean
1) Specific. gravity on oven dried basis = D/ (C-(A-B))	*1.903*	*1.914*	*1.904*	***1.907***
2) Specific. gravity on a SSD basis = C/ (C-(A-B))	*2.155*	*2.159*	*2.155*	***2.157***
3) Apparent Specific. Gravity = D/ (D-(A-B))	*2.544*	*2.538*	*2.544*	***2.542***
4) Water absorption (% of dry mass) = 100 (C-D)/D	*13.25*	*12.86*	*13.24*	***13.06***

- **Specific gravity and water absorption of pre-coated volcanic scoria aggregates samples at respectively 5%, 10% and 15%.**

Specific gravity and water absorption of pre-coated volcanic scoria aggregates samples was as shown in Figure 4.2 and appendix 4. It is noticeable from the data provided in that, the specific gravity and water absorption of the aggregates decrease when the plastic content over the aggregates increase. From 0% to 15% of waste plastic, the water absorption was found to decrease by about 13.06% to 5.67%.

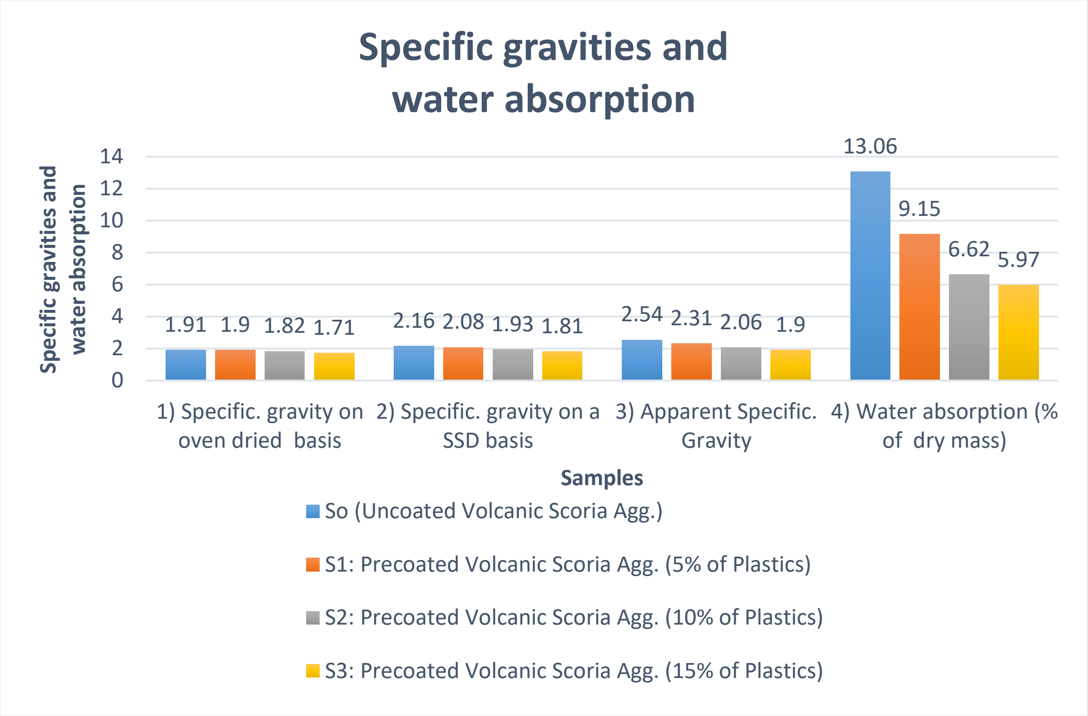


Figure 4.2 Specific gravities and water absorption of volcanic scoria aggregates samples.

- **Bulk unit weight of uncoated volcanic scoria aggregates (Loose and compacted)**

Table 4.5 gives the bulk density of uncoated volcanic scoria aggregates. The Loose bulk density (1013.57 kg/m3) is lower than 1200 kg/m3, as prescribed by the standard. Those properties make them acceptable as LWA for production of LWC.

Table 4.5: Bulk density of uncoated volcanic scoria aggregates.

Bulk Density of scoria aggregates (Oven dried)			
Loose Bulk Density of scoria aggregates			
Tests	1	2	3
Weight of Tare M1 (g)	1553.5	1553.5	1553.5

Weight of Tare + Scoria Agg. M2 (g)	3662.5	3628	3643
Weight of Scoria Agg. M3 = M2-M1 (g)	2109	2074.5	2089.5
Volume of the Tare (V=2063 cm3)	2063	2063	2063
Loose Bulk Density ϕsc = M3/V (g/cm3)	1.022	1.005	1.013
Mean of Loose Bulk Density (g/cm3)	**1.01357**		
Mean of Loose Bulk Density (kg/m3)	***1013.57***		
Rodded Bulk Density of Volcanic Scoria Agg.			
Tests	1	2	3
Weight of Tare M1 (g)	1554	1554	1554
Weight of Tare + Scoria M2 (g)	3987.5	3995.5	3976.5
Weight of Scoria M3 = M2-M1 (g)	2433.5	2441.5	2422.5
Volume of the Tare (V=2063 cm3)	2063	2063	2063
Rodded Bulk Density ϕsc = M3/V (g/cm3)	1.179	1.183	1.174
Mean of rodded Bulk Density (g/cm3)	**1.17910**		
Mean of rodded Bulk Density. (kg/m3)	***1179.10***		

- **Bulk unit weight of pre-coated volcanic scoria aggregates samples (Loose and compacted) at respectively 5%, 10% and 15%.**

Table 4.6 gives the bulk density of pre-coated volcanic scoria aggregates samples. The same observations were done as regard to the bulk density. It decreased when the plastic content over the aggregates increased, as shown in Figures 4.3 and 4.4.

Table 4.6: Bulk density of pre-coated volcanic scoria aggregates samples.

	Pre-coated scoria (**5% of Plastics**)	Pre-coated scoria (**10% of Plastics**)	Pre-coated scoria (**15% of Plastics**)
1) Loose bulk density of Volcanic scoria (oven dried) (kg/m3)	987.55	958.63	916.46
2) compacted bulk density of Volcanic scoria (oven dried) (kg/m3)	1149.02	1115.20	1066.14

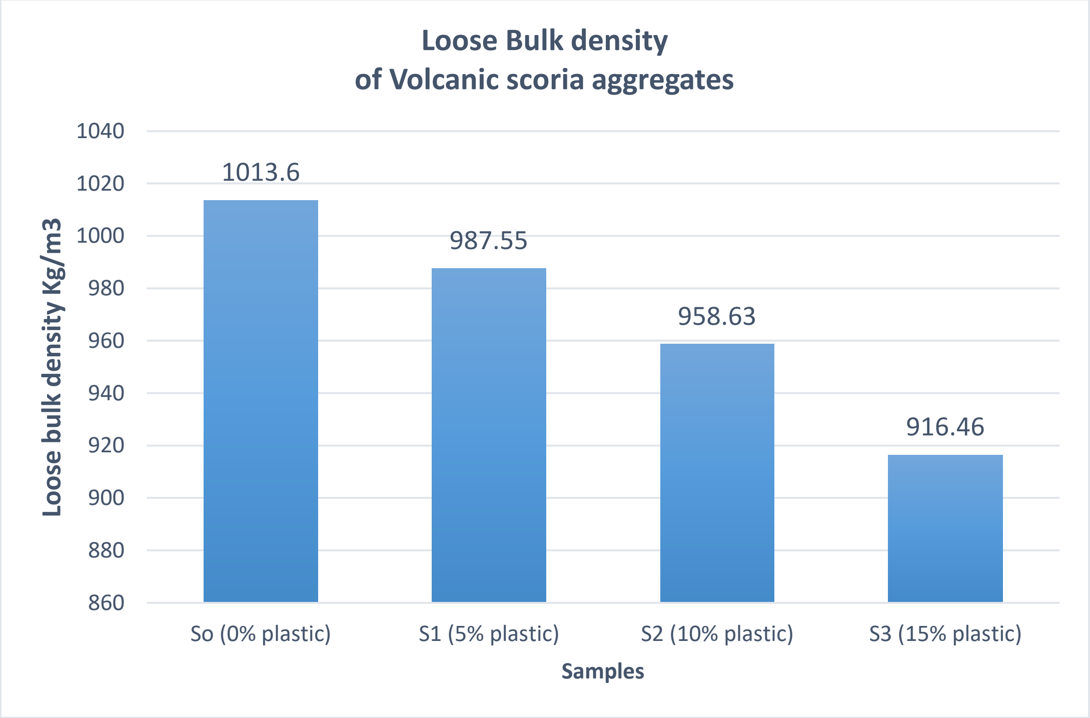


Figure 4.3: Loose bulk density of different volcanic scoria aggregates samples

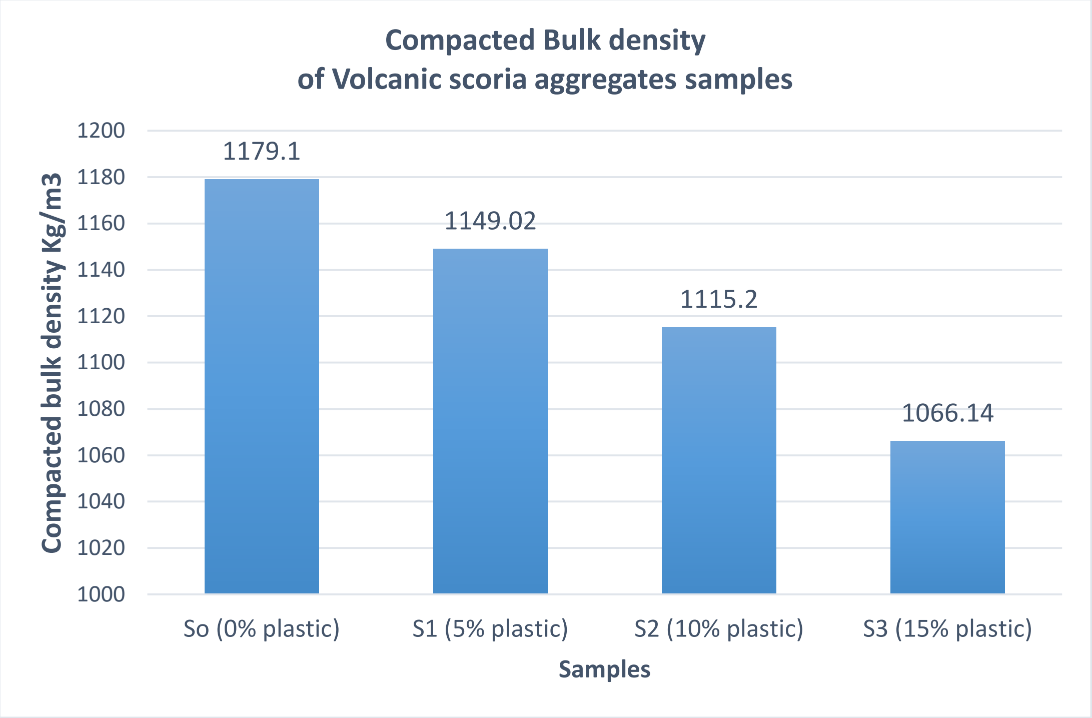


Figure 4.4: Compacted bulk density of different volcanic scoria aggregates samples

- **Particle size distribution of the aggregates**

The particles sizes distribution of scoria aggregates was found as shown in Table 4.7. The initial weight of sample was 9000 g. According to ASTM C330 Standard, the percentage by mass passing the sieves were all in the recommended ranges. So, the scoria aggregates samples are well graded. Figure 4.5 shows the grading curve.

Table 4.7: Particles size distribution of Scoria aggregates

Sieve size	***Mass retained (g)***	***percentage retained***	***Cumulative percentage by weight passing***	***Cumulative percentage retained***	***Limits (Upper-Lower) as prescribed by the standard ASTM C330-05***
25	0	0	***100***	0	***100***
19	6.75	0.075	***99.92***	0.076	***90-100***
12.5	903.5	10.10	***90.01***	10.18	***90-100***
9.52	4850.5	54.26	***35.35***	64.45	***10-50***
4.75	2709.75	30.31	***5.23***	94.76	***0-15***
2.36	426.75	4.77	***0.46***	99.54	***0-15***
1.18	28.75	0.32	***0.14***	99.86	***0-15***
0.6	0	0	***0.14***	99.86	***0-15***
0.3	0	0	***0.14***	99.86	***0-15***
0.150	0	0	***0.14***	99.86	***0-15***
Fine (Pan)	12.5	0.14			***0-10***
Total	8938	100		232.516	

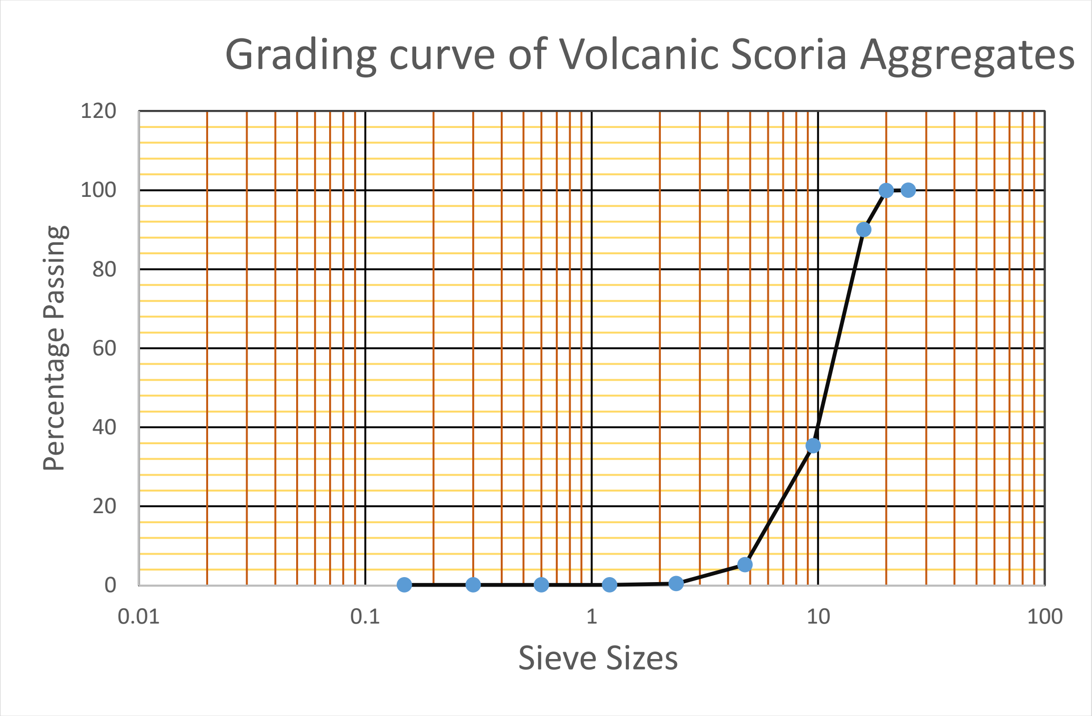


Figure 4.5 grading curve of volcanic scoria aggregates

4.2.3 Sisal fibers

The chemical composition of the sisal fibers were obtained and presented in appendix 5.

4.3 Mix Proportions and results

4.3.1 Mixes Proportions

Three different methods for designing structural lightweight concrete as prescribed by ACI 211.2-98 (Standard practice for selecting proportion for structural lightweight concrete) were applied here;

- The weight method: specific gravity pycnometer,
- The absolute volume Method,
- The volumetric method (damp or loose volume method).

The design was carried out using the three different approaches, with the purpose to find the one giving the best results regarding the expected design strength, the workability, and the dry density. Table 4.8 gives the proportions found for each methods.

Table 4.8: Mix design proportion for each method used

Mix design Method	**Lightweight Coarse aggregate content (SSD) kg/m3**	**Sand content (SSD) kg/m3**	**Water cement ratio (W/C)**	**Water content kg/m3**	**Cement content kg/m3**
Method 1: *Weight method*	848.03	339.12	0.45	187	415.6
Method 2:*Absolute volume method*	516	764.64	0.45	187	415.6
Method 3:*Damp loose method*	710.36	775.93	0.45	187	374.86

The absolute volume method was chosen for the continuity, because it provided the best results in terms of expected design strength, workability and density. Table 4.9 shows the mix proportions retained for the lightweight concretes with uncoated and waste plastics pre-coated scoria aggregates at different percentages by weight replacement of aggregates.

Table 4.9 Different mix proportions with different waste plastic content over the scoria aggregates.

Mix design	**Lightweight Coarse aggregate content (SSD) kg/m3**	**Sand content (SSD) kg/m3**	**Water cement ratio (W/C)**	**Water content kg/m3**	**Cement content kg/m3**	**Waste plastic content %, by weight of scoria (Kg/m3)**
So *(Control)*	516	764.64	0.45	187	415.6	0%
S1 *(95% Scoria+5% plastics)*	490.2	764.64	0.45	187	415.6	5%(25.8)
S2 *(90% Scoria+10% plastics)*	464.4	764.64	0.45	187	415.6	10%(51.6)
S3 *(85% Scoria+15% plastics)*	438.6	764.64	0.45	187	415.6	15%(77.4)

Then, Table 4.10 shows the different mix proportions having sisal fibers at different percentage in the concrete matrix by weight of cement.

Table 4.10 Different mix proportions incorporating sisal fibers at different percentage in the matrix.

Mix design	**Lightweight Coarse aggregate content (SSD), kg/m3**	**Sand content (SSD) kg/m3**	**Water cement ratio (W/C)**	**Water content kg/m3**	**Cement content kg/m3**	**Fiber content (%) Added**
So *(Control)*	516	764.64	0.45	187	415.6	0%
S1 *(95% Scoria+5% plastics) + 0% Fiber*	516	764.64	0.45	187	415.6	0%
S1 *(95% Scoria+5% plastics)* **+ 1% Fiber**	516	764.64	0.45	187	415.6	1%
S1 *(95% Scoria+5% plastics)* **+ 1.5% Fiber**	516	764.64	0.45	187	415.6	1.5%
S1 *(95% Scoria+5% plastics)* **+ 2% Fiber**	516	764.64	0.45	187	415.6	2%

4.3.2 Results

i. General results at 7 days for the 3 mix design approaches

The compressive, splitting tensile strengths at 7 days, dry density and slump for each mix design method is presented in Table 4.11.

Table 4.11: Compressive, splitting tensile strengths at 7 days, dry density and slump for each mix design method

Mix design Method	***7 days compressive strength (MPa)***	***7 days Splitting tensile strength (MPa)***	***24 hours-Dry density (kg/m3)***	***Slump (mm)***
Method 1: *Weight method*	17.89	1.77	1820	15.5
Method 2:*Absolute volume method*	***21.81***	***2.44***	***1847***	***50***
Method 3:*Damp loose method*	18.97	1.95	1837	94

The results in the Table justify why the absolute volume method was chosen to proceed. The lightweight concrete mix designed by the absolute volume method fitted into all the requirements provided by ACI 211.2-98, ASTM C330, and ASTM C567, regarding the minimum 28 days-compressive strength (≥17.2 MPa) and the maximum unit weight of concrete (≤1842 kg/m^3).

ii. Workability: Slump test

- **<u>Uncoated and Pre-coated volcanic scoria aggregates lightweight concrete at different percentages of waste plastic over the aggregates</u>**

The slump test was carried out in-situ in order to test the workability of each mix. Below are the slump test results for the different mixes using uncoated and pre-coated volcanic scoria aggregates. Tests were conducted according to the standard prescribed in BSEN 12350 (2009). The cone was filled in three layers, each one compacted 25 times using a tamping rod with a diameter of 16 mm. Figure 4.6 shows the slump values obtained for each lightweight concrete sample made with pre-coated aggregates at 5%, 10% and 15%. According to the results the increase of waste plastic pre-coating the scoria aggregates resulted lower slump of the resulting lightweight concrete. The more was plastic on the aggregates, the lesser was the density of the aggregates and therefore the lower the density of the resulting lightweight concrete. Thus, their reduced weight affect the slump values, since the slump also depends on the density of the constituents materials of the concrete.

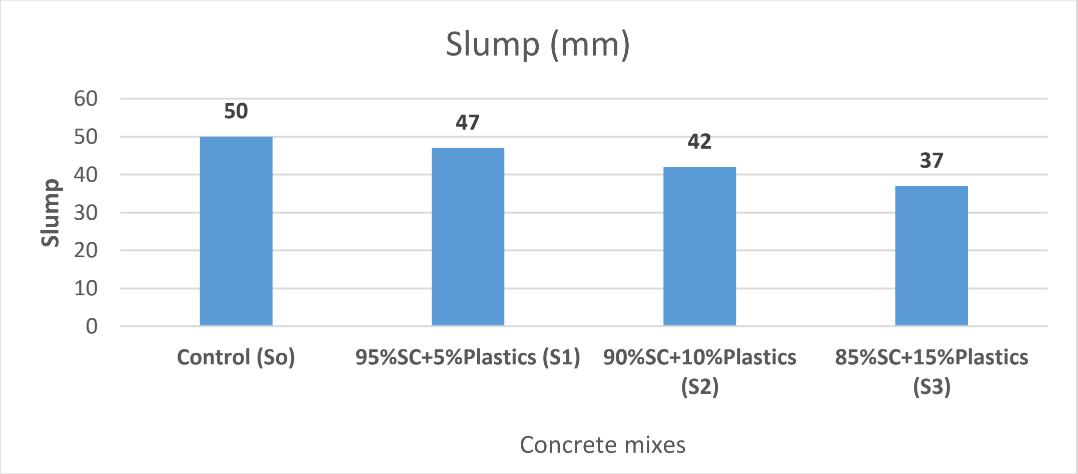


Figure 4.6: Slump variation with different waste plastics content over the aggregates in the lightweight concrete mixes.

- **<u>Lightweight concrete with different percentages of sisal fibers in the matrix</u>**

The results obtained are shown in Figure 4.7. It shows a decrease of the slump values with the increase of sisal fibers content in the lightweight concrete matrix, until no slump observed with 2% of fiber. This can be directly related to the absorption capability of the sisal fibers. Their presence reduces the amount of mixing water in the mix, thus affecting the slump values.

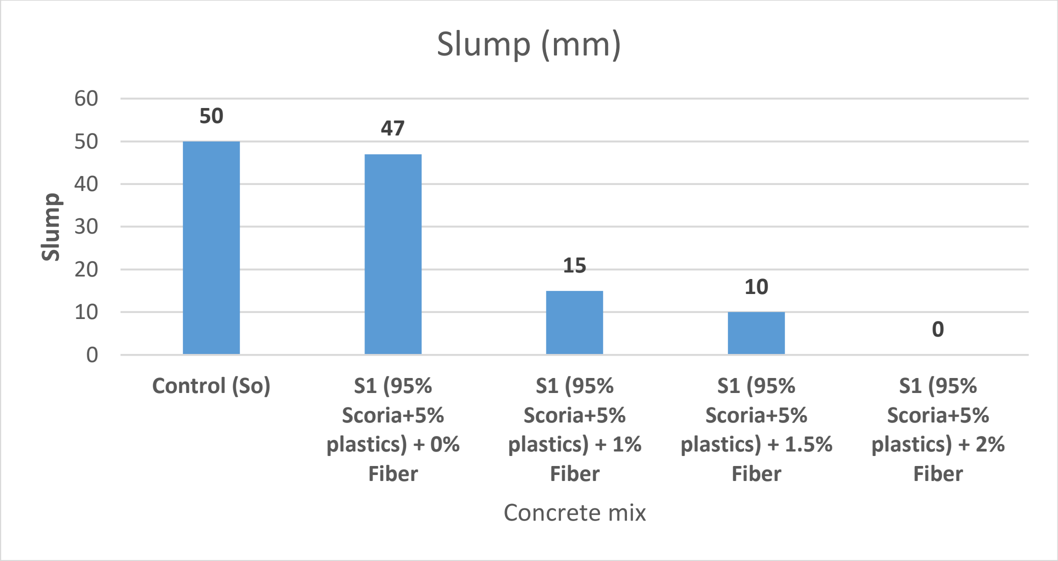


Figure 4.7: Slump variation for the different mixes with different percentages of sisal fibers in the lightweight concrete matrix.

iii. Dry density

- **<u>Uncoated and Pre-coated volcanic scoria aggregates lightweight concrete at different percentages of plastics over the aggregates</u>**

For each mix, 3 cubes of 150 mm x150 mm x150 mm were casted for the dry density. The specimens were demoulded 24 hours later after casting, and left in a room temperature for 24 hours before drying them at 105±5 °C in an oven for another 24 hours. The results portrays a decrease of the dry density of the resulting lightweight concrete when the waste plastic contents on the scoria aggregates increase. This can be explained by the fact that the unit weight of the pre-coated scoria aggregates also decrease when we increase the plastic content on the aggregates, therefore affects the unit weight of the resulting mix. Figure 4.8 gives the density values for all the concrete specimens containing different waste plastic content on aggregates.

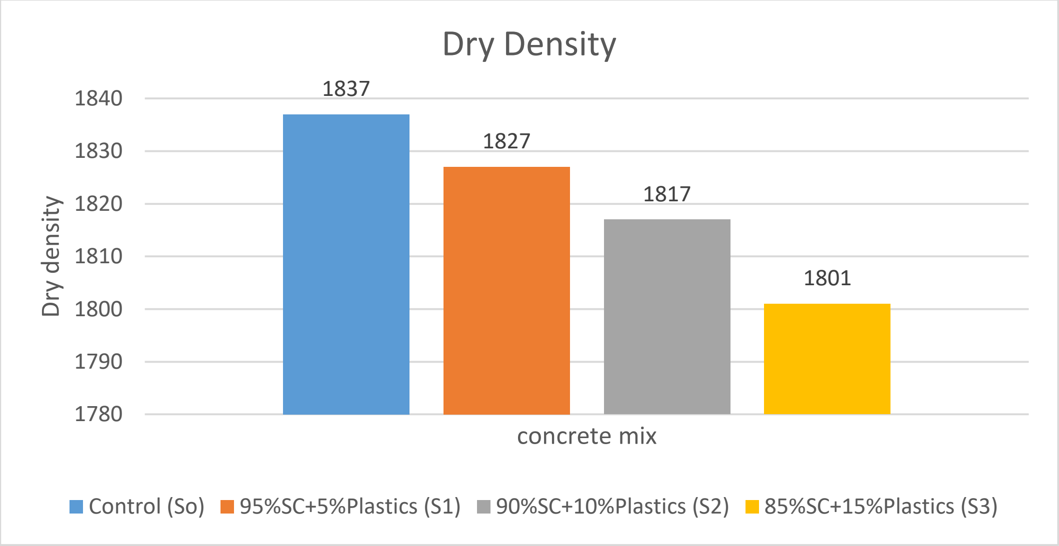


Figure 4.8: Dry density for the different mixes with uncoated and pre-coated scoria aggregates at different percentages.

- **Lightweight concrete with different percentages of sisal fibers in the matrix**

Figure 4.9 shows the results regarding the dry density of the lightweight concrete specimens containing sisal fibers. The dry density decreases with the increase of sisal fibers contents. This can be explained by the light nature of the sisal fibers. It affects the lightweight concrete density by reducing its unit weight.

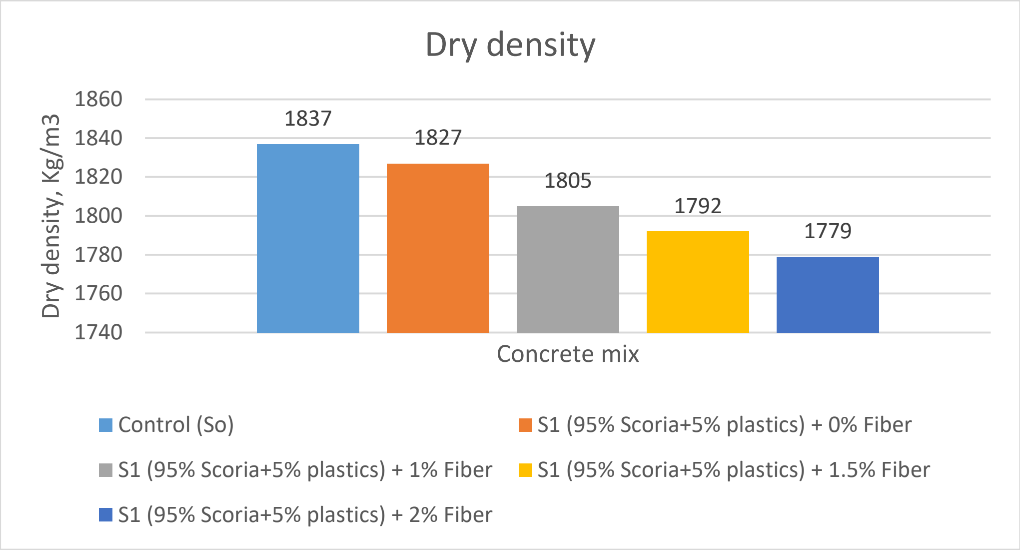


Figure 4.9: Dry density for the different mixes with different percentage of sisal fibers in the lightweight concrete matrix.

iv. Strengths

❖ ***Compressive strength***

The compressive strength was carried out on cylinders of Ø150 mm x 300 mm using an UTM Compression machine according to the specifications of ACI 211.2-98 and ASTM C330. The tests were carried out at 7 and 28 days.

▪ **Uncoated and Pre-coated volcanic scoria aggregates lightweight concrete at different percentages of plastics over the aggregates**

The results showed that the lightweight concrete specimen with 5% of waste plastic pre-coated aggregates gave the highest compressive strength. At 28 days, the compressive strength of that lightweight concrete specimen was found to increase by 10.46% as compared to the control. However, after the waste plastic content of 5%, the compressive strength was found decreasing with the increase of the waste plastic content. The waste plastic pre-coating the scoria aggregates helped to reduce their water absorption capability from 13.06% to 9.15%, resulting in the increase of the concrete compressive strength, because lesser mixing water was required. However, after 5%, the compressive strength started to decrease. The explanations can be regarding the thickness of the coating material. At a certain high contents (after 5%) of waste plastics on the scoria aggregates, the thickness of the plastic on the aggregates becomes deeper as to affect the bonding between the cement and the other constituents materials, leading to the loss of compressive strength. The results are shown in Figure 4.10.

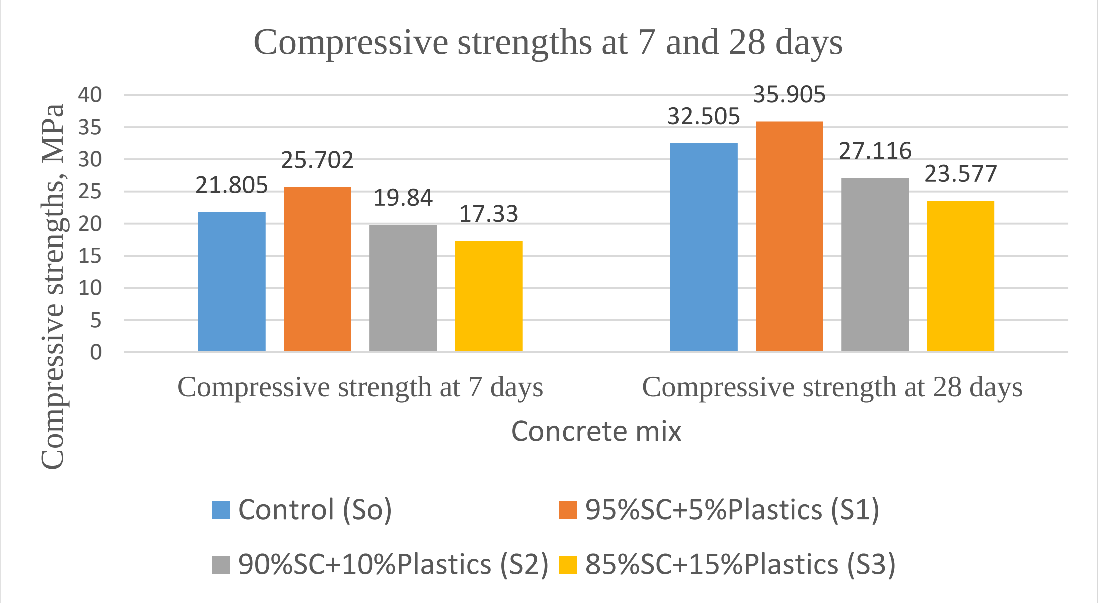


Figure 4.10: Compressive strengths at 7 and 28 days of the different concrete samples containing different waste plastics contents over the aggregates.

- **Lightweight concrete with different percentages of sisal fibers in the matrix**

The lightweight concrete specimen with waste plastic pre-coated scoria aggregates at 5% was casted with different sisal fibers contents in the concrete matrix and tested for compressive strength at 7 and 28 days. The results showed that the compressive strength decreased with the addition of sisal fibers in comparison with the control specimen, as shown in Figure 4.11. With the addition of 1% of fibers by weight of cement, the compressive strength decreased by 25.49%. Sisal fiber is not a cementitious material and its presence in the concrete matrix reduces the bonding between the cement and the other constituent materials. This can explained what was observed regarding the compressive strength.

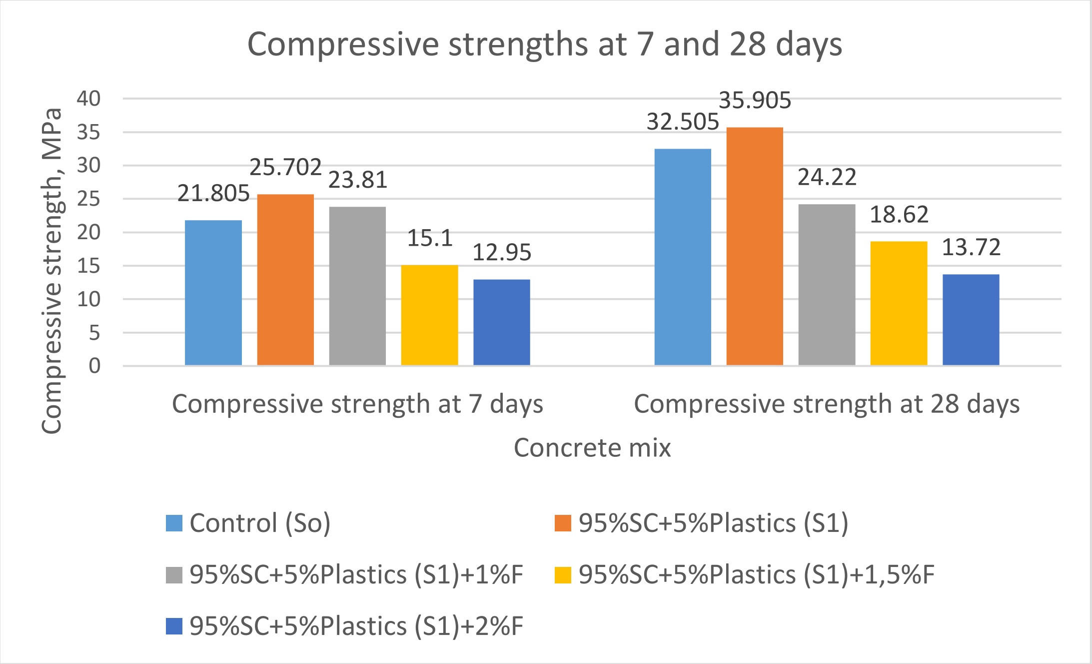


Figure 4.11: Compressive strengths at 7 and 28 days of the different concrete samples containing different sisal fibers contents in the matrix

- **Splitting tensile strength**
  - **<u>Uncoated and pre-coated volcanic scoria aggregates concrete at different percentages</u>**

The same trend as what was gotten with the compressive strength, was also observed regarding the splitting tensile strength test results on lightweight concrete specimens containing waste plastic pre-coated scoria aggregates at different percentages. The results showed that the lightweight concrete specimen with 5% of waste plastic pre-coated aggregates gave the highest splitting tensile strength, as shown in Figure 4.12. At 28 days, it was found to increase by 1.82% as compared to the control. Thereafter, the increase of the waste plastic content affects negatively the splitting tensile strength of the resulting lightweight concrete. It was found decreasing. The same explanations stated above regarding the influence of high waste plastic content on the compressive strength of the resulting concrete remain valid here as regards to the splitting tensile strength.

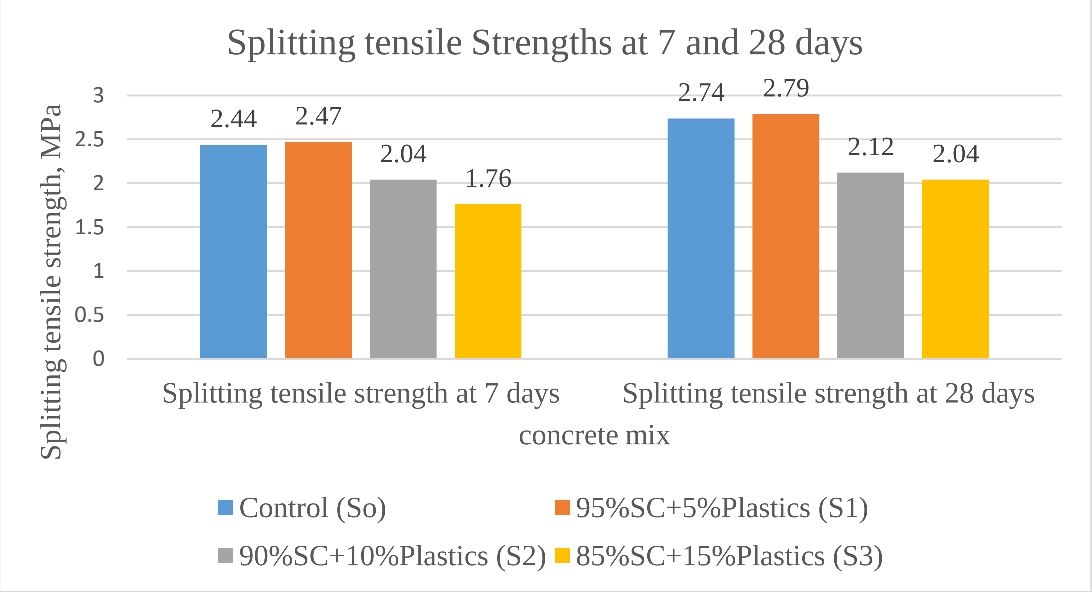


Figure 4.12: Splitting tensile strengths at 7 and 28 days of the different concrete samples containing different waste plastics contents over the aggregates.

- **Lightweight concrete with different percentages of sisal fibers in the matrix**

The lightweight concrete specimen with waste plastic pre-coated scoria aggregates at 5% was casted with 1%, 1.5% and 2% of sisal fibers in the concrete matrix and tested for splitting tensile strength at 7 and 28 days. The results are shown in Figure 4.13.

They showed that 1% of sisal fibers content by weight of cement was the best percentage. With the addition of 1% of fibers, the splitting tensile strength was found to increase by 6.20% as compared to the control, then decreased with the addition of 1.5% and 2%. That increase can be explained by the fact that sisal fiber has a relatively good resistance in traction as compared to the concrete. Therefore, its presence in the concrete matrix improves the tensile strength of the resulting concrete.

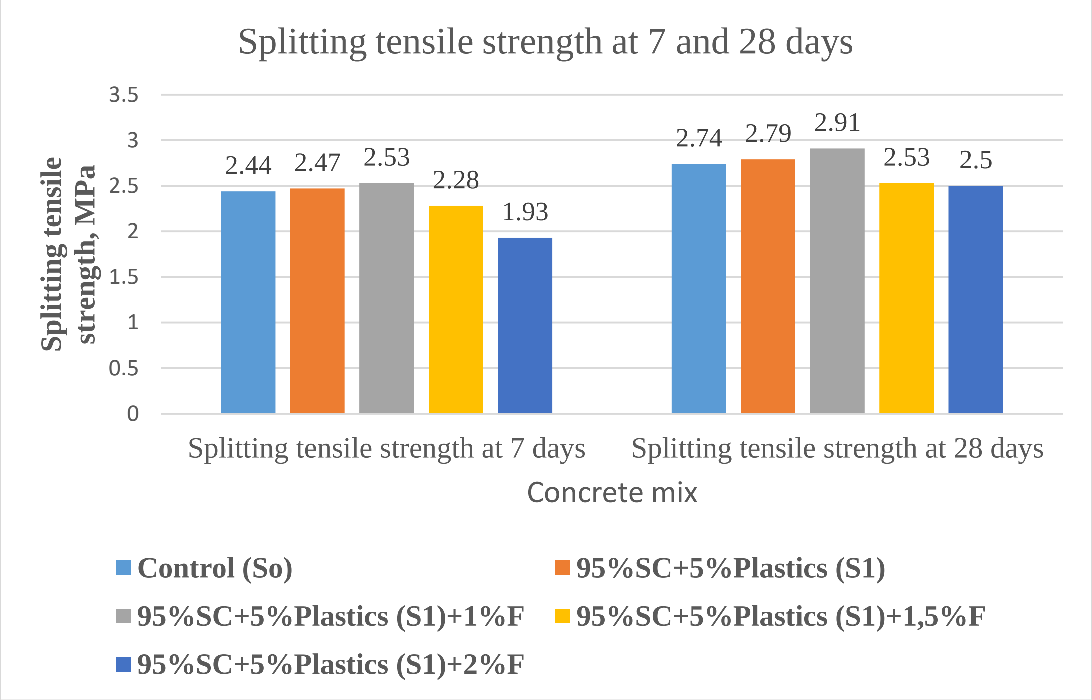


Figure 4.13: Splitting tensile strengths at 7 and 28 days of the different concrete samples containing different sisal fibers contents in the matrix.

- **Flexural strength**
  - **Uncoated and pre-coated volcanic scoria aggregates concrete at different percentages**

A slight increase of the flexural strength of about 3.43% was noticed with the lightweight concrete specimen made with waste plastic pre-coated scoria aggregates at 5%. Figure 4.14 shows the results obtained for the different specimens tested for flexural strength.

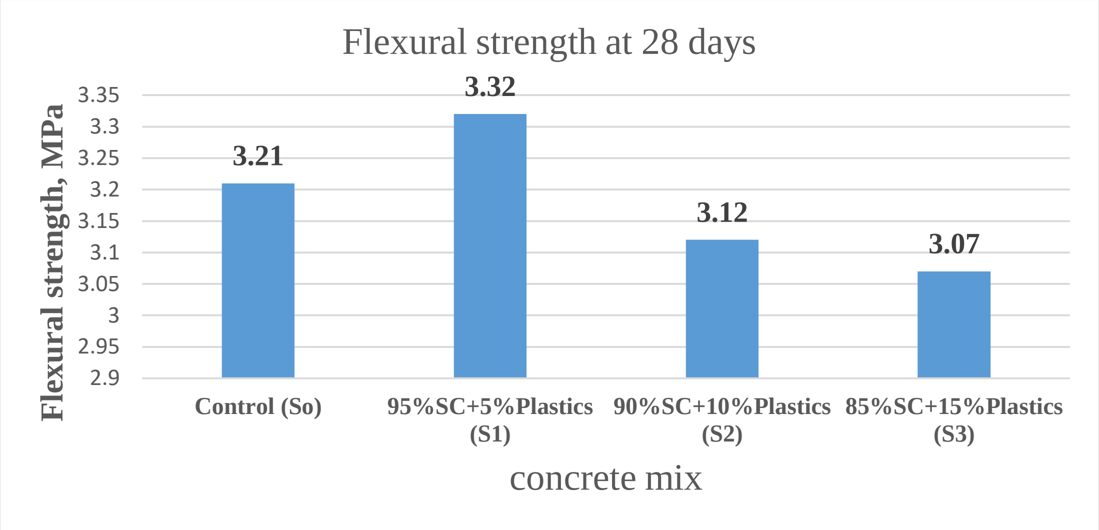


Figure 4.14: Flexural strengths at 28 days of the different mix concrete samples containing different waste plastics contents over the aggregates.

- **<u>Lightweight concrete with different percentages of sisal fibers in the matrix</u>**

The results showed that the lightweight concrete specimen with waste plastic pre-coated scoria aggregates at 5% having 1% of sisal fibers in the matrix was the best mix as regards to the flexural strength, as shown in Figure 4.15 With the addition of 1% of fibers, the flexural strength was found to increase by 40.81% as compared to the control, then decreased with the addition of 1.5% and 2%; however, the strengths values were found greater for all the specimens containing fibers as compared to the control mix. The explanations were in line with what was explained above regarding the increase of the splitting tensile strength due to the presence of fibers in the matrix. Sisal fiber can actually increase the flexural strength of concrete due to its good resistance in traction as compared to that of the lightweight concrete.

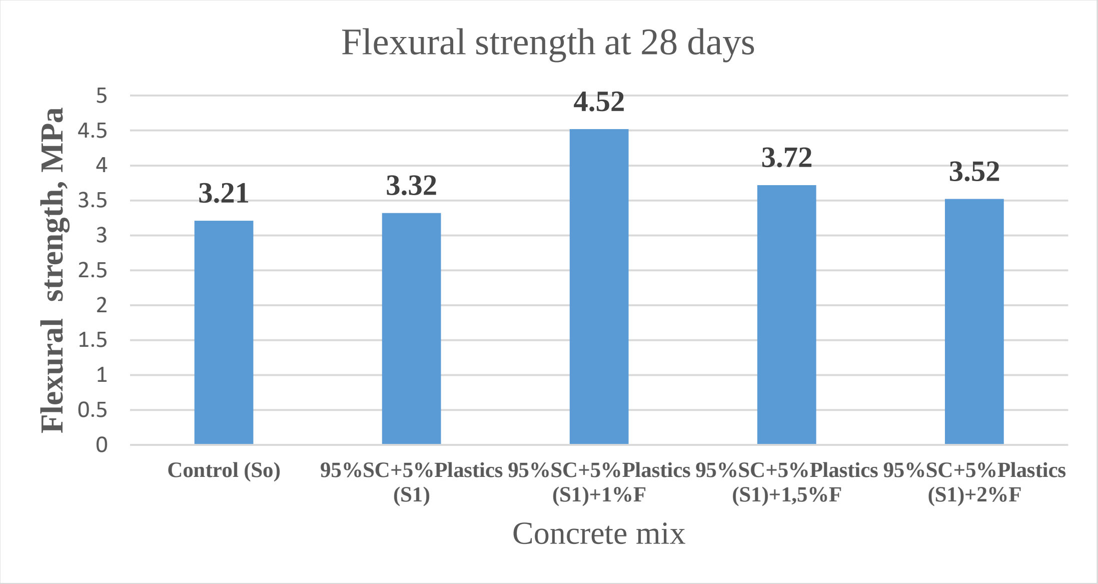


Figure 4.15: Flexural strengths at 28 days of the different mix concrete samples containing different sisal fibers contents in the matrix.

v. Durability Performance

❖ Chloride penetration resistance

The main objective of this experiment was to evaluate the free chloride penetration depth in the concrete specimens. The two main concrete specimens were under the experiment, the control lightweight concrete specimen S_0 and the resulted lightweight concrete specimen with 5% of plastics over the scoria aggregates and 1% of sisal fibers in the matrix, named S_1. The specimens were immersed into a sodium chloride solution at 3% for a duration of up to 45 days. The silver nitrate colorimetric method was used as it is a very easy and quick way to measure the free chloride penetration depth in concrete. With the method, at the date of testing, the concrete specimen cylinders of size Ø100x200 were split longitudinally as shown in Plate 4.1, then silver nitrate solution was sprayed onto the freshly fractured cross section of concrete. In the presence of chloride, silver ions reacted with and produced a white precipitate of silver chloride. The results obtained showed that the lightweight concrete specimens with waste plastic pre-coated scoria aggregates at 5% having 1% of fibers in the matrix were more resistant to the penetration of chloride at any date of testing, as compared to the control. The depths of penetration were found always smaller throughout the testing period than that of the control specimen. The Figure 4.16 shows the penetration depths recorded at 7, 28 and 45 days.

Plate 4.1: Cylinder specimen split at the required age to evaluate the chloride penetration depth.

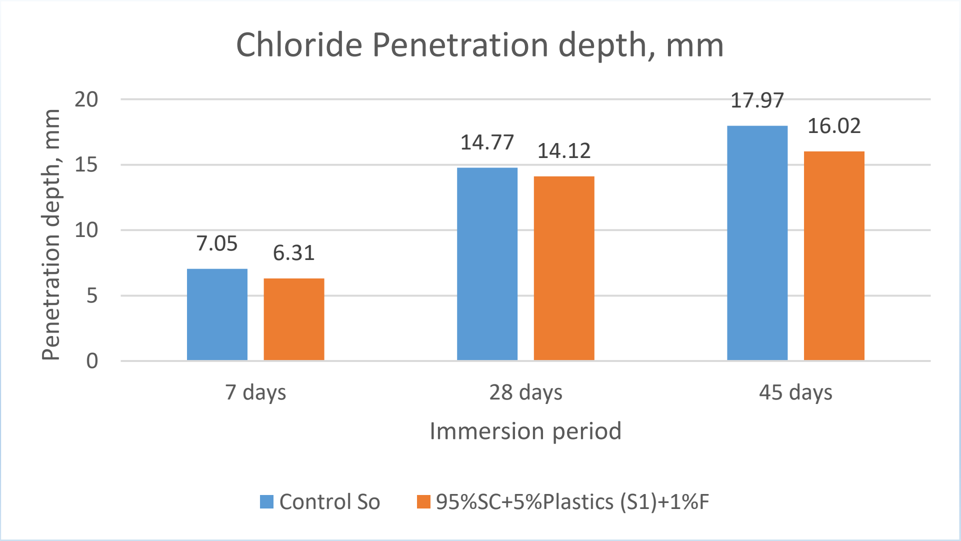


Figure 4.16**:** Depth of chloride ion penetration through the concrete specimens.

- **Acid attack resistance**

After 28 days curing in water, two mix concrete specimens (the control S_0 made with uncoated scoria aggregates and the lightweight concrete mix S_1 made with pre-coated scoria aggregates at 5% and containing sisal fibers at 1%) were immersed in a 1% hydrochloric acid (HCl) solution for 45 days (1080 hours) in a container. In order to minimize the evaporation, the specimens were kept covered throughout the testing period. Similar specimens from each batch were kept in water during the same period of time to compare the strength and weight values after the testing period.

Acid attack resistance was evaluated by determining the weight loss (WL) and compressive strength loss (SL) of the specimens using the expressions (Equations 4.1 and 4.2):

$$\text{WL (\%)} = \frac{w_1 - w_2}{w_1} \text{ x } 100 \text{ (\%)} \qquad \text{(Equation 4.1)}$$

Where w_1 and w_2 are the weights of the specimens (in kilograms) before and after immersion in 1% hydrochloric acid (HCL) solution for the testing period.

$$\text{SL (\%)} = \frac{f_{c1} - f_{c2}}{f_{c1}} \text{ x } 100 \text{ (\%)} \qquad \text{(Equation 4.2)}$$

Where f_{c1} represents the compressive strength of the specimens cured in water and f_{c2} is the compressive strength of the specimens after exposure to 1% hydrochloric acid (HCL) solution for the testing period.

- ***<u>Weight Loss</u>***

The results obtained showed that the control specimen S_0 was more resistant to acid attack throughout the testing period than S_1 specimen made with pre-coated aggregates containing sisal fibers in the matrix, regarding the weight loss. The calculations were done using Equation 4.1 and the results are presented in Figure 4.17.

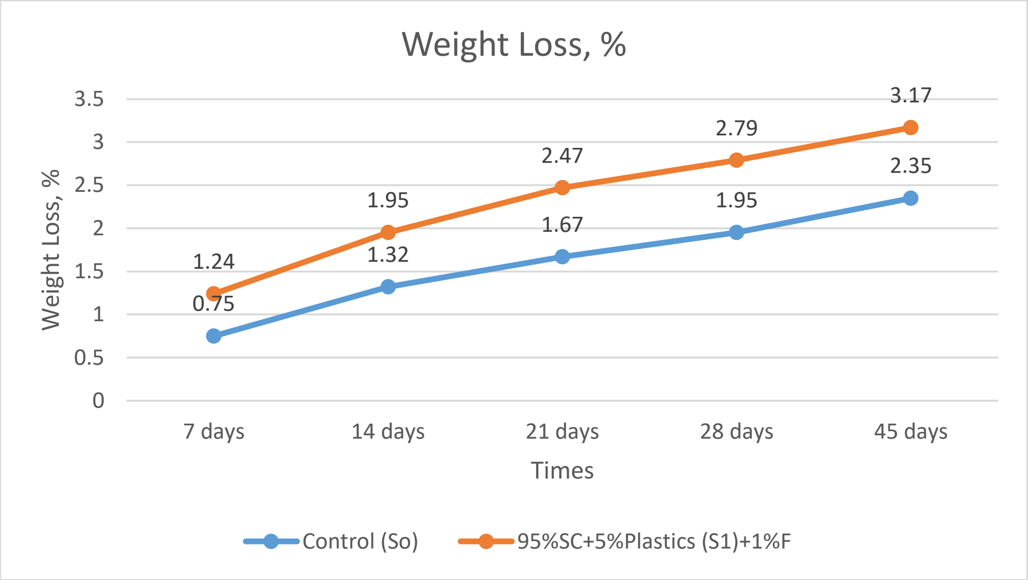


Figure 4.17: Weight loss in % of lightweight concrete specimens

- ***<u>Compressive Strength loss</u>***

After 45 days exposure to hydrochloric acid (HCL), the two lightweight concrete specimens were tested for residual compressive strength. It was calculated using the original cross-sectional area. The strength loss was determined with reference to the strength of concrete without exposure.

Figure 4.18 shows the compressive strength of the specimens after 14 and 45 days exposure in 1% hydrochloric acid (HCL) solution. Figure 4.19 shows the compressive strength of the specimens after 14 and 45 days cured in water, conducted at the same time with specimens immersed in the acid solution. The percentages of compressive strength loss for each specimen are shown on Figure 4.20. Equation 4.2 was used to obtain the results regarding the percentage of compressive strength loss of the specimens cured in the 2 conditions within the same testing period. The computation portrays the loss regarding the compressive strengths of specimens when they were water cured compared to when they were soaked in 1% hydrochloric acid (HCL) solution for up to 45 days. The control specimen S_0 was found more resistant to acid attack than the specimen S_1 made with pre-coated aggregates and having sisal fibers in the matrix, as regards to the compressive strength loss throughout the testing period. S_1 specimen exhibited the highest compressive strength loss found to be about 39.92%, as compared to that of about 32.07% noticed with the control specimen S_0.

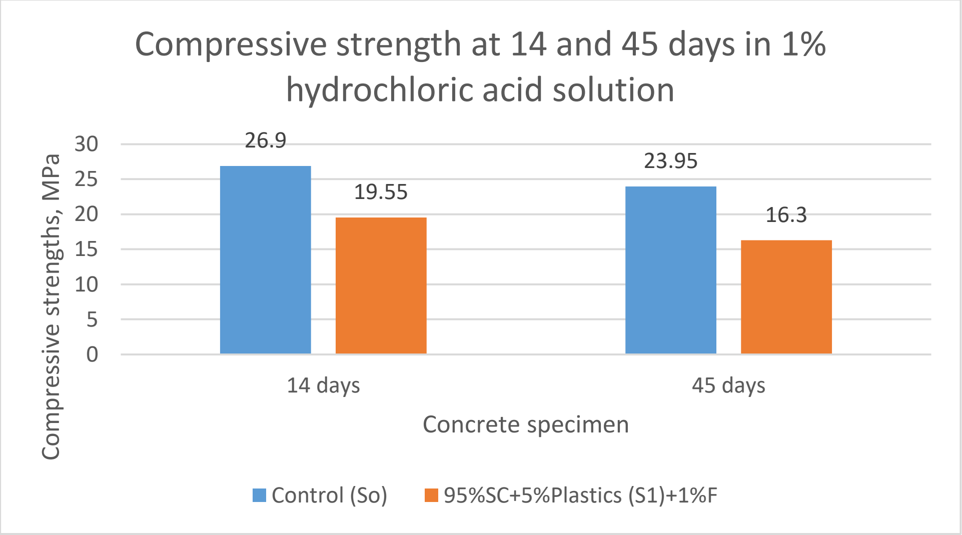


Figure 4.18: Compressive strength at 14 and 45 days in 1% hydrochloric acid solution

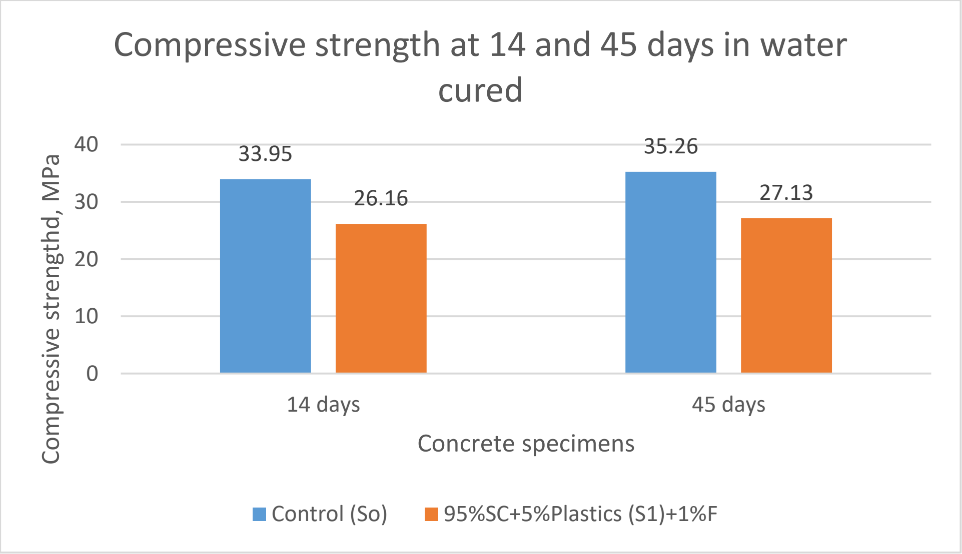


Figure 4.19: Compressive strength at 14 and 45 days in water cured

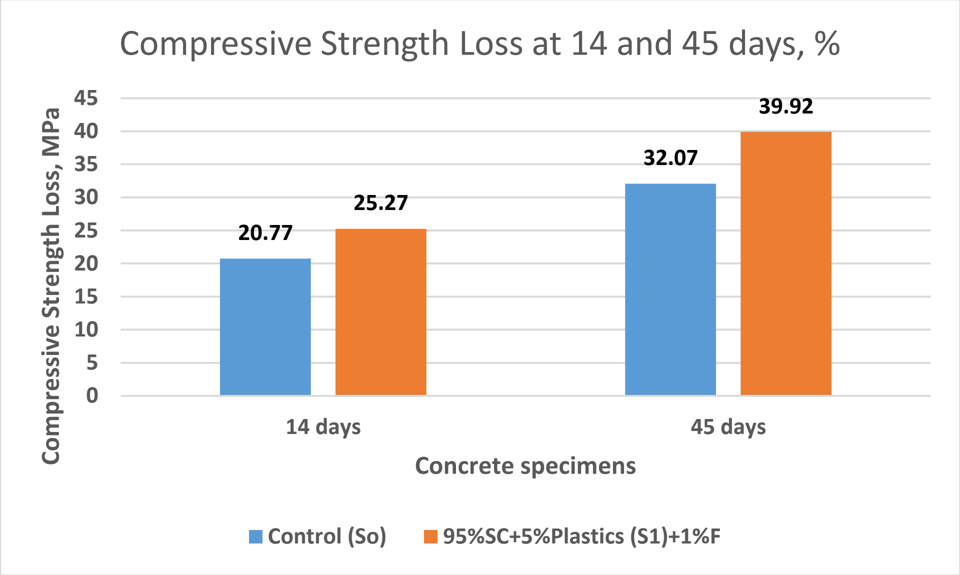


Figure 4.20: Compressive strength loss at 14 and 45 days

vi. Visual Inspection

The physical apprearence of both lighweight concrete specimens S_0 and S_1 under some specific conditions (in water, in 1% hydrochloric acid solution after a specified time), and after compression tests was shown in Appendix 6, 7, 8 and 9. The change on the physical appearance of specimens and the mode of rupture during the compression tests can be observed. Appendix 6 shows the hysical appearance of control lightweight concrete specimens S_0 (cylinders of Ø150mm x Height 300 mm and cylinders of Ø100mm x Height 200 mm), (a) after 28+45 days water cured, (b) water cured for 28 days, and soaked in 1% HCL acid solution for 45 days. Appendix 7 shows the physical appearance of lightweight concrete specimens S_1 (cylinders of Ø150mm x Height 300 mm and cylinders of Ø100mm x Height 200 mm), (a) after 28+45 days water cured, (b) water cured for 28 days, and soaked in 1% HCL acid solution for 45 days. Appendix 8 shows the physical appearance of control lightweight concrete specimens S_0 (cylinders of Ø150mm x Height 300 mm) after compression test, (a) water cured for

28+45 days, (b) water cured for 28 days, and soaked in 1% HCL solution for 45 days. Appendix 9 shows the physical appearance of lightweight concrete specimens S_1 (cylinders of Ø150mm x Height 300 mm) after compression test, (a) water cured for 28+45 days, (b) water cured for 28 days, and soaked in 1% HCL solution for 45 days.

4.4 Structural performance: Flexural tests on beams

In this experiment 2 sets of 3 beams were tested under flexure. The first set was made up of lightweight control concrete with uncoated scoria aggregates and without sisal fibers in the matrix (S_0), and the second one was made up of lightweight concrete with waste plastic pre-coated scoria aggregates at 5% and having sisal fibers at 1% in the matrix (S_1). Several parameters were of interest such as the first crack and failure load, the failure mode and crack patterns, the mid-span deflections, the ultimate moments and curvatures, the flexural stress-strain behaviors, the concrete stress-strain distributions (compressive stress-stain distributions, principal stress-strain distributions and shear stress-strains distributions) and steel strains distribution (load-tensile steel strain distribution, load-steel compressive strain distribution).

4.4.1 First Crack Load

The first crack in both sets of beams appeared approximately at 10 to 30 mm from the mid span at the region of maximum moment; then, followed by diagonal cracks from the points of loading towards the supports. One important observation was made regarding the crack openings. In fact they were larger in S_0 beams than in S_1 beams; this was an indicator of the fact that the presence of fibers in the concrete matrix effectively controlled the cracks. Figure 4.21 shows region of pure shear and pure bending along the loaded beam for a given P. The first crack and failure loads for all beam specimens are listed in Table 4.12. It was also noticeable that with S_0 beam specimens, the first crack appeared suddenly and propagated relatively faster until failure, than with S_1 beam specimens; S_1 beams exhibited less brittle failure. However, the first crack loads for S_0 beam specimens were found slightly greater than for S_1 beam specimens; but the failure loads were found almost the same for both S_0 and S_1 beams specimens. The onset of failure was first noticed in the tension zone of the beams (at the bottom) by the cracking of concrete.

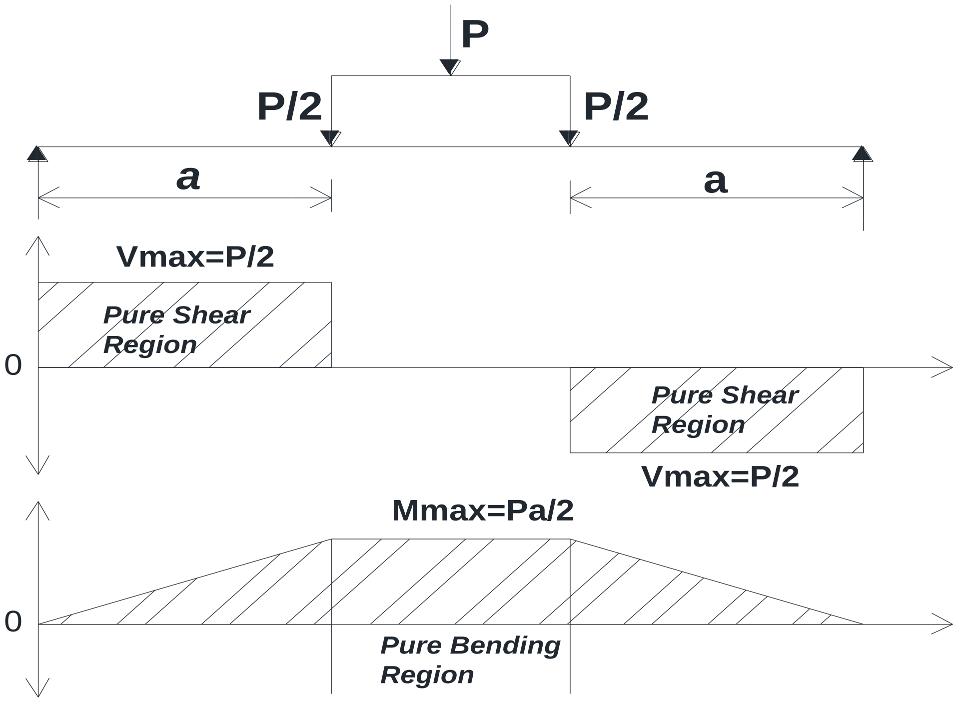


Figure 4.21 Shear force and bending moment diagrams for a beam under four point loads.

Table 4.12: First crack, ultimate loads and moments for S_0 and S_1 beams specimens.

Beams types	First crack Load (KN)	First crack moment (KN.m)	Ultimate Load (KN)	Ultimate Moment (KN.m)
So: LWC with uncoated scoria, having no NSF	79.92	14.99	113.36	21.26
S$_1$: LWC with pre-coated scoria, having NSF	72.10	13.52	113.20	21.22

4.4.2 Failure Load

The failure loads of both beams specimens S_0 and S_1 can be seen in the Table 4.12. They are almost the same. This indicates that, although fibers decreases the compressive strength of the resulting lightweight concrete, the effect on the ultimate load is almost negligible. Therefore S_1 beams can be as structurally efficient as S_0 beams, since beams could sustain more loads at higher failure strains than that for S_0 beams, due to fibers which controlled cracks and acted as cracks arresters.

4.4.3 Failure Mode and Crack Patterns

Flexural tests on beams were set as shown in Figure 4.21. This case was a four point loads flexural test. When the set up for the test was ready, with all the equipment fixed and connected to the data logger (Hydraulic jack, load cell, LVDT and strains gauges) and checked accordingly, the test started by increasing the load until failure. The data were recorded with a particular look at the failure mode and crack patterns. There were basically two main types of failure mode, depending generally on the length of the beam or the span to depth ratio, namely the diagonal tension failure and the flexural failure.

The failure mode observed was both the diagonal tension failure and the flexural failure. The failure started at the bottom part of the beams in the tension zone, by the cracking of concrete due to high flexural tensile stresses greater than the tensile strength of the beams. This was flexural type of failure. It could have been can due to the compression stresses causing the crushing of the extreme fibers in compression at the top of beams. Then, inclined cracks appeared and propagated diagonally in the shear span. This was diagonal tension failure, due to high shear stresses. Diagonal tension failure type, could have been due to inadequate shear reinforcements. These cracks forms after steel has yielded. *Plate 4.6* shows the crack pattern and failure modes of the beam specimens.

(a) S$_0$ beams

(b) S_1 beams

Plate 4.2 Crack pattern and failure modes of the beams specimens

4.4.4 Mid-span deflections

Both S_0 and S_1 beams exhibited similar bending behaviors as shown in load mid-span deflection curves (Figure 4.22). The curves showed basically three main phases regarding the load-deflection during the test. In the first phase, as the load increased, the deflection also increased. This can be seen as the elastic phase. Then, came the second phase where the deformations were still increasing for almost constant loads and finally started to decrease until complete failure of the beams specimens; this was the last phase. The curves portray that, in the second phase S_0 beams were slightly more resistant to bending than S_1 beam specimens, carrying more loads for the same deformation; thus appear to be stiffer than S_1 beam specimens. However, S_0 showed a relatively brittle behavior with an earlier and sudden fracture, after a relatively little plastic deformation phase as compared to S_1 beam specimens which remains stable for a relatively longer period as the load and the deformations increased. The propagation of cracks formed was relatively faster making S_0 beam specimens less stable. Therefore, S_1 beam specimens appeared to be more ductile than S_0 beams. They exhibited larger deformations than S_0 beams as failure occurs but remain stable. This was because of the presence of sisal fibers in the concrete matrix of S_1 beams, that allowed them to exhibit extensive plastic deformation before and after the formation of cracks which remain stable as the applied stresses are increased.

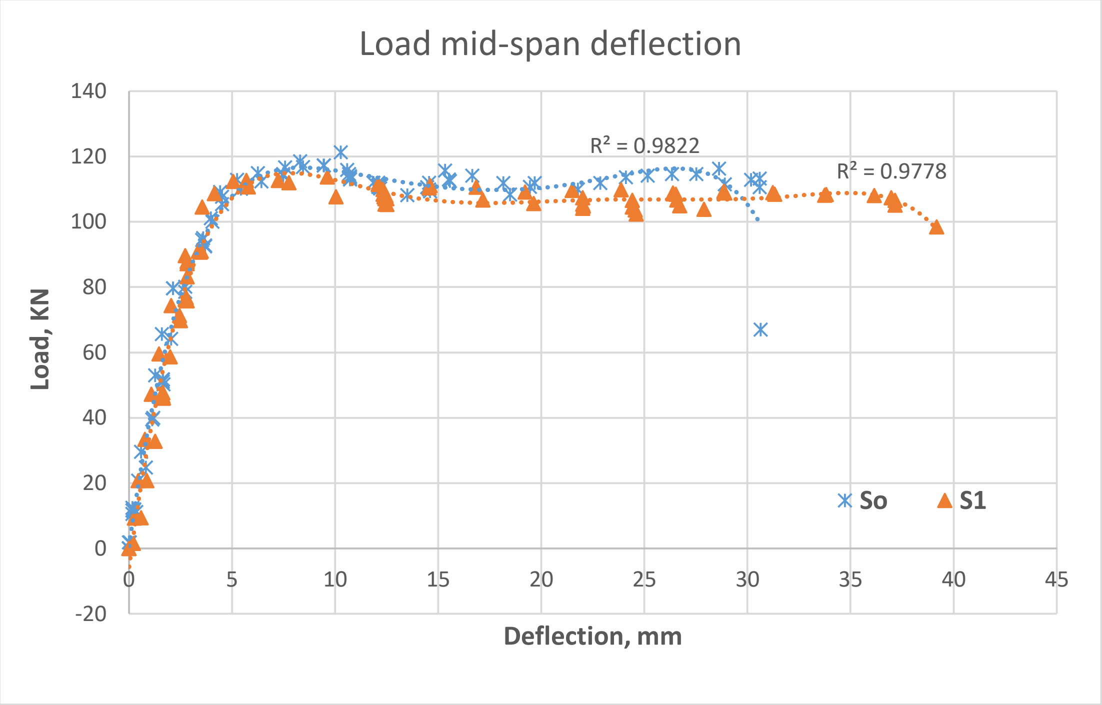


Figure 4.22 Load mid-span deflection curves for S_0 and S_1 beams specimens

British Standards BS 8110 provides a recommendation regarding the allowable deflection which should be less or equal to: $\frac{Beam\ span}{250}$. Figure 4.23 shows the maximum mid span deflections of the beam specimens at service load. For both S_0 and S_1 beams, the values of maximum deflections recorded are higher than the allowable and the deflection of S_1 beam specimens is 27.94% higher than the deflection of S_0 beam specimens. This can be explained by the higher ductility of S_1 beam specimens.

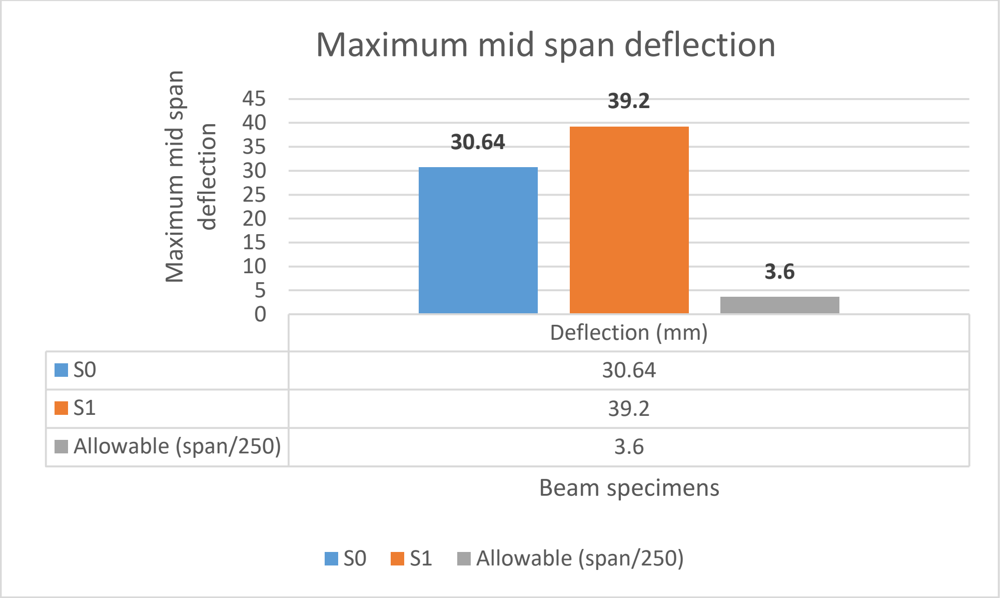
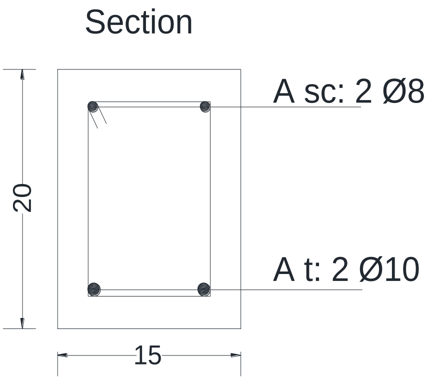


Figure 4.23: Experimental and Allowable Maximum mid-span deflections for S_0 and S_1 beams specimens at service loads.

It is noticeable from the load mid-span deflections curves shown in Figure 4.23 that the value of 3.6 mm representing the allowable deflection falls in the elastic domain. This is because the standards recommend to design structures in the elastic phase of deformations for safety purposes. The values given by Figure 4.23 are the maximum deflection that occurs.

4.4.5 Ultimate Moments and Curvatures

- **Neutral axis Y and Moment of Inertia I**



Asc: Steel reinforcements in compression

At: Steel reinforcements in tension

Figure 4.24: Cross section of the beam.

According to (Group, 2002), the modulus of elasticity of concrete can be estimated from the specified characteristic strength, as follows:

$Eci = Eco * \alpha_E((fck + 8)/10)^{1/3}$, where, $\boldsymbol{E_{ci}}$ is the modulus of elasticity (MPa) at a concrete age of 28 days, $\boldsymbol{f_{ck}}$ is the characteristic strength (MPa) of the concrete, $\boldsymbol{E_{c_0}}$ = 20.5x10^3 MPa, and $\boldsymbol{\alpha_E}$ is a constant parameter depending on the aggregate type, generally taken equal to 1.0.

This implies that for the control concrete specimen Eci = 32 678.1 MPa and Eci = 30 278.13 MPa for the resulting lightweight concrete with pre-coated scoria aggregates having sisal fibers in the matrix. The young modulus of steel being Es=205 000 MPa, we can express the equivalent coefficient n as: $n = \frac{Es}{Eci}$. This coefficient allows to estimate the equivalent section of steel reinforcement in concrete section. For the control concrete $n=6.27$ and $n=6.77$ for the resulting lightweight concrete. The neutral axis is given by the equation below:

$$Y = \frac{\sum AiYi}{\sum Ai} = \frac{AcYc + (n-1)AscYsc + (n-1)AtYt}{Ac + (n-1)Asc + (n-1)At}$$

where Yi are the distances from the center of gravity of each section to the top compression fiber; ***n = 6.27*** and ***Y= 10.070 cm*** for the control specimen, while for the resulting lightweight concrete ***n = 6.77*** and ***Y= 10.077 cm***.

The moment of inertia I of the section is given by the expression:

$$I = \sum(Ii + Aidi^2) = \sum\left(\frac{bh^3}{12} + bhdc^2\right) + \left((n-1)Ascdsc^2\right) + ((n-1)Atdt^2);$$

where, I_i, d_i, and A_i are respectively the moment of inertia of the element about its neutral axis, the distance from its neutral axis to the neutral axis of the whole section and the area of the element. The moment of inertia I of the section was found equal to ***10 763.25 cm***^{4} for the control specimen, and equal to ***10 835.51 cm***^{4} for the resulting concrete.

The Poisson ratio ν of the concrete ranges between 0.14 and 0.26. However the average value ν = 0.20 meets the required accuracy for the design of elements subjected to cracks formation at the ultimate limit state (Group, 2002).

The moment-curvature curves of S_0 and S_1 beam specimens are shown in Figure 4.25. The experimental moment was calculated for each applied load P using the formula: $M = \frac{\boldsymbol{Pa}}{\mathbf{2}}$; with “a” as the shear span. The curvature is given by the expression: $\varnothing = \frac{\xi}{c}$; where ξ is the extreme compression fiber strain corresponding to each load P and a section curvature, and “c” the compression depth or the distance of the top compression fiber from the neutral axis. The strains were obtained at mid span of the beams with the strains gauges, and then used to calculate the curvature Ø. The curves shows almost similar behaviors for the two beam specimens. However, S_1 beam specimens exhibit greater curvatures than S_0 beam specimens. This can be easily explained by the presence of sisal fibers in the concrete matrix of S_1 beam specimen, which makes the beams more elastic and ductile.

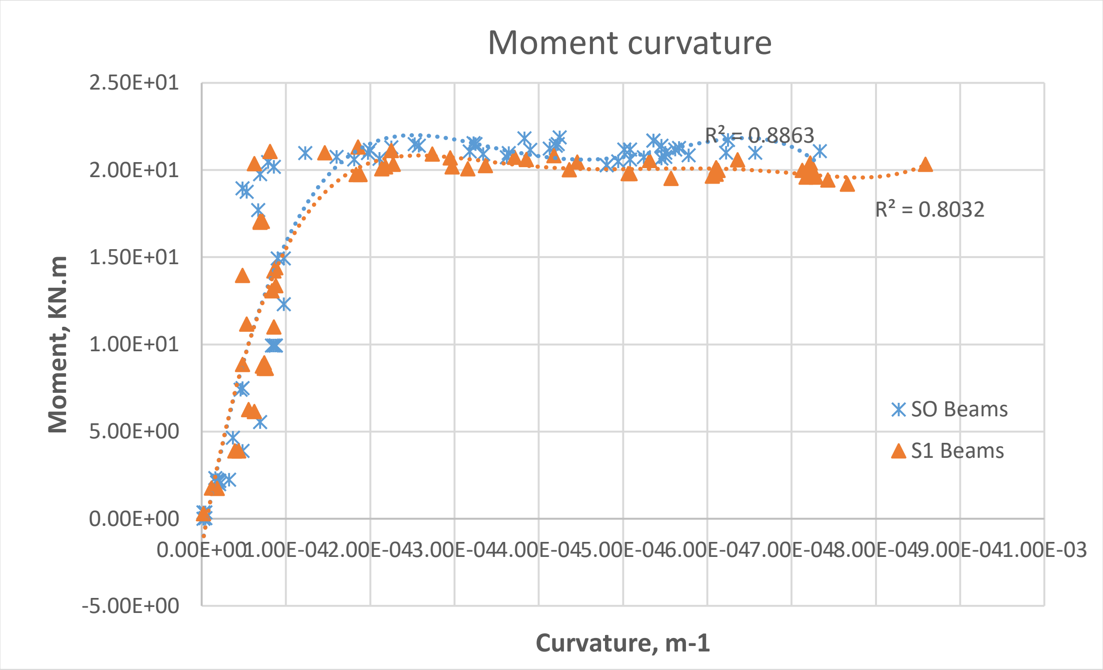


Figure 4.25: Moment-curvature curves for S_0 and S_1 beam specimens

4.4.6 Flexural Stress-Strain behavior

Flexure formula is given by the relation: $\sigma = \frac{MY}{I}$, where σ is the flexural stress.

- $M = \frac{Pa}{2}$, is the maximum bending moment, with "P" the load and "a" the shear span
- Y is the depth of the neutral axis or the distance between the neutral axis and the top fiber of the section

- I is the moment of inertia about the neutral axis of the section

The flexural strain is nominal fractional change in the length of an element of the outer surface of the specimen at the middle of span, where the maximum strain occurs. It is given by:

$\xi f = \frac{6Dd}{L^2}$, where,

D: the maximum deflection of the centre of the beam (mm)

L: the length of the support span (mm)

d: the thickness of the beam (mm)

Figure 4.26 shows the flexural stress-strain curves for S_0 and S_1 beam specimens. The curves show almost similar trends in the stress-strain relationship. However, S_1 beam specimens show greater ability to resist deformation under load than S_0 beam specimens. This means that the flexural strength of S_1 beam specimens is higher than the one of S_0 beam specimens as depicted in Figure 4.26. This higher ability can be attributed to the sisal fibers in the concrete matrix of S_1 beam specimens, which improves the tensile strength of the concrete, while controlling the cracks leading to a higher ability to resist deformations under load.

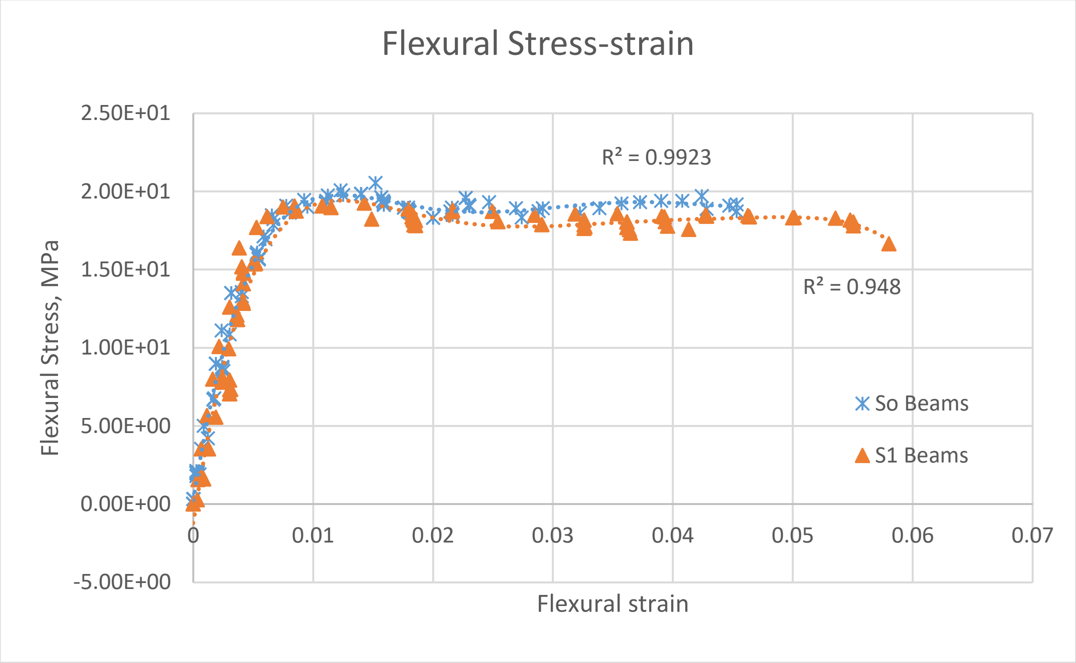


Figure 4.26: Flexural Stress-strain curves for S_0 and S_1 beam specimens

4.4.7 *Strains distributions*

- ***Concrete strain***

Strain gauges were used to monitor the variation of maximum compressive strains on the top surface of the beam with loads as shown in Figure 4.27. The compressive stress-strain curves for S_0 and S_1 beams specimens portrays almost similar behaviors. A relatively straight line is observed at the beginning of curves until a maximum strain of about 0.01‰. It is the elastic region. However, compression failure in S_1 beam specimens was observed to occur when the concrete strains reach about 0.09‰, greater than the value of 0.075‰ observed in S_0 beam specimens. This means S_1 beam specimens are able to resist more to deformations under load than S_0 beam specimens. This can be attributed to the sisal fiber in the concrete matrix of S_1 beam specimens. However, it is important to note that, in general the ultimate strain at failure for normal weight concrete is much higher, about 4 times the maximum value exhibited by S_1

beam specimens. The findings regarding the compressive strains are lower than those of the assumptions provided by BS 8110, Part 1 (1997). The compressive stress on the top compression fiber was calculated using the formula: $\sigma = \frac{MY}{I}$; where M is the maximum bending moment, Y the compression depth and I the moment of inertia of the section about the neutral axis.

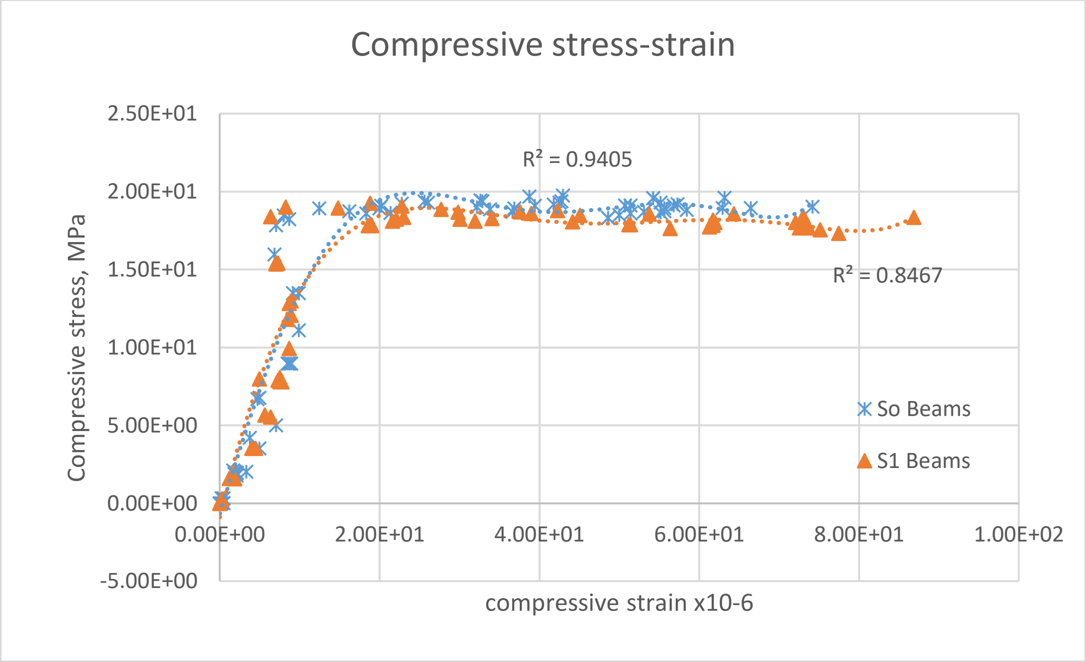
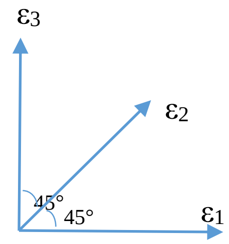


Figure 4.27: Concrete compressive stress-compressive strain of S_0 and S_1 beam specimens.

Principal strains and principal stresses at mid span were also monitored through stains rosettes placed on beams at mid span. Three main steps were followed in order to get the principal stresses and strains:

i. Data collection of strains values measured on the surface of concrete beam specimens using strain rosettes.



$\varepsilon_x = \varepsilon_1, \varepsilon_y = \varepsilon_2$

$\varepsilon_{xy} = \varepsilon_2 - \frac{\varepsilon 1 + \varepsilon 3}{2}$

And the shear strain is computed as $\gamma_{xy} = 2\ \varepsilon_{xy.}$

ii. Computation of principal strains using the strains rosettes data.

$$\xi = \frac{1}{2}\left[\varepsilon_1 + \varepsilon_3 \pm \sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (2\varepsilon_2 - \varepsilon_1 - \varepsilon_3)^2}\right]$$

iii. Computation of principal stresses using principal strains.

$$\sigma = \frac{E}{2}\left[\frac{(\varepsilon_1 + \varepsilon_3)}{1 - \nu} \pm \frac{1}{(1 + \nu)}\sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (2\varepsilon_2 - \varepsilon_1 - \varepsilon_3)^2}\right]$$

E and ν are respectively the modulus of elasticity of concrete and the Poisson ratio for the lightweight concrete considered as found previously. Figure 4.28 shows the maximum principal stress-strain curves for both S_0 and S_1 beam specimens measured at the mid span. From the curves, it was obviously noticed that S_1 beam specimens failed at much higher values of strains than S_0 beam specimens. The failure occurs when both the maximum principal strain and stress are about $1.08\text{x}10^{-3}$ and 21.20 MPa for S_1 beam specimens, while the same are about $5.35\text{x}10^{-4}$ and 13 MPa for S_0 beams specimens.

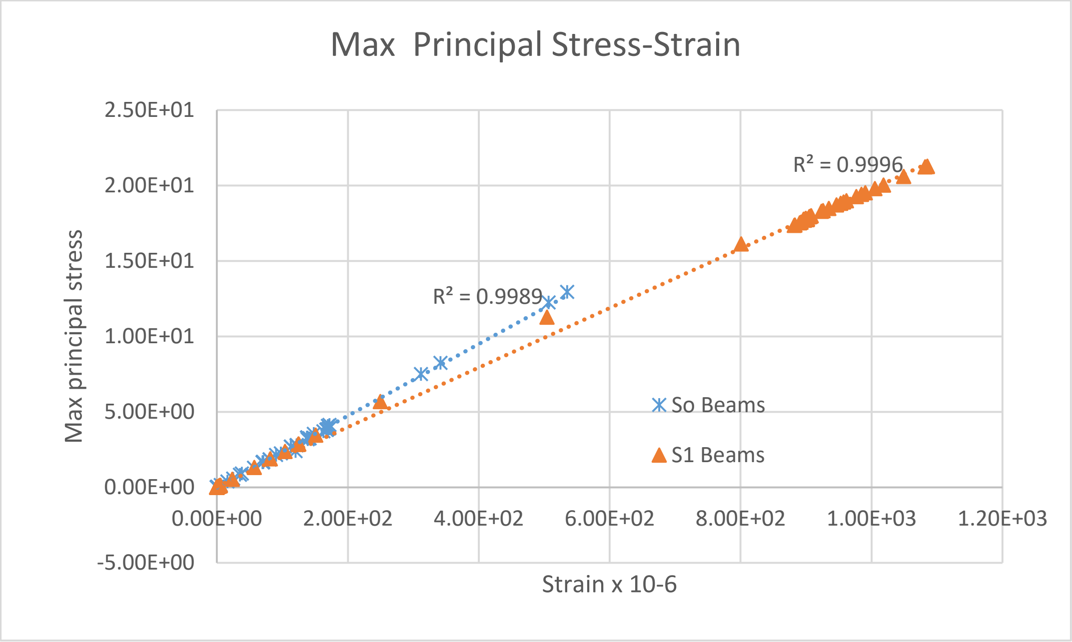


Figure 4.28: Max Principal stress-strain curves of S_0 and S_1 beam specimens.

The maximum shear stresses at mid span of the beams were also evaluated using the data from the strain gauge rosettes placed at the mid span of beams. The maximum shear strains were evaluated as well, using the formulae:

$$\gamma = \sqrt{[(\varepsilon_1 - \varepsilon_3)^2 + {\gamma_{xy}}^2]}$$

$$\tau_{\max} = \frac{E}{2(1+\nu)}\sqrt{2[(\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_2)^2)]}$$

Figure 4.29 shows that S_1 beam specimens exhibit higher shear strains till failure than S_0 beam specimens. The same behavior is also observed regarding the shear stresses. Maximum shear stresses developed in S_1 beam specimen are higher than those exhibited in S_0 beam specimens. Shear stress failure was observed for S_1 beam specimens for shear stain about 1.87×10^{-3} and maximum shear stress about 28.7 MPa, while for S_0 beam specimens the shear failure occurred at the shear strain value of 3.85×10^{-4} and at 9.55 MPa regarding the maximum shear stress.

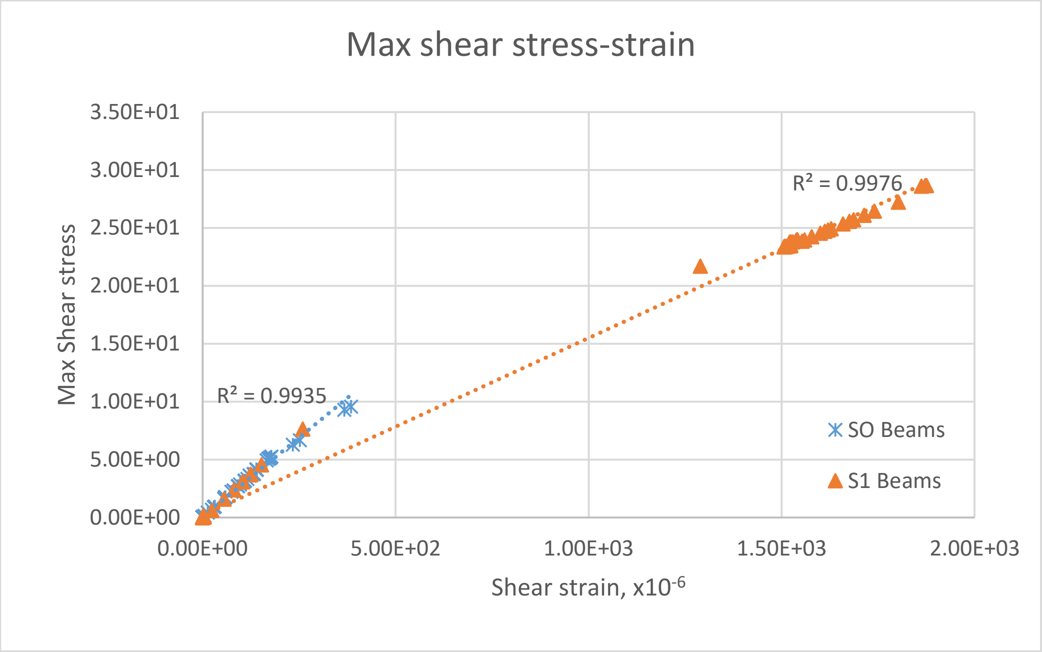


Figure 4.29: Max shear stress-strain curves of S_0 and S_1 beam specimens.

❖ ***Steel Strains***

Electrical resistance gauges were used to monitor the strains on reinforcing bars while loading the beams. They were mounted at the mid span of the beam, both on the two longitudinal reinforcements at the top and at the bottom. The strains gauges on the bottom longitudinal reinforcements were placed in the middle region to monitor the steel tensile strains where the bending moment was maximum. Similarly, the strain gauges placed on the top longitudinal reinforcements were to monitor the steel compression strains at the center top region of the beam, where the compression stress was maximum. Figure 4.30(a) gives the relation between the load and the steel tensile strains and Figure 4.30(b) gives load-steel compressive strain relationship.

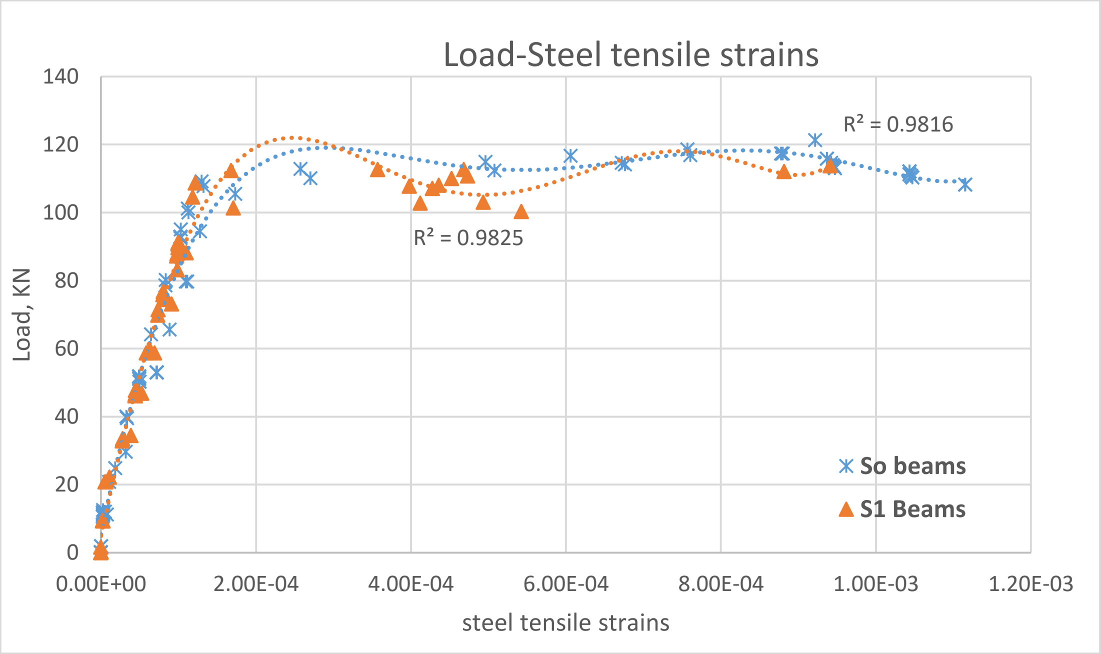


Figure 4.30(a): Load-steel tensile strains curves for S_0 and S_1 beam specimens

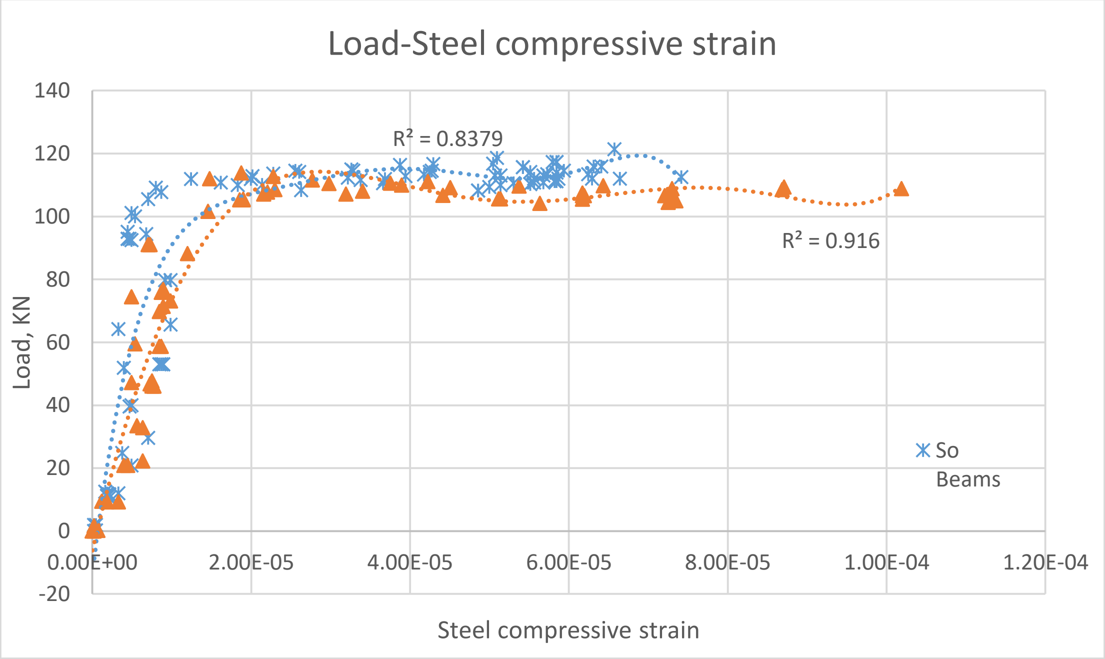


Figure 4.30(b): Load -steel compressive strains curves for S_0 and S_1 beam specimens

The results showed that the bottom reinforcements of S_0 beam specimens exhibited more tensile strains that S_1 beam specimens. This can be explained by the fact that in S_0 beam specimens, the bottom reinforcements were subjected to more tensile stresses.

The steel tensile stresses were reduced in S_1 beam specimens due to the presence of sisal fibers in the concrete matrix which contributed in increasing the tensile strength of the concrete, reducing the tensile stresses on the tensile steel, therefore exhibited less tensile strains. Concerning the top reinforcements, compressive strains in S_1 beam specimens were found higher than in S_0 beam specimens. This was due to the presence of sisal fibers in the matrix reducing the compressive strength of the concrete, therefore the top reinforcements in compression in S_1 beams specimens undergo more compressive stresses.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the experiments carried out and based on the results obtained on the "structural performance of sisal fibers reinforced lightweight concrete with waste plastics pre-coated volcanic scoria aggregates", the following conclusions were drawn:

i. Volcanic scoria locally available in Kenya, collected and manually crushed into particles sizes 4.75-19 mm, were found suitable as aggregates for the production of structural lightweight aggregates concrete in accordance with ASTM C330 Standard requirements. The absolute volume method of mix design, was found to be the best mix design approach.

ii. The study showed that waste plastics as pre-coating material over the scoria aggregates affected the physical and the mechanical properties of the resulting LWC. The percentage of 5% of waste plastic by weight replacement of aggregates was found as the best content to pre-coat the aggregates in a hot mix process, before the use for producing structural lightweight aggregates concrete. Investigations showed a reduction of water absorption capacity of the scoria aggregates from 13.06% to 9.15 % when varying the amount of plastics over the aggregates from 0 to 5%, and an increase of the compressive strength, the splitting tensile strength and the flexural strength by respectively 10.46%, 1.82% and 3.43% at 28 days.

iii. The percentages of 5% of waste plastic as pre-coating material over the scoria aggregates and 1% of sisal fibers in the matrix were found to be the best contents for each parameter improving the properties of the resulting lightweight concrete. The 28 days splitting tensile strength and the 28 days flexural strength of the resulting lightweight concrete were found to increase respectively by 6.20% and 40.81%, as compared to the control specimen made with uncoated scoria aggregates having no fibers. However, the compressive strength was found reduced by 25.5% as well as the slump and the air-dry density of the resulting lightweight concrete.

iv. The specimen S_1 (lightweight concrete with pre-coated aggregates at 5%, with 1% of sisal fibers in the matrix) was found to be more resistant to the penetration of chloride throughout the testing period, with the lowest value of penetration depth of 16.02 mm at 45 days as compared to 17.97 mm for the control specimen S_0 (lightweight concrete with uncoated aggregates and without fibers in the matrix). However, S_0 concrete specimens showed better resistance to hydrochloric acid attack as compared to S_1 concrete specimens.

v. S_1 beam specimens were found more structurally efficient than S_0 beam specimens. S_1 beams were able to sustain more loads, with higher failure strains than S_0 beams. This was due to fibers which controlled cracks and acted as cracks arresters. S_1 beams exhibited less brittle failure and the cracks propagation were faster and the openings larger with S_0 beam specimens than with S_1 beam specimens.

5.2 Recommendations

Additional investigations need to be carried out for further verifications on the structural performance of sisal fibers reinforced lightweight concrete with waste plastic pre-coated scoria aggregates. The following are those additional researchable areas:

i. In this research work, only 5%, 10% and 15% of waste plastic content over the aggregates have been investigated on concrete properties, and 5% was found to be the best plastic content improving the strength properties of the concrete. More detailed study should be carried out in the interval 0% to 10% to find out the more precised waste plastic content as pre-coating material over the aggregates, regarding the concrete properties.

ii. In this research study, structural performance analysis was carried out through flexural tests on beams. Further investigations may focus on compression elements such as columns, as well as on the joints between beams and columns on structures.

iii. The structural elements under flexural tests in this study were beams; further study may be done on slabs.

iv. Torsion and bond strength mechanisms can be studied as additional research, to flexure mechanisms done in this study.

v. Due to the higher absorption capability of lightweight aggregates concrete as compared to that of the ordinary normal weight concrete, plastic and drying shrinkage investigations should be done on lightweight concrete specimens, for deeper understanding of the materials.

vi. Durability study was carried out in this study over a period of 45 days only. Further experiments should be done over a longer period such as 90 days and more; Permeability, carbonation resistance and absorption tests should also be done on the lightweight concrete specimens.

vii. This research study was mainly based on the experimental works. However, for deeper understanding of the material behaviors, a finite element modeling need to be carried out. This can be done using finite element softwares such as ABAQUS or SAP. The aim would be to analyze the structural responses of the material, calibrated on the experimental results obtained in the laboratory. Thereafter, assess the structural capacity of various bearing elements under various combination of load types (horizontal loads, vertical loads, and dynamic loads), carry out analysis on the non-linear behaviors of various structural elements made with the specimens in terms of their capacity curves, assess the cracks patterns, enlighten the deformation behaviors modes under loading, observe and analyze the damage mechanisms on structural elements.

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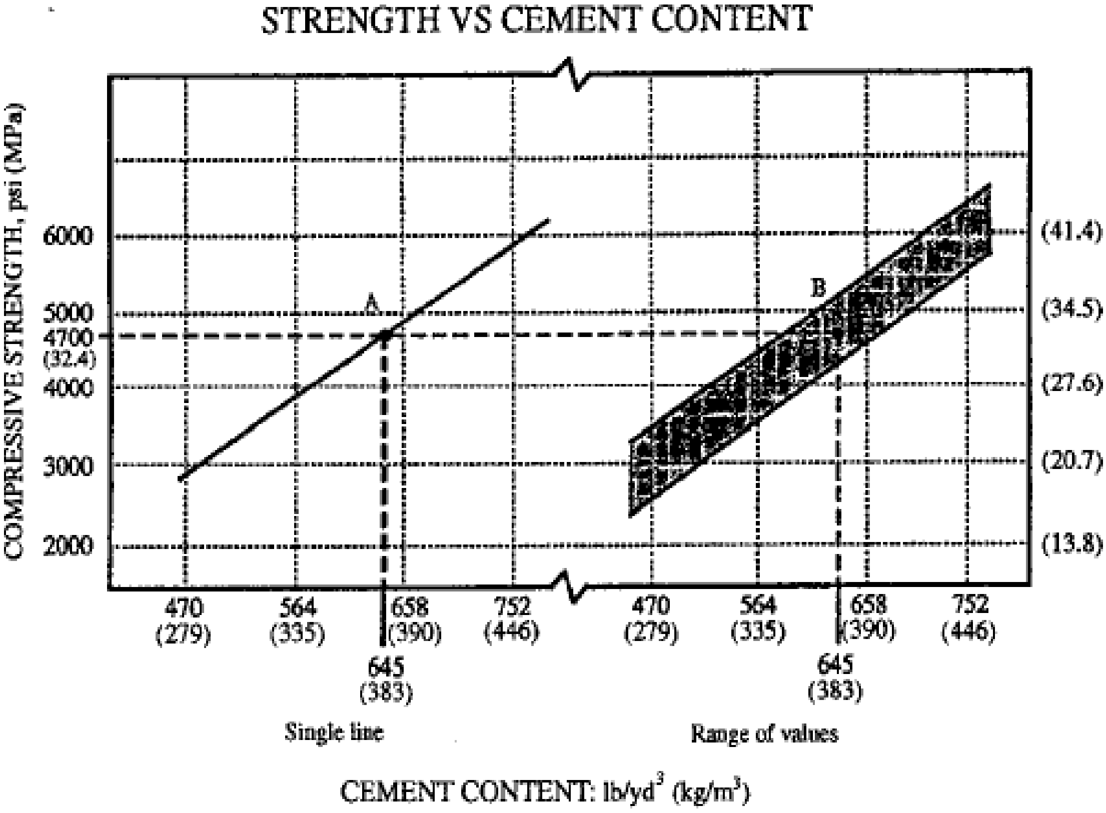
APPENDICES

Appendix 1: Strength versus cement content (damp loose method, ACI 211.2)



Appendix 2: Chemical composition and some physical properties of Bamburi Power Plus

Parameters	*Percentage (%)*
SiO_2	20.61
Al_2O_3	5.05
Fe_2O_3	3.24
CaO	63.37
MgO	0.81
SO_3	2.75
Na_2O	0.15
K_2O	0.52
Free CaO	0.63
Na Eq	0.49
Cl^-	<0.01
LOI	2.90
I.R.	1.00
C_3A	7.91

Table 4.2: Some physical properties of Bamburi Power Plus 42.5

Specific gravity	Loose bulk density (Kg/m^3)	Compacted bulk density (Kg/m^3)
3.197	1162.3	1398

Appendix 3: Chemical composition of volcanic scoria aggregates

Parameters	***Percentage (%)***
SiO_2	72.755
Al_2O_3	13.482
Fe	6.082
K2O	5.129
CaO	1.090
Ti	0.545
Cl	0.333
Mn	0.271
Zr	0.129
Zn	0.048
Nb	0.027
Rb	0.019
Y	0.011
Sr	0.002
C_u	0.002

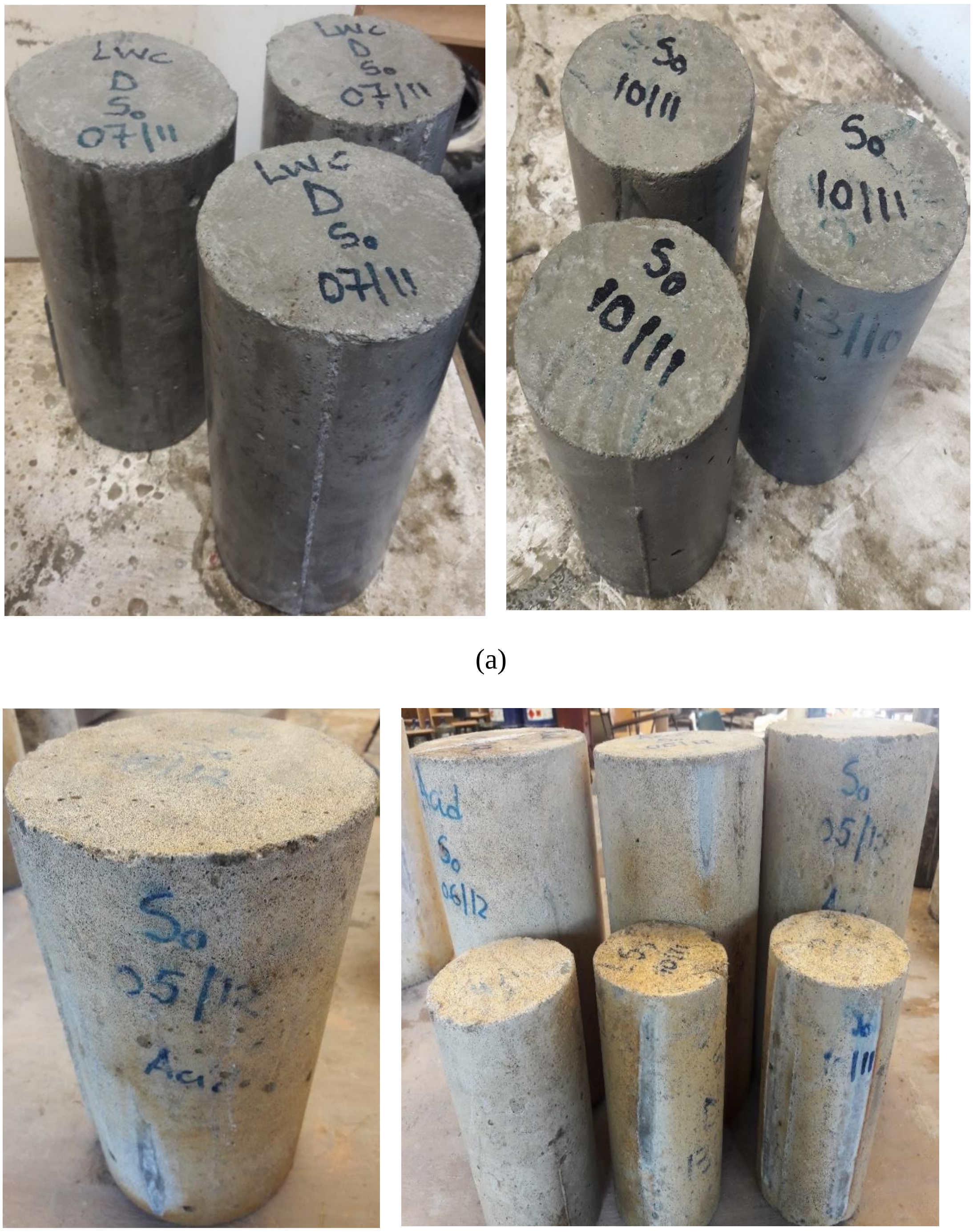
Appendix 4: specific gravity and water absorption of pre-coated volcanic scoria aggregates samples.

	Pre-coated Volcanic Scoria Agg. (**5% of Plastics**)	Pre-coated Volcanic Scoria Agg. (**10% of Plastics**)	Pre-coated Volcanic Scoria Agg. (**15% of Plastics**)
1) Specific. gravity on oven dried basis	1.91	1.81	1.71
2) Specific. gravity on a SSD basis	2.08	1.94	1.81
3) Apparent Specific. Gravity	2.31	2.06	1.90
4) Water absorption (% of dry mass)	9.15	6.62	5.67

Appendix 5: Chemical composition of the sisal fibers used in the study

Parameters	***Percentage (%)***
CaO	40.404
K_2O	31.178
MgO	20.933
Fe	1.758
Al_2O_3	1.563
Cl	1.424
S	1.094
$P2O5$	0.978
Ti	0.370
Sr	0.087
Zn	0.075
Rb	0.052
Mn	0.034
Cr	0.025
Cu	0.011
Zr	0.010
Y	0.03

Appendix 6: Physical appearance of control lightweight concrete specimens S$_0$ (cylinders of Ø150mm x Height 300 mm and cylinders of Ø100mm x Height 200 mm), (a) after 28+45 days water cured, (b) water cured for 28 days, and soaked in 1% HCL acid solution for 45 days.



(a)

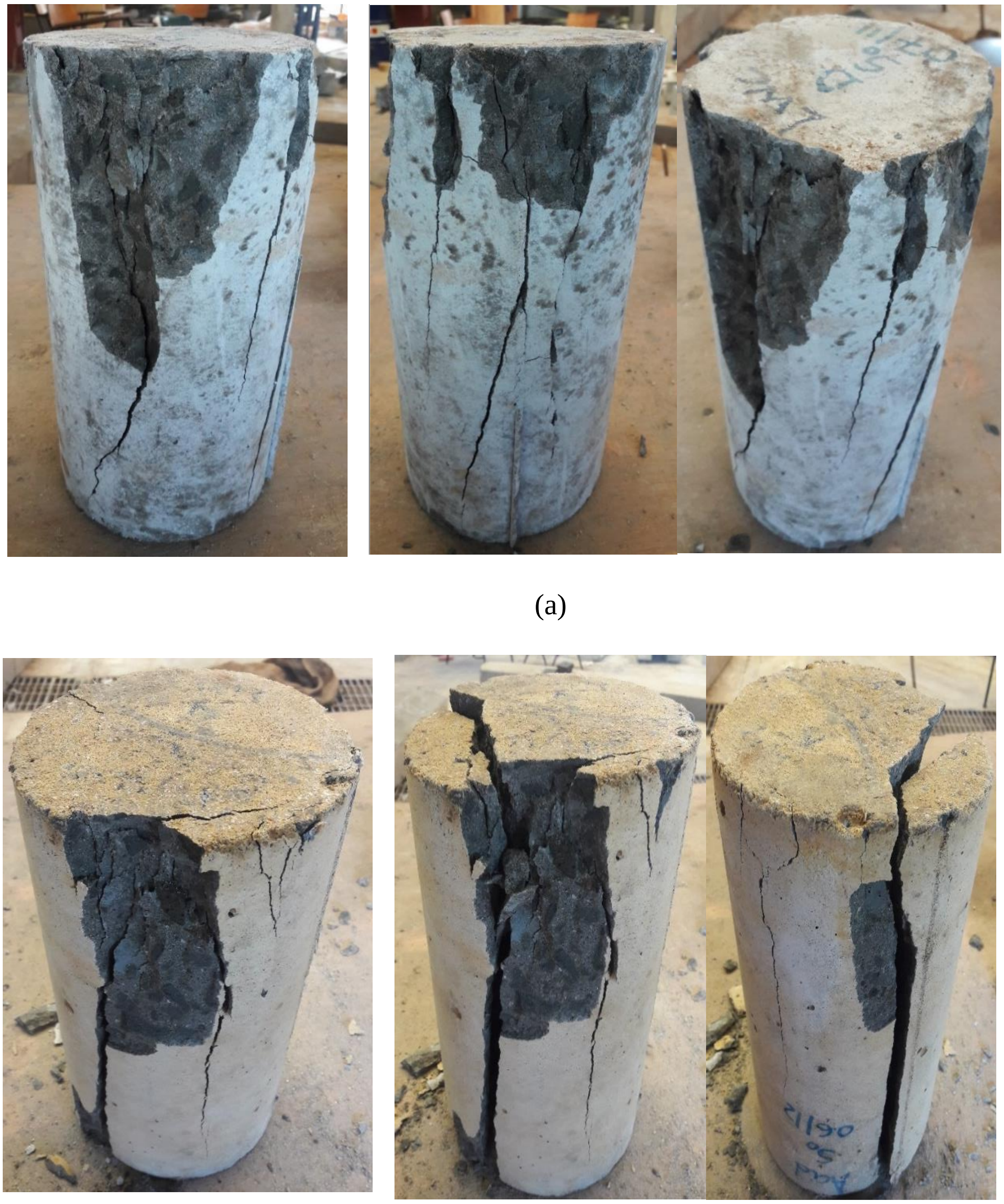
(b)

Appendix 7: Physical appearance of lightweight concrete specimens S1 (cylinders of Ø150mm x Height 300 mm and cylinders of Ø100mm x Height 200 mm), (a) after 28+45 days water cured, (b) water cured for 28 days, and soaked in 1% HCL acid solution for 45 days.

(a)

(b)

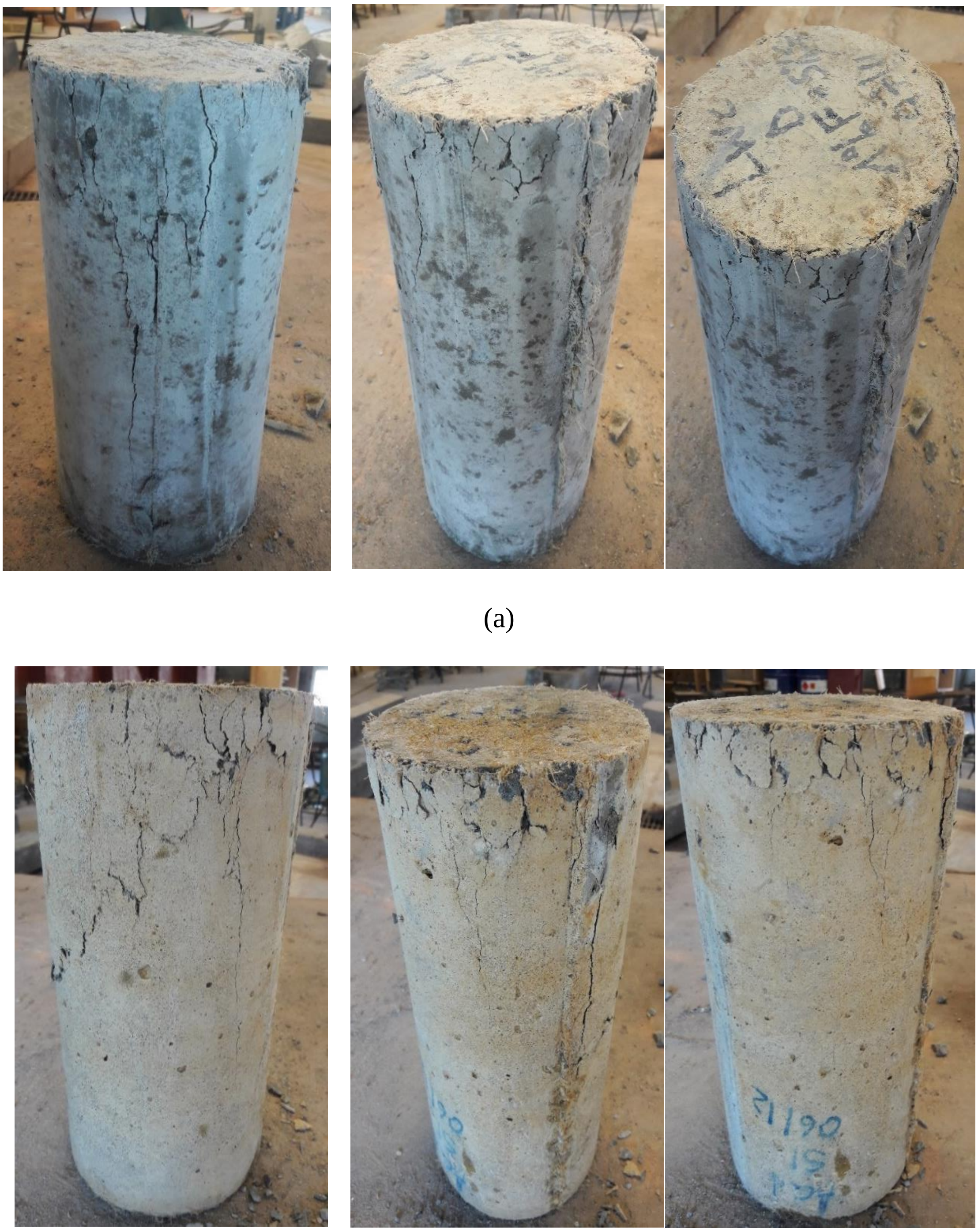
Appendix 8: Physical appearance of control lightweight concrete specimens S0 (cylinders of Ø150mm x Height 300 mm) after compression test, (a) water cured for 28+45 days, (b) water cured for 28 days, and soaked in 1% HCL solution for 45 days.



(a)

(b)

Appendix 9: Physical appearance of lightweight concrete specimens S1 (cylinders of Ø150mm x Height 300 mm) after compression test, (a) water cured for 28+45 days, (b) water cured for 28 days, and soaked in 1% HCL solution for 45 days.



(a)

(b)

Appendix 10: Load- raw deflection data

S_0 beam specimen's data

Load (KN)	0.01	0.16	1.92	12.48	11.84	11.68	11.52	10.56	12	20.8	29.6
Deflection (mm)	0.01	0.01	0.01	0.182	0.228	0.182	0.228	0.182	0.273	0.456	0.593

Load (KN)	52.96	65.6	79.68	79.68	94.4	105.44	0.01	1.92	11.2	24.8	40
Deflection (mm)	1.278	1.598	2.146	2.146	3.561	4.520	0.01	0.045	0.365	0.821	1.187

Load (KN)	39.52	51.84	51.68	51.04	50.24	64.16	80.16	78.56	95.04	92.8	92.48
Deflection (mm)	1.141	1.643	1.643	1.643	1.689	2.054	2.739	2.739	3.607	3.698	3.698

Load (KN)	101.12	100	109.12	107.68	112.8	110.08	114.88	112.32	116.64	114.56	114.08

Deflection (mm)	3.972	4.063	4.429	4.520	5.251	5.433	6.255	6.438	7.579	7.488	7.488

Load (KN)	118.5	116.8	117.28	117.28	117.28	121.28	115.84	114.56	113.92	113.44	112.96
Deflection (mm)	8.310	8.447	9.45	9.452	9.452	10.273	10.593	10.684	10.730	10.730	10.730

Load (KN)	112	112	111.2	110.72	110.72	110.24	108.16	112	110.56	109.92	109.28
Deflection (mm)	11.872	12.100	12.100	12.146	12.100	12.191	13.515	14.566	14.474	14.566	14.611

Load (KN)	115.68	112.96	112.48	114.08	111.84	108.32	110.72	111.84	109.92	111.84	113.6
Deflection (mm)	15.34	15.525	15.570	16.666	18.173	18.493	19.452	19.680	21.780	22.876	24.109

Load (KN)	114.08	114.56	114.56	116.32	111.52	112.8	113.28	110.56	67.04
Deflection (mm)	25.159	26.347	27.534	28.630	28.904	30.182	30.593	30.593	30.639

S_1 beam specimen’s data

Load (KN)	0.01	1.6	9.44	20.8	32.8	47.68	46.72	46.4	46.08	46.08	58.72
Deflection (mm)	0.01	0.228	0.593	0.867	1.278	1.643	1.643	1.643	1.643	1.689	2.009

Load (KN)	71.36	69.76	76.8	75.84	91.04	91.04	90.72	108.64	112.64	110.72	112
Deflection (mm)	2.465	2.511	2.785	2.831	3.378	3.515	3.472	4.155	5.707	5.799	7.762

Load (KN)	113.76	111.52	108.48	107.68	107.04	105.44	105.28	110.4	110.56	109.12	109.6

Deflection (mm)	9.634	12.100	12.328	12.374	12.420	12.420	12.511	14.566	16.849	19.223	21.506

Load (KN)	109.76	108.8	106.72	104.96	109.28	108.48	108.32	0.01	9.28	20.8	33.44
Deflection (mm)	23.881	26.392	26.575	26.712	28.858	31.324	33.835	0.01	0.273	0.456	0.776

Load (KN)	47.2	59.52	74.4	89.6	83.2	87.84	87.2	104.48	112.32	112.64	107.68
Deflection (mm)	1.095	1.461	2.054	2.739	2.831	2.831	2.831	3.561	5.068	7.2602	10.045

Load (KN)	109.92	108	107.04	111.04	106.72	105.6	104.16	107.36	105.44	104.8	106.56
Deflection (mm)	12.328	12.465	12.511	14.611	17.168	19.63	22.009	22.009	22.009	22.054	24.429

Load (KN)	104.48	103.68	102.4	108.48	108.8	108.96	108.16	108	107.36	106.56	105.12
Deflection (mm)	24.429	24.566	24.611	26.529	28.904	31.232	33.744	36.164	36.98	37.168	37.168

Load (KN)	103.84	98.4
Deflection (mm)	27.899	39.178

Appendix 11: Strain rosette data and processing

S_0 beam specimen's data

ε_1	ε_3	ε_2	Shear strain γxy= 2(ε2-(ε1+ε3)/2)	Max Principal strain ξ x10-6	Max Principal stress σ(MPa)	Max shearing strain γ x10-6	Max Shearing Stress, ζmax (MPa)	Min Principal strain ξ x10-6	Min Principal stress σ(MPa)	Poisson's Ratio, ν	Young's Modulus E, MPa
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
0.00E+00	0.00E+00	4.69E-07	9.39E-07	4.69E-01	8.61E-03	9.39E-01	1.22E-02	-4.69E-01	-8.61E-03	2.00E-01	32678.1
4.69E-07	0.00E+00	0.00E+00	-4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.22E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	0.00E+00	-4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.22E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	4.69E-07	0.00E+00	-9.39E-07	9.39E-01	2.15E-02	9.39E-01	1.22E-02	0.00E+00	4.31E-03	2.00E-01	32678.1
4.69E-07	4.69E-07	0.00E+00	-9.39E-07	9.39E-01	2.15E-02	9.39E-01	1.22E-02	0.00E+00	4.31E-03	2.00E-01	32678.1

0.00E+00	4.69E-07	0.00E+00	-4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	0.00E+00	-4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.22E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
2.44E-05	9.39E-07	1.03E-05	-4.69E-06	2.46E+01	5.68E-01	2.39E+01	6.56E-01	7.07E-01	1.29E-01	2.00E-01	32678.1
5.63E-05	4.69E-07	2.54E-05	-6.10E-06	5.65E+01	1.30E+00	5.62E+01	1.59E+00	3.03E-01	2.66E-01	2.00E-01	32678.1
8.03E-05	0.00E+00	3.76E-05	-5.16E-06	8.04E+01	1.84E+00	8.04E+01	2.30E+00	-8.30E-02	3.67E-01	2.00E-01	32678.1
8.03E-05	0.00E+00	3.80E-05	-4.23E-06	8.03E+01	1.84E+00	8.04E+01	2.30E+00	-5.56E-02	3.67E-01	2.00E-01	32678.1
8.03E-05	0.00E+00	3.80E-05	-4.23E-06	8.03E+01	1.84E+00	8.04E+01	2.30E+00	-5.56E-02	3.67E-01	2.00E-01	32678.1
9.77E-05	0.00E+00	4.88E-05	-1.00E-09	9.77E+01	2.24E+00	9.77E+01	2.83E+00	-2.56E-09	4.48E-01	2.00E-01	32678.1
1.22E-04	0.00E+00	6.71E-05	1.27E-05	1.22E+02	2.79E+00	1.22E+02	3.60E+00	-3.29E-01	5.52E-01	2.00E-01	32678.1
1.21E-04	0.00E+00	6.67E-05	1.22E-05	1.21E+02	2.78E+00	1.22E+02	3.59E+00	-3.07E-01	5.50E-01	2.00E-01	32678.1
1.38E-04	4.69E-07	8.17E-05	2.54E-05	1.39E+02	3.18E+00	1.39E+02	4.13E+00	-6.93E-01	6.20E-01	2.00E-01	32678.1
1.65E-04	9.39E-07	1.06E-04	4.55E-05	1.68E+02	3.84E+00	1.70E+02	5.05E+00	-2.17E+00	7.20E-01	2.00E-01	32678.1
1.65E-04	0.00E+00	1.16E-04	6.76E-05	1.72E+02	3.91E+00	1.79E+02	5.25E+00	-6.65E+00	6.36E-01	2.00E-01	32678.1
1.65E-04	4.69E-07	1.15E-04	6.57E-05	1.71E+02	3.90E+00	1.77E+02	5.20E+00	-5.86E+00	6.51E-01	2.00E-01	32678.1

1.62E-04	0.00E+00	1.14E-04	6.48E-05	1.69E+02	3.84E+00	1.75E+02	5.14E+00	-6.22E+00	6.31E-01	2.00E-01	32678.1
1.62E-04	0.00E+00	1.14E-04	6.57E-05	1.68E+02	3.82E+00	1.74E+02	5.12E+00	-6.43E+00	6.23E-01	2.00E-01	32678.1
1.62E-04	0.00E+00	1.13E-04	6.48E-05	1.68E+02	3.82E+00	1.74E+02	5.12E+00	-6.26E+00	6.26E-01	2.00E-01	32678.1
1.62E-04	0.00E+00	1.13E-04	6.48E-05	1.68E+02	3.82E+00	1.74E+02	5.12E+00	-6.26E+00	6.26E-01	2.00E-01	32678.1
1.61E-04	0.00E+00	1.13E-04	6.43E-05	1.67E+02	3.81E+00	1.73E+02	5.10E+00	-6.19E+00	6.25E-01	2.00E-01	32678.1
1.58E-04	4.69E-07	1.06E-04	5.26E-05	1.62E+02	3.71E+00	1.66E+02	4.92E+00	-3.80E+00	6.58E-01	2.00E-01	32678.1
1.41E-04	9.39E-07	7.61E-05	9.86E-06	1.41E+02	3.25E+00	1.41E+02	4.13E+00	7.66E-01	6.67E-01	2.00E-01	32678.1
1.41E-04	9.39E-07	7.23E-05	2.81E-06	1.41E+02	3.23E+00	1.40E+02	4.08E+00	9.25E-01	6.67E-01	2.00E-01	32678.1
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
4.69E-07	0.00E+00	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.72E-02	-9.72E-02	3.69E-04	2.00E-01	32678.1
5.63E-06	9.39E-07	4.23E-06	1.88E-06	5.81E+00	1.37E-01	5.06E+00	1.49E-01	7.58E-01	4.41E-02	2.00E-01	32678.1
1.60E-05	2.82E-06	1.08E-05	2.82E-06	1.61E+01	3.82E-01	1.34E+01	3.99E-01	2.67E+00	1.35E-01	2.00E-01	32678.1
3.47E-05	6.10E-06	2.39E-05	7.04E-06	3.52E+01	8.33E-01	2.95E+01	8.75E-01	5.68E+00	2.92E-01	2.00E-01	32678.1
3.76E-05	6.57E-06	2.58E-05	7.51E-06	3.80E+01	9.00E-01	3.19E+01	9.47E-01	6.12E+00	3.15E-01	2.00E-01	32678.1
6.90E-05	1.27E-05	4.88E-05	1.60E-05	7.01E+01	1.66E+00	5.86E+01	1.74E+00	1.16E+01	5.87E-01	2.00E-01	32678.1
6.85E-05	1.31E-05	4.93E-05	1.69E-05	6.98E+01	1.66E+00	5.79E+01	1.72E+00	1.19E+01	5.93E-01	2.00E-01	32678.1

6.85E-05	1.31E-05	4.98E-05	1.78E-05	6.99E+01	1.66E+00	5.82E+01	1.72E+00	1.17E+01	5.90E-01	2.00E-01	32678.1
6.90E-05	1.31E-05	4.98E-05	1.74E-05	7.03E+01	1.67E+00	5.85E+01	1.73E+00	1.18E+01	5.94E-01	2.00E-01	32678.1
6.85E-05	1.31E-05	5.02E-05	1.88E-05	7.01E+01	1.66E+00	5.85E+01	1.73E+00	1.16E+01	5.87E-01	2.00E-01	32678.1
6.90E-05	1.36E-05	5.02E-05	1.78E-05	7.04E+01	1.67E+00	5.82E+01	1.72E+00	1.22E+01	6.03E-01	2.00E-01	32678.1
6.90E-05	1.31E-05	5.02E-05	1.83E-05	7.05E+01	1.67E+00	5.88E+01	1.74E+00	1.17E+01	5.91E-01	2.00E-01	32678.1
6.90E-05	1.36E-05	5.02E-05	1.78E-05	7.04E+01	1.67E+00	5.82E+01	1.72E+00	1.22E+01	6.03E-01	2.00E-01	32678.1
6.95E-05	1.31E-05	5.02E-05	1.78E-05	7.09E+01	1.68E+00	5.91E+01	1.75E+00	1.18E+01	5.95E-01	2.00E-01	32678.1
6.90E-05	1.31E-05	5.02E-05	1.83E-05	7.05E+01	1.67E+00	5.88E+01	1.74E+00	1.17E+01	5.91E-01	2.00E-01	32678.1
8.78E-05	1.74E-05	6.57E-05	2.63E-05	9.02E+01	2.14E+00	7.52E+01	2.22E+00	1.50E+01	7.58E-01	2.00E-01	32678.1
1.09E-04	2.49E-05	8.54E-05	3.66E-05	1.13E+02	2.69E+00	9.21E+01	2.70E+00	2.11E+01	1.00E+00	2.00E-01	32678.1
1.09E-04	2.54E-05	8.54E-05	3.66E-05	1.13E+02	2.68E+00	9.12E+01	2.67E+00	2.15E+01	1.01E+00	2.00E-01	32678.1
1.31E-04	3.47E-05	1.09E-04	5.26E-05	1.38E+02	3.30E+00	1.10E+02	3.17E+00	2.81E+01	1.28E+00	2.00E-01	32678.1
1.31E-04	3.47E-05	1.09E-04	5.26E-05	1.38E+02	3.30E+00	1.10E+02	3.17E+00	2.81E+01	1.28E+00	2.00E-01	32678.1
1.31E-04	3.47E-05	1.09E-04	5.21E-05	1.38E+02	3.28E+00	1.09E+02	3.15E+00	2.81E+01	1.28E+00	2.00E-01	32678.1
1.31E-04	3.52E-05	1.09E-04	5.16E-05	1.38E+02	3.29E+00	1.09E+02	3.14E+00	2.87E+01	1.29E+00	2.00E-01	32678.1
1.31E-04	3.52E-05	1.09E-04	5.16E-05	1.38E+02	3.29E+00	1.09E+02	3.14E+00	2.87E+01	1.29E+00	2.00E-01	32678.1

1.40E-04	3.99E-05	1.19E-04	5.87E-05	1.48E+02	3.54E+00	1.16E+02	3.31E+00	3.19E+01	1.41E+00	2.00E-01	32678.1
1.59E-04	4.84E-05	1.39E-04	7.14E-05	1.70E+02	4.06E+00	1.32E+02	3.72E+00	3.79E+01	1.65E+00	2.00E-01	32678.1
1.61E-04	4.98E-05	1.42E-04	7.37E-05	1.72E+02	4.13E+00	1.33E+02	3.75E+00	3.87E+01	1.68E+00	2.00E-01	32678.1
2.83E-04	1.06E-04	2.71E-04	1.54E-04	3.11E+02	7.50E+00	2.34E+02	6.27E+00	7.72E+01	3.20E+00	2.00E-01	32678.1
3.08E-04	1.23E-04	3.01E-04	1.72E-04	3.41E+02	8.23E+00	2.52E+02	6.67E+00	8.88E+01	3.60E+00	2.00E-01	32678.1
4.46E-04	2.00E-04	4.60E-04	2.74E-04	5.07E+02	1.23E+01	3.68E+02	9.27E+00	1.39E+02	5.51E+00	2.00E-01	32678.1
4.67E-04	2.18E-04	4.89E-04	2.94E-04	5.35E+02	1.30E+01	3.85E+02	9.55E+00	1.50E+02	5.89E+00	2.00E-01	32678.1

S_1 beam specimen’s data

ε_1	**ε_3**	**ε_2**	**Shear Strain γxy= 2(ε2-(ε1+ε3)/2)**	**Max Principal strain ξ x10-6**	**Max Principal stress σ (MPa)**	**Max shearing strain γ x10-6**	**Max Shearing Stress, ζmax**	**Min Principal strain ξ x10-6**	**Min Principal stress σ(MPa)**	**Poisson's Ratio ν**	**Young's Modulus E, MPa**
4.69E-07	0.00E+00	0.00E+00	-4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.22E-02	-9.72E-02	3.69E-04	2.00E-01	30278.13
0.00E+00	0.00E+00	4.69E-07	9.39E-07	4.69E-01	8.61E-03	9.39E-01	1.22E-02	-4.69E-01	-8.61E-03	2.00E-01	30278.13

4.69E-07	0.00E+00	0.00E+00	-4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.22E-02	-9.72E-02	3.69E-04	2.00E-01	30278.13
4.69E-07	4.69E-07	4.69E-07	0.00E+00	4.69E-01	1.29E-02	0.00E+00	0.00E+00	4.69E-01	1.29E-02	2.00E-01	30278.13
2.82E-06	2.35E-06	4.69E-07	-4.23E-06	4.71E+00	1.10E-01	4.25E+00	5.02E-02	4.56E-01	3.21E-02	2.00E-01	30278.13
2.82E-06	1.88E-06	9.39E-07	-2.82E-06	3.83E+00	9.18E-02	2.97E+00	3.45E-02	8.63E-01	3.74E-02	2.00E-01	30278.13
2.82E-06	2.35E-06	9.39E-07	-3.29E-06	4.24E+00	1.02E-01	3.32E+00	3.85E-02	9.22E-01	4.06E-02	2.00E-01	30278.13
2.82E-06	1.88E-06	9.39E-07	-2.82E-06	3.83E+00	9.18E-02	2.97E+00	3.45E-02	8.63E-01	3.74E-02	2.00E-01	30278.13
2.82E-06	2.35E-06	9.39E-07	-3.29E-06	4.24E+00	1.02E-01	3.32E+00	3.85E-02	9.22E-01	4.06E-02	2.00E-01	30278.13
2.35E-06	2.35E-06	9.39E-07	-2.82E-06	3.76E+00	9.04E-02	2.82E+00	3.65E-02	9.39E-01	3.88E-02	2.00E-01	30278.13
2.35E-06	2.35E-06	1.41E-06	-1.88E-06	3.29E+00	8.18E-02	1.88E+00	2.44E-02	1.41E+00	4.74E-02	2.00E-01	30278.13
2.35E-06	2.82E-06	1.41E-06	-2.35E-06	3.78E+00	9.30E-02	2.39E+00	3.85E-02	1.39E+00	4.91E-02	2.00E-01	30278.13
2.35E-06	2.82E-06	1.41E-06	-2.35E-06	3.78E+00	9.30E-02	2.39E+00	3.85E-02	1.39E+00	4.91E-02	2.00E-01	30278.13
1.88E-06	2.82E-06	1.41E-06	-1.88E-06	3.40E+00	8.39E-02	2.10E+00	4.39E-02	1.30E+00	4.53E-02	2.00E-01	30278.13
2.35E-06	2.82E-06	4.69E-07	-4.23E-06	4.71E+00	1.10E-01	4.25E+00	6.21E-02	4.56E-01	3.21E-02	2.00E-01	30278.13
2.35E-06	2.35E-06	9.39E-07	-2.82E-06	3.76E+00	9.04E-02	2.82E+00	3.65E-02	9.39E-01	3.88E-02	2.00E-01	30278.13
2.35E-06	3.29E-06	9.39E-07	-3.76E-06	4.75E+00	1.13E-01	3.87E+00	6.56E-02	8.81E-01	4.20E-02	2.00E-01	30278.13
1.88E-06	3.29E-06	1.41E-06	-2.35E-06	3.95E+00	9.62E-02	2.74E+00	6.09E-02	1.21E+00	4.60E-02	2.00E-01	30278.13
2.35E-06	3.29E-06	1.41E-06	-2.82E-06	4.30E+00	1.05E-01	2.97E+00	5.45E-02	1.33E+00	5.03E-02	2.00E-01	30278.13

1.88E-06	3.29E-06	1.41E-06	-2.35E-06	3.95E+00	9.62E-02	2.74E+00	6.09E-02	1.21E+00	4.60E-02	2.00E-01	30278.13
1.88E-06	4.23E-06	1.41E-06	-3.29E-06	5.07E+00	1.21E-01	4.04E+00	9.51E-02	1.03E+00	4.69E-02	2.00E-01	30278.13
1.41E-06	2.82E-06	1.88E-06	-4.70E-07	2.86E+00	7.18E-02	1.48E+00	4.39E-02	1.37E+00	4.45E-02	2.00E-01	30278.13
9.39E-07	3.29E-06	1.88E-06	-4.70E-07	3.31E+00	8.01E-02	2.39E+00	7.10E-02	9.16E-01	3.62E-02	2.00E-01	30278.13
1.41E-06	1.88E-06	2.35E-06	1.41E-06	2.39E+00	5.88E-02	1.48E+00	1.72E-02	9.01E-01	3.16E-02	2.00E-01	30278.13
1.41E-06	1.88E-06	2.82E-06	2.35E-06	2.84E+00	6.72E-02	2.39E+00	2.72E-02	4.46E-01	2.33E-02	2.00E-01	30278.13
0.00E+00	4.69E-07	4.69E-07	4.69E-07	5.67E-01	1.26E-02	6.64E-01	1.22E-02	-9.72E-02	3.69E-04	2.00E-01	30278.13
0.00E+00	0.00E+00	4.69E-07	9.39E-07	4.69E-01	8.61E-03	9.39E-01	1.22E-02	-4.69E-01	-8.61E-03	2.00E-01	30278.13
0.00E+00	0.00E+00	4.69E-07	9.39E-07	4.69E-01	8.61E-03	9.39E-01	1.22E-02	-4.69E-01	-8.61E-03	2.00E-01	30278.13
2.25E-05	0.00E+00	7.04E-06	-8.45E-06	2.33E+01	5.31E-01	2.41E+01	6.13E-01	-7.66E-01	8.93E-02	2.00E-01	30278.13
5.68E-05	1.41E-06	2.63E-05	-5.63E-06	5.70E+01	1.31E+00	5.57E+01	1.58E+00	1.27E+00	2.90E-01	2.00E-01	30278.13
8.17E-05	4.69E-07	4.23E-05	2.35E-06	8.17E+01	1.88E+00	8.13E+01	2.37E+00	4.53E-01	3.85E-01	2.00E-01	30278.13
1.03E-04	4.69E-07	5.87E-05	1.36E-05	1.04E+02	2.38E+00	1.04E+02	3.07E+00	2.10E-02	4.76E-01	2.00E-01	30278.13
1.24E-04	9.39E-07	7.37E-05	2.25E-05	1.25E+02	2.87E+00	1.25E+02	3.71E+00	-8.50E-02	5.71E-01	2.00E-01	30278.13
1.23E-04	9.39E-07	7.37E-05	2.30E-05	1.25E+02	2.86E+00	1.25E+02	3.70E+00	-1.32E-01	5.68E-01	2.00E-01	30278.13
1.23E-04	9.39E-07	7.37E-05	2.30E-05	1.25E+02	2.86E+00	1.25E+02	3.70E+00	-1.32E-01	5.68E-01	2.00E-01	30278.13
1.23E-04	9.39E-07	7.37E-05	2.35E-05	1.24E+02	2.85E+00	1.24E+02	3.69E+00	-1.80E-01	5.65E-01	2.00E-01	30278.13

1.49E-04	4.69E-07	9.30E-05	3.66E-05	1.51E+02	3.46E+00	1.53E+02	4.54E+00	-1.76E+00	6.53E-01	2.00E-01	30278.13
2.39E-04	4.69E-07	1.71E-04	1.03E-04	2.50E+02	5.68E+00	2.60E+02	7.61E+00	-1.02E+01	9.11E-01	2.00E-01	30278.13
4.39E-04	1.88E-06	4.01E-04	3.62E-04	5.04E+02	1.13E+01	5.68E+02	1.54E+01	-6.33E+01	8.60E-01	2.00E-01	30278.13
3.08E-04	4.23E-06	7.83E-04	1.25E-03	8.01E+02	1.61E+01	1.29E+03	2.17E+01	-4.89E+02	-7.54E+00	2.00E-01	30278.13
2.94E-04	6.57E-06	1.07E-03	1.84E-03	1.08E+03	2.12E+01	1.86E+03	2.86E+01	-7.81E+02	-1.29E+01	2.00E-01	30278.13
2.91E-04	7.04E-06	1.07E-03	1.85E-03	1.09E+03	2.13E+01	1.87E+03	2.87E+01	-7.87E+02	-1.31E+01	2.00E-01	30278.13
2.88E-04	7.04E-06	1.07E-03	1.85E-03	1.09E+03	2.13E+01	1.88E+03	2.86E+01	-7.90E+02	-1.31E+01	2.00E-01	30278.13
2.74E-04	2.21E-05	1.04E-03	1.79E-03	1.05E+03	2.06E+01	1.80E+03	2.72E+01	-7.53E+02	-1.25E+01	2.00E-01	30278.13
2.73E-04	2.21E-05	1.01E-03	1.72E-03	1.02E+03	2.00E+01	1.74E+03	2.64E+01	-7.23E+02	-1.19E+01	2.00E-01	30278.13
2.73E-04	2.25E-05	9.96E-04	1.70E-03	1.00E+03	1.98E+01	1.71E+03	2.61E+01	-7.09E+02	-1.17E+01	2.00E-01	30278.13
2.72E-04	2.25E-05	9.81E-04	1.67E-03	9.90E+02	1.95E+01	1.69E+03	2.57E+01	-6.96E+02	-1.14E+01	2.00E-01	30278.13
2.71E-04	2.21E-05	9.75E-04	1.66E-03	9.84E+02	1.94E+01	1.68E+03	2.56E+01	-6.91E+02	-1.13E+01	2.00E-01	30278.13
2.71E-04	2.25E-05	9.67E-04	1.64E-03	9.76E+02	1.93E+01	1.66E+03	2.53E+01	-6.83E+02	-1.12E+01	2.00E-01	30278.13
2.70E-04	2.44E-05	9.52E-04	1.61E-03	9.61E+02	1.90E+01	1.63E+03	2.49E+01	-6.67E+02	-1.09E+01	2.00E-01	30278.13
2.70E-04	2.44E-05	9.48E-04	1.60E-03	9.57E+02	1.89E+01	1.62E+03	2.48E+01	-6.63E+02	-1.08E+01	2.00E-01	30278.13
2.69E-04	2.39E-05	9.43E-04	1.59E-03	9.53E+02	1.88E+01	1.61E+03	2.47E+01	-6.59E+02	-1.07E+01	2.00E-01	30278.13
2.69E-04	2.39E-05	9.37E-04	1.58E-03	9.46E+02	1.87E+01	1.60E+03	2.45E+01	-6.54E+02	-1.07E+01	2.00E-01	30278.13

2.68E-04	2.39E-05	9.25E-04	1.56E-03	9.35E+02	1.85E+01	1.58E+03	2.42E+01	-6.43E+02	-1.05E+01	2.00E-01	30278.13
2.66E-04	2.58E-05	9.16E-04	1.54E-03	9.26E+02	1.83E+01	1.56E+03	2.39E+01	-6.34E+02	-1.03E+01	2.00E-01	30278.13
2.67E-04	2.68E-05	9.14E-04	1.53E-03	9.23E+02	1.83E+01	1.55E+03	2.39E+01	-6.30E+02	-1.02E+01	2.00E-01	30278.13
2.65E-04	2.58E-05	8.98E-04	1.51E-03	9.08E+02	1.80E+01	1.52E+03	2.35E+01	-6.17E+02	-9.99E+00	2.00E-01	30278.13
2.65E-04	2.58E-05	8.97E-04	1.50E-03	9.07E+02	1.80E+01	1.52E+03	2.34E+01	-6.16E+02	-9.97E+00	2.00E-01	30278.13
2.65E-04	2.54E-05	8.97E-04	1.50E-03	9.06E+02	1.80E+01	1.52E+03	2.34E+01	-6.16E+02	-9.97E+00	2.00E-01	30278.13
2.65E-04	2.49E-05	8.95E-04	1.50E-03	9.05E+02	1.79E+01	1.52E+03	2.34E+01	-6.15E+02	-9.96E+00	2.00E-01	30278.13
2.66E-04	2.35E-05	8.95E-04	1.50E-03	9.05E+02	1.79E+01	1.52E+03	2.35E+01	-6.16E+02	-9.97E+00	2.00E-01	30278.13
2.65E-04	2.21E-05	8.90E-04	1.49E-03	9.00E+02	1.78E+01	1.51E+03	2.34E+01	-6.12E+02	-9.91E+00	2.00E-01	30278.13
2.65E-04	2.11E-05	8.89E-04	1.49E-03	8.99E+02	1.78E+01	1.51E+03	2.34E+01	-6.13E+02	-9.93E+00	2.00E-01	30278.13
2.65E-04	2.07E-05	8.86E-04	1.49E-03	8.96E+02	1.78E+01	1.51E+03	2.33E+01	-6.10E+02	-9.89E+00	2.00E-01	30278.13
2.66E-04	1.97E-05	8.86E-04	1.49E-03	8.96E+02	1.77E+01	1.51E+03	2.34E+01	-6.11E+02	-9.89E+00	2.00E-01	30278.13
2.60E-04	7.04E-06	8.92E-04	1.52E-03	9.02E+02	1.78E+01	1.54E+03	2.39E+01	-6.35E+02	-1.04E+01	2.00E-01	30278.13
2.60E-04	6.10E-06	8.87E-04	1.51E-03	8.97E+02	1.77E+01	1.53E+03	2.38E+01	-6.31E+02	-1.04E+01	2.00E-01	30278.13
2.60E-04	5.16E-06	8.91E-04	1.52E-03	9.02E+02	1.78E+01	1.54E+03	2.39E+01	-6.36E+02	-1.05E+01	2.00E-01	30278.13
2.60E-04	4.69E-06	8.91E-04	1.52E-03	9.01E+02	1.77E+01	1.54E+03	2.39E+01	-6.37E+02	-1.05E+01	2.00E-01	30278.13
2.59E-04	2.35E-06	8.90E-04	1.52E-03	9.01E+02	1.77E+01	1.54E+03	2.40E+01	-6.39E+02	-1.05E+01	2.00E-01	30278.13

2.59E-04	1.41E-06	8.81E-04	1.50E-03	8.92E+02	1.76E+01	1.52E+03	2.38E+01	-6.32E+02	-1.04E+01	2.00E-01	30278.13
2.59E-04	9.39E-07	8.79E-04	1.50E-03	8.90E+02	1.75E+01	1.52E+03	2.38E+01	-6.31E+02	-1.04E+01	2.00E-01	30278.13
2.52E-04	5.16E-06	8.73E-04	1.49E-03	8.83E+02	1.74E+01	1.51E+03	2.34E+01	-6.26E+02	-1.03E+01	2.00E-01	30278.13
2.52E-04	4.69E-06	8.72E-04	1.49E-03	8.82E+02	1.74E+01	1.51E+03	2.34E+01	-6.26E+02	-1.03E+01	2.00E-01	30278.13

Appendix 12: Moment-curvature, compressive stress-strain data for s_0 and s_1 beam specimens

S_0 Beam specimen's data					**S_1 Beam specimen's data**				
Moment (KNm)	**Concrete compressive strain, ε**	**Curvature (ε/y),m^{-1}**	**Concrete compressive stress (My/I), MPa**	**I=10763.25 cm4, y=10.07 cm, I/y (cm^3)**	**Moment (KNm)**	**Concrete compressive strain, ε**	**Curvature (ε/y), m^{-1}**	**Concrete compressive stress (My/I), MPa**	**I=10835.25 cm4, y=10.077 cm, I/y (m3)**
3.00E-02	4.69E-07	4.64E-06	2.71E-02	1068.781	3.00E-01	2.35E-07	2.32E-06	2.71E-01	1075.275
3.60E-01	2.35E-07	2.32E-06	3.25E-01	1068.781	1.77E+00	1.17E-06	1.16E-05	1.60E+00	1075.275
2.34E+00	1.64E-06	1.63E-05	2.11E+00	1068.781	3.90E+00	4.46E-06	4.41E-05	3.52E+00	1075.275

2.22E+00	1.88E-06	1.86E-05	2.00E+00	1068.781	6.15E+00	6.34E-06	6.27E-05	5.55E+00	1075.275
2.22E+00	1.88E-06	1.86E-05	2.00E+00	1068.781	8.94E+00	7.51E-06	7.43E-05	8.07E+00	1075.275
2.22E+00	1.88E-06	1.86E-05	2.00E+00	1068.781	8.76E+00	7.28E-06	7.20E-05	7.91E+00	1075.275
2.19E+00	2.11E-06	2.09E-05	1.98E+00	1068.781	8.70E+00	7.51E-06	7.43E-05	7.85E+00	1075.275
2.16E+00	2.11E-06	2.09E-05	1.95E+00	1068.781	8.64E+00	7.75E-06	7.66E-05	7.80E+00	1075.275
2.10E+00	1.88E-06	1.86E-05	1.90E+00	1068.781	8.64E+00	7.51E-06	7.43E-05	7.80E+00	1075.275
2.07E+00	1.88E-06	1.86E-05	1.87E+00	1068.781	8.64E+00	7.75E-06	7.66E-05	7.80E+00	1075.275
2.10E+00	1.88E-06	1.86E-05	1.90E+00	1068.781	1.10E+01	8.69E-06	8.59E-05	9.94E+00	1075.275
1.98E+00	2.11E-06	2.09E-05	1.79E+00	1068.781	1.34E+01	8.92E-06	8.82E-05	1.21E+01	1075.275
2.25E+00	3.29E-06	3.25E-05	2.03E+00	1068.781	1.31E+01	8.45E-06	8.36E-05	1.18E+01	1075.275
3.90E+00	4.93E-06	4.88E-05	3.52E+00	1068.781	1.44E+01	8.92E-06	8.82E-05	1.30E+01	1075.275
5.55E+00	7.04E-06	6.97E-05	5.01E+00	1068.781	1.42E+01	8.69E-06	8.59E-05	1.28E+01	1075.275

9.93E+00	8.45E-06	8.36E-05	8.96E+00	1068.781	1.71E+01	7.28E-06	7.20E-05	1.54E+01	1075.275
9.93E+00	8.92E-06	8.82E-05	8.96E+00	1068.781	1.71E+01	7.04E-06	6.97E-05	1.54E+01	1075.275
9.93E+00	8.92E-06	8.82E-05	8.96E+00	1068.781	1.71E+01	7.04E-06	6.97E-05	1.54E+01	1075.275
9.93E+00	8.69E-06	8.59E-05	8.96E+00	1068.781	1.70E+01	7.04E-06	6.97E-05	1.54E+01	1075.275
1.23E+01	9.86E-06	9.75E-05	1.11E+01	1068.781	2.04E+01	6.34E-06	6.27E-05	1.84E+01	1075.275
1.49E+01	9.86E-06	9.75E-05	1.35E+01	1068.781	2.10E+01	1.48E-05	1.46E-04	1.90E+01	1075.275
1.49E+01	9.15E-06	9.06E-05	1.35E+01	1068.781	2.13E+01	1.88E-05	1.86E-04	1.93E+01	1075.275
1.77E+01	6.81E-06	6.73E-05	1.60E+01	1068.781	2.09E+01	2.77E-05	2.74E-04	1.89E+01	1075.275
1.98E+01	7.04E-06	6.97E-05	1.78E+01	1068.781	2.03E+01	2.30E-05	2.28E-04	1.84E+01	1075.275
1.00E-07	2.35E-07	2.32E-06	9.03E-08	1068.781	2.02E+01	2.21E-05	2.18E-04	1.82E+01	1075.275
3.60E-01	4.69E-07	4.64E-06	3.25E-01	1068.781	2.01E+01	2.16E-05	2.14E-04	1.81E+01	1075.275
2.10E+00	1.88E-06	1.86E-05	1.90E+00	1068.781	1.98E+01	1.90E-05	1.88E-04	1.78E+01	1075.275

4.65E+00	3.76E-06	3.72E-05	4.20E+00	1068.781	1.97E+01	1.90E-05	1.88E-04	1.78E+01	1075.275
7.50E+00	4.93E-06	4.88E-05	6.77E+00	1068.781	1.97E+01	1.85E-05	1.83E-04	1.78E+01	1075.275
7.41E+00	4.69E-06	4.64E-05	6.69E+00	1068.781	2.07E+01	2.98E-05	2.95E-04	1.87E+01	1075.275
1.90E+01	4.93E-06	4.88E-05	1.71E+01	1068.781	2.07E+01	3.76E-05	3.71E-04	1.87E+01	1075.275
1.88E+01	5.40E-06	5.34E-05	1.69E+01	1068.781	2.05E+01	4.51E-05	4.46E-04	1.85E+01	1075.275
2.05E+01	7.98E-06	7.89E-05	1.85E+01	1068.781	2.06E+01	5.38E-05	5.32E-04	1.85E+01	1075.275
2.02E+01	8.69E-06	8.59E-05	1.82E+01	1068.781	2.06E+01	6.43E-05	6.36E-04	1.86E+01	1075.275
2.12E+01	2.02E-05	2.00E-04	1.91E+01	1068.781	2.04E+01	7.30E-05	7.22E-04	1.84E+01	1075.275
2.06E+01	2.14E-05	2.11E-04	1.86E+01	1068.781	2.00E+01	7.28E-05	7.20E-04	1.81E+01	1075.275
2.15E+01	3.26E-05	3.23E-04	1.94E+01	1068.781	1.97E+01	7.35E-05	7.27E-04	1.78E+01	1075.275
2.11E+01	3.22E-05	3.18E-04	1.90E+01	1068.781	1.74E+00	1.88E-06	1.86E-05	1.57E+00	1075.275
2.19E+01	4.30E-05	4.25E-04	1.97E+01	1068.781	3.90E+00	3.99E-06	3.95E-05	3.52E+00	1075.275

2.15E+01	4.27E-05	4.23E-04	1.94E+01	1068.781	6.27E+00	5.63E-06	5.57E-05	5.66E+00	1075.275
2.14E+01	4.25E-05	4.20E-04	1.93E+01	1068.781	8.85E+00	4.93E-06	4.88E-05	7.99E+00	1075.275
2.17E+01	6.31E-05	6.25E-04	1.96E+01	1068.781	1.12E+01	5.40E-06	5.34E-05	1.01E+01	1075.275
2.13E+01	5.73E-05	5.67E-04	1.92E+01	1068.781	1.40E+01	4.93E-06	4.88E-05	1.26E+01	1075.275
2.12E+01	5.68E-05	5.62E-04	1.91E+01	1068.781	2.11E+01	8.22E-06	8.13E-05	1.90E+01	1075.275
2.10E+01	6.64E-05	6.57E-04	1.90E+01	1068.781	2.11E+01	2.28E-05	2.25E-04	1.91E+01	1075.275
2.10E+01	6.29E-05	6.22E-04	1.90E+01	1068.781	2.02E+01	3.00E-05	2.97E-04	1.82E+01	1075.275
2.09E+01	5.85E-05	5.78E-04	1.88E+01	1068.781	2.06E+01	3.90E-05	3.85E-04	1.86E+01	1075.275
2.08E+01	5.56E-05	5.50E-04	1.87E+01	1068.781	2.03E+01	3.40E-05	3.37E-04	1.83E+01	1075.275
2.07E+01	5.52E-05	5.46E-04	1.87E+01	1068.781	2.01E+01	3.19E-05	3.16E-04	1.81E+01	1075.275
2.03E+01	4.86E-05	4.81E-04	1.83E+01	1068.781	2.08E+01	4.23E-05	4.18E-04	1.88E+01	1075.275
2.03E+01	4.86E-05	4.81E-04	1.83E+01	1068.781	2.00E+01	4.41E-05	4.37E-04	1.81E+01	1075.275

2.10E+01	5.56E-05	5.50E-04	1.90E+01	1068.781	1.98E+01	5.12E-05	5.06E-04	1.79E+01	1075.275
2.07E+01	5.31E-05	5.25E-04	1.87E+01	1068.781	1.98E+01	5.14E-05	5.08E-04	1.79E+01	1075.275
2.06E+01	5.14E-05	5.08E-04	1.86E+01	1068.781	1.95E+01	5.63E-05	5.57E-04	1.76E+01	1075.275
2.05E+01	5.00E-05	4.95E-04	1.85E+01	1068.781	2.01E+01	6.17E-05	6.11E-04	1.82E+01	1075.275
2.17E+01	5.42E-05	5.36E-04	1.96E+01	1068.781	2.01E+01	6.17E-05	6.11E-04	1.82E+01	1075.275
2.17E+01	5.42E-05	5.36E-04	1.96E+01	1068.781	1.98E+01	6.17E-05	6.11E-04	1.78E+01	1075.275
2.12E+01	5.14E-05	5.08E-04	1.91E+01	1068.781	1.97E+01	6.13E-05	6.06E-04	1.77E+01	1075.275
2.12E+01	5.07E-05	5.02E-04	1.91E+01	1068.781	2.00E+01	6.17E-05	6.11E-04	1.80E+01	1075.275
2.11E+01	7.42E-05	7.34E-04	1.90E+01	1068.781	2.00E+01	6.17E-05	6.11E-04	1.80E+01	1075.275
2.14E+01	5.52E-05	5.46E-04	1.93E+01	1068.781	2.00E+01	6.20E-05	6.13E-04	1.80E+01	1075.275
2.10E+01	3.69E-05	3.65E-04	1.89E+01	1068.781	2.00E+01	7.21E-05	7.13E-04	1.80E+01	1075.275
2.08E+01	1.62E-05	1.60E-04	1.87E+01	1068.781	1.96E+01	7.25E-05	7.17E-04	1.77E+01	1075.275

2.10E+01	1.24E-05	1.23E-04	1.89E+01	1068.781	1.96E+01	7.37E-05	7.29E-04	1.77E+01	1075.275
2.06E+01	1.83E-05	1.81E-04	1.86E+01	1068.781	1.94E+01	7.51E-05	7.43E-04	1.75E+01	1075.275
2.10E+01	2.00E-05	1.97E-04	1.89E+01	1068.781	1.92E+01	7.75E-05	7.66E-04	1.73E+01	1075.275
2.13E+01	2.28E-05	2.25E-04	1.92E+01	1068.781	2.03E+01	8.69E-05	8.59E-04	1.84E+01	1075.275
2.14E+01	2.61E-05	2.58E-04	1.93E+01	1068.781					
2.15E+01	2.56E-05	2.53E-04	1.94E+01	1068.781					
2.15E+01	3.29E-05	3.25E-04	1.94E+01	1068.781					
2.18E+01	3.87E-05	3.83E-04	1.97E+01	1068.781					
2.09E+01	3.38E-05	3.34E-04	1.89E+01	1068.781					
2.12E+01	3.94E-05	3.90E-04	1.91E+01	1068.781					
2.12E+01	4.18E-05	4.13E-04	1.92E+01	1068.781					
2.07E+01	3.66E-05	3.62E-04	1.87E+01	1068.781					

Appendix 13: Load- steel tensile strains data

S_0 beam specimen's data

Load (KN)	0.16	1.92	12.48	11.84	11.84	11.84	11.68	11.52	11.2	11.04	11.2
Steel tensile strain, ε	1.00E-09	4.69E-07	2.58E-06	2.82E-06	2.82E-06	2.82E-06	2.82E-06	2.58E-06	2.58E-06	2.82E-06	2.82E-06

Load (KN)	10.56	12	20.8	29.6	52.96	52.96	52.96	52.96	65.6	79.68	79.68
Steel tensile strain, ε	2.35E-06	5.40E-06	1.06E-05	3.19E-05	7.21E-05	7.21E-05	7.21E-05	7.18E-05	8.85E-05	1.11E-04	1.10E-04

Load (KN)	94.4	105.44	0.0001	1.92	11.2	24.8	40	39.52	51.84	51.84	51.68
Steel tensile strain, ε	1.28E-04	1.73E-04	1.00E-09	4.69E-07	7.51E-06	1.83E-05	3.31E-05	3.38E-05	4.95E-05	4.93E-05	4.93E-05

Load (KN)	51.68	51.68	51.68	51.04	51.04	50.24	50.24	64.16	80.16	78.56	95.04
Steel tensile strain, ε	4.93E-05	4.93E-05	4.93E-05	4.95E-05	4.95E-05	4.98E-05	4.98E-05	6.48E-05	8.38E-05	8.33E-05	1.03E-04

Load (KN)	92.8	92.8	92.8	92.48	101.12	100	109.12	107.68	112.8	110.08	114.88
Steel tensile strain, ε	1.03E-04	1.03E-04	1.03E-04	1.03E-04	1.12E-04	1.13E-04	1.30E-04	1.32E-04	2.58E-04	2.70E-04	4.96E-04

Load (KN)	112.32	116.64	114.56	114.08	118.56	116.8	117.28	117.28	117.28	121.28	115.84
Steel tensile strain, ε	5.08E-04	6.06E-04	6.72E-04	6.77E-04	7.57E-04	7.61E-04	8.78E-04	8.78E-04	8.80E-04	9.22E-04	9.37E-04

Load (KN)	115.84	114.56	113.92	113.44	113.44	112.96	112	112	112	111.2	111.2
Steel tensile strain, ε	9.37E-04	9.42E-04	9.45E-04	9.46E-04	9.46E-04	9.47E-04	1.04E-03	1.04E-03	1.04E-03	1.04E-03	1.04E-03

Load (KN)	110.72	110.72	110.24	108.16	108.16
Steel tensile strain, ε	1.05E-03	1.05E-03	1.05E-03	1.12E-03	1.12E-03

<u>S_1 beam specimen's data</u>

Load (KN)	0.0001	1.6	9.44	20.8	32.8	47.68	46.72	46.4	46.08	46.08	46.08
Steel tensile strain, ε	1.00E-09	1.00E-09	2.11E-06	5.16E-06	2.75E-05	4.46E-05	4.46E-05	4.41E-05	4.44E-05	4.41E-05	4.41E-05

Load (KN)	58.72	71.36	69.76	76.8	75.84	91.04	91.04	91.04	90.72	108.64	112.64
Steel tensile strain, ε	5.85E-05	7.37E-05	7.32E-05	8.03E-05	8.00E-05	1.01E-04	1.00E-04	9.95E-05	9.95E-05	1.22E-04	4.68E-04

Load (KN)	110.72	112	113.76	0.0001	9.28	20.8	33.44	47.2	59.52	74.4	89.6
Steel tensile strain, ε	4.73E-04	8.82E-04	9.41E-04	1.00E-09	2.82E-06	6.34E-06	2.79E-05	4.72E-05	6.34E-05	8.03E-05	9.95E-05

Load (KN)	83.2	87.84	87.2	104.48	112.32	112.64	107.68	109.92	108	107.04	0.16
Steel tensile strain, ε	9.84E-05	9.81E-05	9.77E-05	1.19E-04	1.68E-04	3.57E-04	3.98E-04	4.53E-04	4.36E-04	4.28E-04	4.69E-07

Load (KN)	9.28	22.24	34.4	46.88	58.72	73.12	88.16	101.28	100.32	103.04	102.72
Steel tensile strain, ε	2.35E-06	1.10E-05	3.85E-05	5.26E-05	6.92E-05	9.13E-05	1.10E-04	1.71E-04	5.43E-04	4.93E-04	4.12E-04

Appendix 14: Flexural stress-strain data for s_0 and s_1 beam specimens

S_0 Beam specimen's data					S_1 Beam specimen's data				
Moment (KN.m)	**Deflection (mm)**	**Flexural stress (My/I),MPa**	**Flexural strain ξf=6Dd/L2**	**I=10763.25 cm4, y=10.07 cm, I/y (cm^3)**	**Moment (KN.m)**	**Deflection (mm)**	**Flexural stress (My/I),MPa**	**Flexural strain ξf=6Dd/L2**	**I=10835.25 cm4, y=10.077 cm, I/y (m3)**
3.00E-02	0.001	2.71E-02	1.481E-06	1068.781	1.00E-03	0.001	9.03E-04	1.4815E-06	1075.275
3.60E-01	0.001	3.25E-01	1.481E-06	1068.781	3.00E-01	0.22831	2.71E-01	0.00033824	1075.275
2.34E+00	0.182648	2.11E+00	0.0002706	1068.781	1.77E+00	0.59361	1.60E+00	0.00087942	1075.275
2.22E+00	0.182648	2.00E+00	0.0002706	1068.781	3.90E+00	0.86758	3.52E+00	0.0012853	1075.275
2.22E+00	0.228311	2.00E+00	0.0003382	1068.781	6.15E+00	1.27854	5.55E+00	0.00189413	1075.275
2.22E+00	0.228311	2.00E+00	0.0003382	1068.781	8.94E+00	1.64384	8.07E+00	0.00243531	1075.275
2.19E+00	0.182648	1.98E+00	0.0002706	1068.781	8.76E+00	1.64384	7.91E+00	0.00243531	1075.275
2.16E+00	0.228311	1.95E+00	0.0003382	1068.781	8.70E+00	1.64384	7.85E+00	0.00243531	1075.275

2.10E+00	0.228311	1.90E+00	0.0003382	1068.781	8.64E+00	1.64384	7.80E+00	0.00243531	1075.275
2.07E+00	0.228311	1.87E+00	0.0003382	1068.781	8.64E+00	1.64384	7.80E+00	0.00243531	1075.275
2.10E+00	0.228311	1.90E+00	0.0003382	1068.781	8.64E+00	1.6895	7.80E+00	0.00250296	1075.275
1.98E+00	0.182648	1.79E+00	0.0002706	1068.781	1.10E+01	2.00913	9.94E+00	0.00297649	1075.275
2.25E+00	0.273973	2.03E+00	0.0004059	1068.781	1.34E+01	2.46575	1.21E+01	0.00365297	1075.275
3.90E+00	0.456621	3.52E+00	0.0006765	1068.781	1.31E+01	2.51142	1.18E+01	0.00372062	1075.275
5.55E+00	0.593607	5.01E+00	0.0008794	1068.781	1.44E+01	2.78539	1.30E+01	0.0041265	1075.275
9.93E+00	1.278539	8.96E+00	0.0018941	1068.781	1.42E+01	2.83105	1.28E+01	0.00419415	1075.275
9.93E+00	1.278539	8.96E+00	0.0018941	1068.781	1.71E+01	3.379	1.54E+01	0.00500592	1075.275
9.93E+00	1.278539	8.96E+00	0.0018941	1068.781	1.71E+01	3.51598	1.54E+01	0.00520886	1075.275
9.93E+00	1.278539	8.96E+00	0.0018941	1068.781	1.71E+01	3.51598	1.54E+01	0.00520886	1075.275
1.23E+01	1.598174	1.11E+01	0.0023677	1068.781	1.70E+01	3.47032	1.54E+01	0.00514121	1075.275

1.49E+01	2.146119	1.35E+01	0.0031794	1068.781	2.04E+01	4.15525	1.84E+01	0.00615593	1075.275
1.49E+01	2.146119	1.35E+01	0.0031794	1068.781	2.11E+01	5.70776	1.91E+01	0.00845595	1075.275
1.77E+01	3.561644	1.60E+01	0.0052765	1068.781	2.08E+01	5.79909	1.87E+01	0.00859124	1075.275
1.98E+01	4.520548	1.78E+01	0.0066971	1068.781	2.10E+01	7.76256	1.90E+01	0.01150008	1075.275
1.00E-03	0.001	9.03E-04	1.481E-06	1068.781	2.13E+01	9.6347	1.93E+01	0.01427363	1075.275
1.00E-03	0.001	9.03E-04	1.481E-06	1068.781	2.09E+01	12.1005	1.89E+01	0.01792661	1075.275
3.60E-01	0.045662	3.25E-01	6.765E-05	1068.781	2.03E+01	12.3288	1.84E+01	0.01826484	1075.275
2.10E+00	0.365297	1.90E+00	0.0005412	1068.781	2.02E+01	12.3744	1.82E+01	0.01833249	1075.275
4.65E+00	0.821918	4.20E+00	0.0012177	1068.781	2.01E+01	12.4201	1.81E+01	0.01840013	1075.275
7.50E+00	1.187215	6.77E+00	0.0017588	1068.781	1.98E+01	12.4201	1.78E+01	0.01840013	1075.275
7.41E+00	1.141553	6.69E+00	0.0016912	1068.781	1.97E+01	12.5114	1.78E+01	0.01853544	1075.275
9.72E+00	1.643836	8.77E+00	0.0024353	1068.781	1.97E+01	12.5114	1.78E+01	0.01853544	1075.275

9.72E+00	1.643836	8.77E+00	0.0024353	1068.781	2.07E+01	14.5662	1.87E+01	0.02157957	1075.275
9.69E+00	1.643836	8.75E+00	0.0024353	1068.781	2.07E+01	16.8493	1.87E+01	0.02496196	1075.275
9.69E+00	1.643836	8.75E+00	0.0024353	1068.781	2.05E+01	19.2237	1.85E+01	0.02847961	1075.275
9.69E+00	1.643836	8.75E+00	0.0024353	1068.781	2.06E+01	21.5069	1.85E+01	0.031862	1075.275
9.69E+00	1.643836	8.75E+00	0.0024353	1068.781	2.06E+01	23.8813	1.86E+01	0.03537967	1075.275
9.57E+00	1.643836	8.64E+00	0.0024353	1068.781	2.04E+01	26.3927	1.84E+01	0.03910028	1075.275
9.57E+00	1.643836	8.64E+00	0.0024353	1068.781	2.00E+01	26.5753	1.81E+01	0.03937087	1075.275
9.42E+00	1.689498	8.50E+00	0.002503	1068.781	1.97E+01	26.7123	1.78E+01	0.03957382	1075.275
9.42E+00	1.689498	8.50E+00	0.002503	1068.781	2.05E+01	28.8585	1.85E+01	0.04275326	1075.275
1.20E+01	2.054795	1.09E+01	0.0030441	1068.781	2.03E+01	31.3242	1.84E+01	0.04640622	1075.275
1.50E+01	2.739726	1.36E+01	0.0040589	1068.781	2.03E+01	33.8356	1.83E+01	0.05012684	1075.275
1.47E+01	2.739726	1.33E+01	0.0040589	1068.781	1.00E-03	0.001	9.03E-04	1.4815E-06	1075.275

1.78E+01	3.607306	1.61E+01	0.0053442	1068.781	1.74E+00	0.27397	1.57E+00	0.00040589	1075.275
1.74E+01	3.69863	1.57E+01	0.0054795	1068.781	3.90E+00	0.45662	3.52E+00	0.00067648	1075.275
1.74E+01	3.69863	1.57E+01	0.0054795	1068.781	6.27E+00	0.77626	5.66E+00	0.00115001	1075.275
1.74E+01	3.69863	1.57E+01	0.0054795	1068.781	8.85E+00	1.09589	7.99E+00	0.00162354	1075.275
1.73E+01	3.69863	1.56E+01	0.0054795	1068.781	1.12E+01	1.46119	1.01E+01	0.00216472	1075.275
1.90E+01	3.972603	1.71E+01	0.0058853	1068.781	1.40E+01	2.0548	1.26E+01	0.00304414	1075.275
1.88E+01	4.063927	1.69E+01	0.0060206	1068.781	1.68E+01	2.73973	1.52E+01	0.00405885	1075.275
2.05E+01	4.429224	1.85E+01	0.0065618	1068.781	1.56E+01	2.83105	1.41E+01	0.00419415	1075.275
2.02E+01	4.520548	1.82E+01	0.0066971	1068.781	1.65E+01	2.83105	1.49E+01	0.00419415	1075.275
2.12E+01	5.251142	1.91E+01	0.0077795	1068.781	1.64E+01	2.83105	1.48E+01	0.00419415	1075.275
2.06E+01	5.43379	1.86E+01	0.0080501	1068.781	1.96E+01	3.56164	1.77E+01	0.00527651	1075.275
2.15E+01	6.255708	1.94E+01	0.0092677	1068.781	2.11E+01	5.06849	1.90E+01	0.00750888	1075.275

2.11E+01	6.438356	1.90E+01	0.0095383	1068.781	2.11E+01	7.26027	1.91E+01	0.01075596	1075.275
2.19E+01	7.579909	1.97E+01	0.0112295	1068.781	2.02E+01	10.0457	1.82E+01	0.01488246	1075.275
2.15E+01	7.488584	1.94E+01	0.0110942	1068.781	2.06E+01	12.3288	1.86E+01	0.01826484	1075.275
2.14E+01	7.488584	1.93E+01	0.0110942	1068.781	2.03E+01	12.4658	1.83E+01	0.01846778	1075.275
2.22E+01	8.310502	2.01E+01	0.0123119	1068.781	2.01E+01	12.5114	1.81E+01	0.01853544	1075.275
2.19E+01	8.447489	1.98E+01	0.0125148	1068.781	2.08E+01	14.6119	1.88E+01	0.02164721	1075.275
2.20E+01	9.452055	1.98E+01	0.014003	1068.781	2.00E+01	17.169	1.81E+01	0.02543548	1075.275
2.20E+01	9.452055	1.98E+01	0.014003	1068.781	1.98E+01	19.6347	1.79E+01	0.02908844	1075.275
2.20E+01	9.452055	1.98E+01	0.014003	1068.781	1.98E+01	19.6347	1.79E+01	0.02908844	1075.275
2.27E+01	10.27397	2.05E+01	0.0152207	1068.781	1.95E+01	22.0091	1.76E+01	0.03260612	1075.275
2.17E+01	10.59361	1.96E+01	0.0156942	1068.781	2.01E+01	22.0091	1.82E+01	0.03260612	1075.275
2.17E+01	10.59361	1.96E+01	0.0156942	1068.781	2.01E+01	22.0091	1.82E+01	0.03260612	1075.275

2.15E+01	10.68493	1.94E+01	0.0158295	1068.781	1.98E+01	22.0091	1.78E+01	0.03260612	1075.275
2.14E+01	10.73059	1.93E+01	0.0158972	1068.781	1.97E+01	22.0548	1.77E+01	0.03267376	1075.275
2.13E+01	10.73059	1.92E+01	0.0158972	1068.781	2.00E+01	24.4292	1.80E+01	0.03619144	1075.275
2.13E+01	10.73059	1.92E+01	0.0158972	1068.781	2.00E+01	24.4292	1.80E+01	0.03619144	1075.275
2.12E+01	10.73059	1.91E+01	0.0158972	1068.781	2.00E+01	24.4292	1.80E+01	0.03619144	1075.275
2.10E+01	11.87215	1.90E+01	0.0175884	1068.781	2.00E+01	24.4292	1.80E+01	0.03619144	1075.275
2.10E+01	11.87215	1.90E+01	0.0175884	1068.781	1.96E+01	24.4292	1.77E+01	0.03619144	1075.275
2.10E+01	12.10046	1.90E+01	0.0179266	1068.781	1.96E+01	24.4292	1.77E+01	0.03619144	1075.275
2.09E+01	12.10046	1.88E+01	0.0179266	1068.781	1.94E+01	24.5662	1.75E+01	0.03639439	1075.275
2.09E+01	12.10046	1.88E+01	0.0179266	1068.781	1.92E+01	24.6119	1.73E+01	0.03646203	1075.275
2.08E+01	12.14612	1.87E+01	0.0179943	1068.781	2.03E+01	26.5297	1.84E+01	0.03930323	1075.275
2.08E+01	12.10046	1.87E+01	0.0179266	1068.781	2.04E+01	28.9041	1.84E+01	0.0428209	1075.275

2.07E+01	12.19178	1.87E+01	0.0180619	1068.781	2.04E+01	31.2329	1.84E+01	0.04627093	1075.275
2.03E+01	13.51598	1.83E+01	0.0200237	1068.781	2.03E+01	33.7443	1.83E+01	0.04999154	1075.275
2.03E+01	13.51598	1.83E+01	0.0200237	1068.781	2.03E+01	36.1644	1.83E+01	0.05357686	1075.275
2.10E+01	14.56621	1.90E+01	0.0215796	1068.781	2.01E+01	36.9863	1.82E+01	0.05479452	1075.275
2.07E+01	14.47489	1.87E+01	0.0214443	1068.781	2.00E+01	37.169	1.80E+01	0.05506511	1075.275
2.06E+01	14.56621	1.86E+01	0.0215796	1068.781	1.97E+01	37.169	1.78E+01	0.05506511	1075.275
2.05E+01	14.61187	1.85E+01	0.0216472	1068.781	1.95E+01	27.8995	1.76E+01	0.04133265	1075.275
2.17E+01	15.34247	1.96E+01	0.0227296	1068.781	1.85E+01	39.1781	1.67E+01	0.0580416	1075.275
2.17E+01	15.34247	1.96E+01	0.0227296	1068.781	1.82E+01	2.60274	1.64E+01	0.00385591	1075.275
2.12E+01	15.52511	1.91E+01	0.0230002	1068.781	8.13E+00	2.10046	7.34E+00	0.00311179	1075.275
2.12E+01	15.52511	1.91E+01	0.0230002	1068.781	8.13E+00	2.10046	7.34E+00	0.00311179	1075.275
2.11E+01	15.57078	1.90E+01	0.0230678	1068.781	8.13E+00	2.10046	7.34E+00	0.00311179	1075.275

2.14E+01	16.66667	1.93E+01	0.0246914	1068.781	8.10E+00	2.0548	7.31E+00	0.00304414	1075.275
2.10E+01	18.17352	1.89E+01	0.0269237	1068.781	8.79E+00	2.0548	7.93E+00	0.00304414	1075.275
2.03E+01	18.49315	1.83E+01	0.0273973	1068.781	7.80E+00	2.0548	7.04E+00	0.00304414	1075.275
2.08E+01	19.45205	1.87E+01	0.0288179	1068.781	7.80E+00	2.0548	7.04E+00	0.00304414	1075.275
2.10E+01	19.68037	1.89E+01	0.0291561	1068.781					
2.06E+01	21.78082	1.86E+01	0.0322679	1068.781					
2.10E+01	22.87671	1.89E+01	0.0338914	1068.781					
2.13E+01	24.10959	1.92E+01	0.0357179	1068.781					
2.14E+01	25.15982	1.93E+01	0.0372738	1068.781					
2.15E+01	26.34703	1.94E+01	0.0390326	1068.781					
2.15E+01	27.53425	1.94E+01	0.0407915	1068.781					
2.18E+01	28.63014	1.97E+01	0.042415	1068.781					

2.09E+01	28.90411	1.89E+01	0.0428209	1068.781	
2.12E+01	30.18265	1.91E+01	0.044715	1068.781	
2.12E+01	30.59361	1.92E+01	0.0453239	1068.781	
2.07E+01	30.59361	1.87E+01	0.0453239	1068.781	