INFLUENCE OF NYLON FIBER AND BLAST FURNACE SLAG ON THE MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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The thesis titled “Influence of Nylon Fiber and Blast Furnace Slag on the Mechanical Properties of Recycled Aggregate Concrete”, submitted by “Sk. Rakibul Islam”, Student ID: “0419042350 P”, Session: “April, 2019”, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil and Structural Engineering on “March 29, 2022”.

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DECLARATION

It is hereby declared that except for the contents where specific references have been made to the work of others, the study contained in this thesis is the result of experiments carried out by the author under the supervision of **Dr. Rupak Mutsuddy**, Assistant Professor, Department of Civil Engineering, Bangladesh University of Engineering andTechnology. No part of this thesis has been submitted to any other university or educational establishment for a degree, diploma or other qualification.

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ABSTRACT

Construction and demolition debris can be crushed to produce recycled concrete aggregate which might be an alternative to conventional natural stone aggregate. Recycled aggregate concrete, being eco-friendly, is an interesting research topic to the scholars. However, mechanical strength of recycled aggregate concrete is lower than that of natural aggregate concrete due to presence of old mortar in the interfacial transition zone around the coarse aggregates. Incorporation of fiber and partial replacement of binder with pozzalonic materials showed improvement of the mechanical strength. Nylon fiber as a synthetic fiber is generally available in Bangladesh. Ground Granulated Blast-furnace Slag (GGBS), which is a by-product in iron industries, is considered as waste though it has pozzalonic properties. Hence, this study investigates the mechanical properties of nylon fiber reinforced recycled aggregate concrete with partial replacement of Ordinary Portland Cement (OPC) with Ground Granulated Blast-furnace Slag (GGBS).

Mechanical properties of hardened concrete usually includes compressive strength, splitting tensile strength, flexural strength or modulus of rupture, flexural toughness, modulus of elasticity, and Poisson’s ratio. In this study, all the aforementioned properties were determined in accordance with ASTM standards. Concrete cylinders were tested for the determination of compressive strength, splitting tensile strength, modulus of elasticity and Poisson’s ratio. Rebound hammer test was also performed to compare the compressive strength from non-destructive test with the actual strength. Moreover, concrete prisms were cast for conducting the flexural test. Apart from these, mechanical properties of aggregates and binder were also observed. Two types of coarse aggregate i.e. natural stone aggregate and recycled concrete stone aggregate were used in this study. Nylon being used in rope available in local market was the main source of nylon fiber with the aspect ratio of 200. Nylon fiber offers ductility to the concrete and acts as crack arrester. Besides, partial replacement of OPC with GGBS produce more calcium silicate hydrate resulting pore refinement.

It was found that incorporation of nylon fiber with 0.1% volume fraction and 10% replacement of OPC with GGBS in recycled aggregate concrete increased the compressive strength of recycled aggregate about 10.9% compared to that of natural stone aggregate concrete. Though fiber and GGBS did not improve splitting strength and flexural strength, the fiber showed resistance to crack propagation and hence the broken parts of the tested samples did not fall apart. Moreover, just 0.2% volume fraction of nylon fiber can increase the flexural toughness about 73.8% compared to the flexural toughness of conventional concrete. Both nylon fiber and GGBS have no significant effect on modulus of elasticity and Poisson’s ratio. On the other hand, rebound hammer test provides conservative estimates of compressive strength of the nylon fiber reinforced recycled aggregate concrete. Considering the combined effect of nylon fiber and GGBS on all the mechanical properties especially on compressive strength, the performance of recycled aggregate concrete can be improved ensuring effective recycling of concrete waste.

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LIST OF ABBREVIATIONS OF TECHNICAL SYMBOLS AND TERMS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BFS	Blast Furnace Slag
BS	British Standard
C&D	Construction and Demolition
CDW	Construction and Demolition Waste
CSH	Calcium Silicate Hydrate
CTM	Compressive Testing Machine
FM	Fineness Modulus
FRC	Fiber Reinforced Concrete
GGBS	Ground Granulated Blast-furnace Slag
GFRC	Glass Fiber Reinforced Concrete
HDPE	High Density Polythylene
LAA	Los Angeles Abrasion
MK	Metakaolin
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
NA	Natural Aggregate
NAC	Natural Aggregate Concrete
NDT	Non-Destructive Test
NF	Nylon Fiber
NFRC	Natural Fiber Reinforced Concrete/Nylon Fiber Reinforced Concrete
OD	Oven-dry
OPC	Ordinary Portland Cement
PCC	Portland Composite Cement
PET	Polythylene Terephthalate
PP	Polypropylene
RA	Recycled Aggregate
RAC	Recycled Aggregate Concrete
RCA	Recycled Concrete Aggregate
RCC	Reinforced Cement Concrete
RCPT	Rapid Chloride Penetration Test
RMT	Rapid Migration Test
SCM	Supplementary Cementitious Material
SFRC	Steel Fiber Reinforced Concrete
SNFRC	Synthetic Fiber Reinforced Concrete
SSD	Saturated Surface Dry
UTM	Universal Testing Machine

Chapter 1

INTRODUCTION

1.1 General

Concrete is versatile, durable, and cost-effective building material widely used because of its desirable engineering properties i.e. high strength, workability, durability, resistance to water etc. It can be molded into any desired shape before it reaches the plastic state. Concrete is a composite construction material composed primarily of coarse aggregate, fine aggregate, cement, and water. The use of cost-effective raw materials for its production makes it economical. However, setting, hardening, and strengthening of concrete involves various physiochemical reactions and sometimes lead to unpredictable results because of its heterogeneous composition. To make good concrete with desired properties, varieties of innovative materials such as fibers, admixtures and construction chemicals, pozzolans and different concrete making techniques are scientifically adopted in modern construction.

Globally, the large amount of consumption of natural resources in concrete, increases demand on its constituent materials including aggregate. Recycled concrete aggregate (RCA) produced from construction and demolition waste can be an alternative to natural aggregates. RCA can be reused reducing the wastage of embodied energy of construction materials. Demolished wastes are crushed, screened and washed to produce the required grading and used for concrete production. Studies showed that recycled aggregate concrete (RAC) possesses comparatively low compressive strength, low tensile strength, limited ductility and little resistance to cracking. However, researchers are working on the improvement of the mechanical properties of RAC.

On the other hand, it has been recognized that the addition of small, closely spaced and uniformly dispersed fibers to concrete would act as a crack arrester and would substantially improve its static and dynamic properties. This type of concrete is known as “Fiber Reinforced Concrete (FRC)”. Different types of fibers are generally incorporated in concrete mix. In Bangladesh, natural fibers are available but requires some sort of processing and not so beneficial. Nylon fiber (NF) is largely available in local market in Bangladesh and can be easily used in concrete. Among all the fibers the nylon fiber is generic and identifies a family of polymers.

Supplementary Cementitious Materials (SCMs) are added to concrete mixtures to improve durability by decreasing permeability. SCMs mitigate alkali reactivity and improve the properties of concrete through hydraulic or pozzolanic activity or both. SCMs can be added to concrete as a partial replacement of Ordinary Portland cement or blended cements. Commonly used SCMs are fly ash, Ground Granulated Blast-furnace Slag (GGBS), Silica fume, Calcium Carbonate, and Natural Pozzolans - such as calcined clays, shale, and metakaolin. SCMs are generally produced as by-product and sometimes are considered as industrial waste. Ground Granulated Blast-furnace Slag (GGBS) is often used in concrete in combination with Portland cement as part of blended cement. GGBS reacts with $Ca(OH)_2$, hydration product of cement and produces additional calcium silicate hydrate (CSH) gel that increases the density of concrete matrix and decreases the porosity. Concrete containing ground granulated slag develops strength over a longer period, leading to reduced permeability and better durability. Concrete made with slag cement has higher long-term compressive and flexure strengths compared to Portland cement concrete.

RAC are generally used as landfill which has a negative environmental effect. GGBS is also generally considered as industrial waste. Reusing RAC in combination of GGBS can consume these waste construction materials efficiently. Incorporation of nylon fiber and partial replacement on cement using GGBS may add more strength to low strength concrete. RAC would help save natural resources and reuse the waste aggregates in an eco-friendly way. Individual studies have been conducted regarding the mechanical properties of recycled aggregate concrete, nylon fiber reinforced concrete and supplementary cementitious materials. Combined effect of RCA, nylon fiber and GGBS should be observed comparing the mechanical properties of natural aggregate concrete (NAC). Further work needs to be done on the application of nylon fiber and RAC in structural components.

1.2 Objectives

The overall objective of the research work is to study the mechanical properties of concrete which uses nylon fiber reinforced recycled concrete aggregate, partial replacement of cement with blast furnace slag and to compare various parameters so as to achieve strength requirements. The specific objectives of this research are:

1. To study the effect of nylon fiber reinforcement on compressive strength, splitting tensile strength of concrete cylinders using natural stone chips, recycled aggregates and to determine parameters such as modulus of elasticity and Poisson’s ratio of concrete.
2. To study the flexural strength of concrete prisms made of natural stone chips, recycled aggregates with nylon fiber and to determine parameters such as modulus of rupture of concrete.
3. To study the effect of blast furnace slag on the mechanical properties of nylon fiber reinforced recycled aggregate.
4. To compare the non-destructive test (Rebound Hammer) results with the compressive strength of concrete.
5. To determine the effect of nylon fiber on the energy absorption capacity of the concrete mix.

1.3 Scope of Work

The study will give a preview of the mechanical properties of nylon fiber reinforced recycled aggregate concrete such as splitting tensile strength, compressive strength, flexural strength and toughness of concrete, modulus of elasticity and Poisson’s ratio. Fiber reinforced concrete is the composite material containing fibers in the cement matrix in a randomly distributed manner. Properties of fiber reinforced concrete obviously depend upon the type, size and shape of the aggregate, type of fiber, fiber content, orientation and distribution of the fibers, mixing, and compaction techniques of concrete. This study mainly explores the effect of nylon fiber and GGBS on the mechanical properties of RAC. In Bangladesh, nylon and construction and demolition waste are locally available material. In this research, mechanical properties of RAC has been studied where GGBS and nylon fiber have been used.

1.4 Outline of the Methodology

The work was related to defining the effect of nylon fiber and GGBS on the mechanical properties of recycled aggregate concrete. In order to reach the aim, the relevant previous research works have been studied and necessary information have been collected for appropriate testing methodology. The required materials were estimated and collected first and then their physical properties were examined. The experiments had been done according to ASTM standard. To do so required number of specimens (cylindrical and prisms) were prepared and tested accordingly. After the completion of the tests, the results were collected to calculate the compressive strengths, splitting tensile strengths and flexural strengths (modulus of rupture). Accordingly, from the result, the optimum volume fraction of nylon fiber and partial replacement of Ordinary Portland Cement (OPC) with GGBS in RAC were established for target compressive strength. Finally, conclusions and recommendations have been drawn based on the analysis of the results.

1.5 The Layout of the Thesis

The layout of this thesis has been designed as follows:

Chapter 1 describes the background of the study, the major objectives and scope of the research and the methodology of the work.

Chapter 2 is mainly based on the literature review related to the present study. It provides a brief description of recycled aggregate concrete, fiber reinforced concrete, the effect of partial replacement of cement with slag.

Chapter 3 provides the experimental program and methodology for the present study, physical and mechanical properties of different materials used in this research. This chapter also provides information about concrete mixing, casting, and curing. Finally, it provides a description of the workability of fresh concrete and mechanical properties of hardened concrete properties i.e. compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, Poisson’s ratio and rebound number.

Chapter 4 provides the results of hardened concrete, the effects of different fiber percentages and partial replacement of OPC with GGBS on compressive strength, modulus of elasticity, Poisson’s ratio, splitting tensile strength, flexural strength, and rebound number.

Chapter 5 presents the limitations and conclusion of the study, and also suggestions for future work.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Concrete is a composite materials composed of aggregates and binder. Aggregates, which account for 60 to 75 percent of the total volume of concrete, are divided into two distinct categories - fine and coarse (de Brito and Saikia, 2013). Coarse aggregate provide the main volume of the concrete whereas fine aggregate act as filler. Coarse aggregates are any particles greater than 0.19 inch, but generally range between 3/8 inch to 1.5 inch in diameter. Gravels constitute the majority of coarse aggregate used in concrete with crushed stone making up most of the remainder. Natural aggregate (NA) i.e. different types of stones are common to mixing concrete and hence well documented mechanical properties of such type of concrete are available. Fine aggregates generally consist of natural sand or crushed stone with most particles passing through a 3/8 inch sieve. Cement is generally used as binder in concrete (de Brito and Saikia, 2013).

It is reported that the total annual concrete production in the world is more than 10 billion tons. More than 0.9, 5, and 0.6 billion tons of Portland cement, aggregate and potable water, respectively, are necessary for the production of such an amount of concrete. The massive use of concrete as a construction material is due to its versatile properties. Properties such as strength, durability, affordability and abundance of raw materials make concrete the first choice material for most construction purposes (de Brito and Saikia, 2013).

Urbanization has generated a high demand for construction aggregates. Increased volume of construction debris may provide as an additional source for aggregates. Development and extraction of natural aggregate resources (primarily crushed stone and sand and gravel) are increasingly being constrained by urbanization, zoning regulations, increased costs, and environmental concerns, while use of recycled materials from roads and buildings is growing as a supplement to natural aggregates. Recycling represents one way to convert a waste product into a resource. It has the potential to extend the life of natural resources by supplementing resource supply, reduce environmental disturbance around construction sites, and enhance sustainable development of our natural resources (Wilburn and Goonan, 1998).

The Advancing Sustainable Materials Management: 2018 Fact Sheet (2020) showed that about 600 million tons of construction and demolition (C&D) debris were generated in the United States in 2018, which is more than twice the amount of generated municipal solid waste. Demolition represents more than 90 percent of total C&D debris generation, while construction represents less than 10 percent. Just over 455 million tons of C&D debris were directed to next use and just under 145 million tons were sent to landfills. After demolition of old roads and buildings, the removed concrete is often considered worthless and disposed of as demolition waste. By collecting the used concrete and breaking it up, recycled concrete aggregate (RCA) is created (McNeil and Kang, 2013). The energy consumed to produce 1 ton of NA and RCA was determined as 21112 KJ/ton and 16178 KJ/ton respectively. The production of RCA showed a 30.5% savings in the energy consumption compared to that of NA (Ittyeipe et al. 2020).

The Freedonia Group in 2012 predicted that the increasing demand of construction aggregate would be 48.3 billion metric tons by the year 2015 (Yehia et al. 2015). The main consumers of construction aggregate are Asia and Pacific as shown in Figure 2.1 (The Freedonia, 2012).

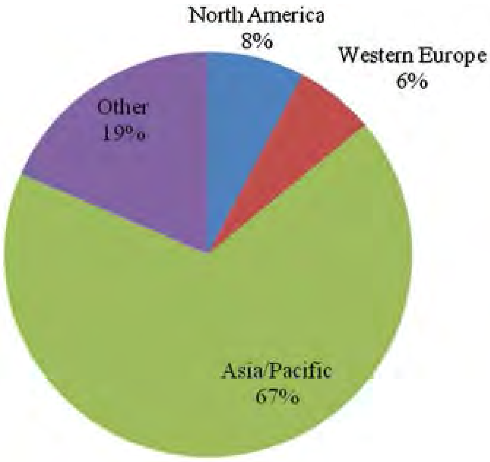


Figure 2.1 Demand on construction aggregates worldwide
(The Freedonia Group 2012)

Over the past 60 years, the world cement map has changed noticeably. North America and Europe’s share in world cement consumption has been declining from around 80% in the 1950’s to around 20% recently. On the other hand, Asia-pacific and the Middle East & Africa represent the largest geographic market and are expected to increase over the foreseeable years to come (Salman, 2017).

Using recycled concrete from old demolished structure as a replacement to aggregates is a good practice to conserve natural aggregates. Another practical solutions to conserve natural resources is to use supplementary cementitious material such as fly ash, slag, silica fume etc. as a replacement to cement thereby the microstructure, mechanical and durability characteristics of concrete can be improved (Nair and Johny, 2016). These supplementary cementitious materials are generally by-product from different industries. Research on using recycled aggregate in concrete is one of the interesting topics because of lower consumption of energy (Figure 2.2).

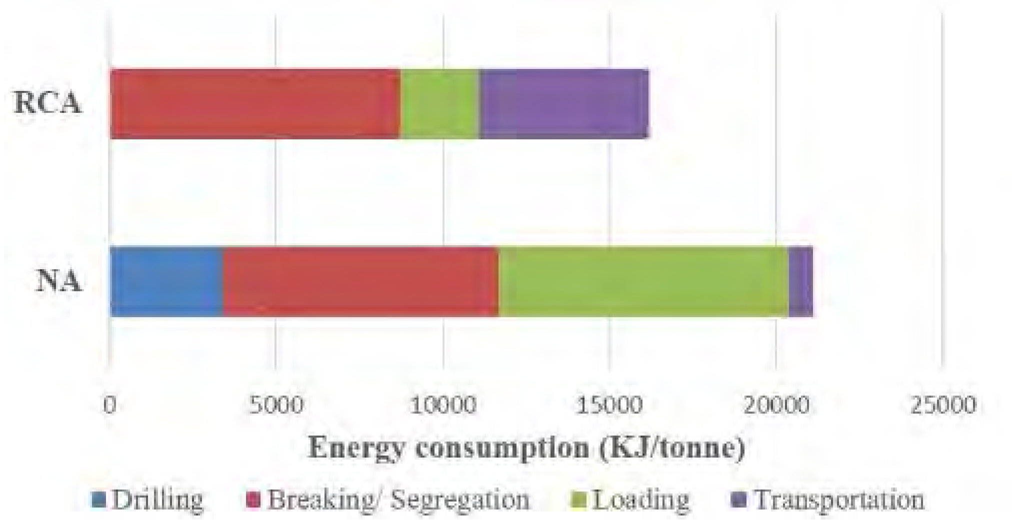


Figure 2.2 Energy consumption involved in the different stages of production of 1 ton of natural and recycled concrete aggregate (Ittyeipe et al. 2020).

Considering environmental preservation and effective utilization of resources, use of recycled aggregate derived from construction and demolition waste is growing all over the world. By using recycled concrete aggregate and Ground Granulated Blast-furnace Slag (GGBS) in concrete, environmental problem can be reduced to some extent (Deepa and Anup, 2016).

Since most of the structures in urban areas are of reinforced cement concrete (RCC) structures and in many cases they requires demolition and so reuse of the aggregates can be a better option. Hence, the mechanical properties of recycled aggregate concrete (RAC) is of great interest. Besides, using fiber reinforcement in concrete and study on the mechanical properties is also demanding sector of research. Concrete produced using both recycled concrete as aggregate and fiber reinforcement is a new prospect. Few studies have concentrated on the properties of concrete made using recycled stone concrete and few studies on using fiber reinforcement. Sources of fiber reinforcement are quite available in Bangladesh and so it will require the study on the effect of fiber reinforcement on the properties of the concrete made of recycled aggregate. Concrete using recycled stone aggregate will be used as a basis for comparing the properties of concrete using both recycled derivatives of the parent concrete and fiber reinforcement specially using nylon fiber. This chapter will primarily discuss about the available studies on the various mechanical properties of concrete made using recycled concrete aggregate, application of supplementary cementitious materials and nylon fiber as fiber reinforcement in concrete.

2.2 Recycled Concrete Aggregate

Recycled concrete aggregates are the materials usually recovered from demolition projects then crushed, screened and washed to produce the required grading for the further usage in any construction. Yearly, vast amount of concrete being produced and also demolition generates huge amount of demolition waste from old concrete structures. So, the reuse of concrete waste by the construction industry is becoming increasingly important. Besides, land for disposal of the waste materials are becoming limited for increasing demands of lands. Transportation cost is another big issue in managing the concrete wastes. Hence, reuse of demolition waste appears to be an effective solution of waste management.

Millions of tons of construction and demolitions wastes (CDW) are generated annually by the concrete industry, and these wastes most times end up in landfills where they contaminate the environment. As the global demand for concrete increases with a consequential increase in the consumptions of its components, the use of alternative materials as components in concrete will create a pathway to meet the future demand for concrete. One of the sustainable way is replacing the most voluminous component of concrete (i.e. coarse aggregates) with CDW (Adesina, 2018).

Due to the presence of impurities, attached cement and mortar on RCA, characteristics (chemical composition) of RCA such as shape, texture, density, specific gravity, porosity and absorption are appreciably affected (Danish and Mosaberpanah, 2021). In the subcontinent, concrete structures generally use natural aggregates or crushed burnt clay brick chips. Hence, recycled stone concrete aggregate and recycled brick concrete aggregate will be available respectively. In Bangladesh, the volume of demolished concrete is increasing owing to the deterioration of concrete structures and the replacement of many low-rise buildings by relatively high-rise buildings attributable to the booming of real estate business. Disposal of the demolished concrete is becoming a great concern to the developers of the buildings. If the demolished concrete is used for new construction, the disposal problem will be solved, the demand for new aggregates will be reduced, and finally consumption of the natural resources for making aggregate will be reduced (Mohammed et al. 2014). Generally recycled aggregates are cheaper than natural aggregates but less suitable on the basis of strength. Though there is some durability issues, but recycled aggregate provide economic and environmental advantages (Danish and Mosaberpanah, 2021).

Production of the raw materials of the concrete has significant environmental impact (Rahal, 2007). Also, construction and demolition waste (CDW) is a considerable issue from environmental point of view. As the amount of construction and demolition waste (CDW) has increased considerably over the last few years, the recycling and the reuse of this material is necessary considering the impact (Etxeberria et al. 2007a). The process of crushing concrete to produce coarse aggregate for the production of new concrete can ensure environment-friendly concrete. Waste concrete management and preservation of landfills and natural sources of aggregates are also be ensured. Researchers are working on the comparison of the mechanical properties of recycled aggregate concrete (RAC) and the conventional natural aggregate concrete (NAC) (Rahal, 2007). With respect to compressive strength, concrete made with 100% of recycled coarse aggregate with lower w/c ratio can have larger compressive strength (Etxeberria et al. 2007b). A large number of experiments has been conducted worldwide last couple of decades on NAC and RAC. The relations between the compressive strength, the density, the splitting tensile strength, the flexural strength, and the elastic modulus of NAC and RAC are investigated (Xiao et al. 2007). Ozbakkaloglu et al. (2018) showed that RAC with up to 25% recycled aggregate content exhibit up to 5% lower elastic modulus, 8% lower flexural strength, 8% lower splitting tensile strength, 4% higher water absorption, and 12% higher 70-day drying shrinkage compared to NAC. The differences between the properties of NAC and RAC containing 100% recycled aggregate are significant. RCA shows up to 14% lower elastic modulus, 27% lower flexural strength, 24% lower splitting tensile strength, 8%

higher water absorption, and 20% higher 70-day drying shrinkage (Ozbakkaloglu et al. 2018). If w/c ratio is high then quality of recycled aggregate do not affect the compressive strength of concrete (Ryu, 2002). Again, strength depends on the quality of interfacial transition zone (ITZ). Experiments shows that older ITZ is better than new ITZ in RAC (Ryu, 2002).

2.3 Influence of Aggregates on Mechanical Properties of Concrete

Performance of concrete is evaluated from mechanical properties which include compressive strength, tensile strength, modulus of rupture, modulus of elasticity, shrinkage, and creep. But compressive strength of concrete is the most important characteristic and it is generally assumed that an improvement in concrete compressive strength will improve its mechanical properties (Ayub et al. 2014).

Concrete strength is affected by many factors, such as quality of raw materials, water-cement ratio, mix ratio, age of concrete, type and degree of compaction, temperature, relative humidity and curing condition and process. If w/c is high then the initial spacing between the cement grains results residual voids not filled by hydration products. A lower w/c means less water and hence lower workability. Lower workability creates difficulty in compaction and the compressive strength reduces (Hassoun and Al-Manaseer, 2012).

Concrete is a mixture of filler and binding material. Recent technology explained the chemical bond at the interface of aggregate and cement paste and hence aggregate influence most of the properties of concrete. Interfacial Transition Zone (ITZ) plays an important role in determining the strength and durability of concrete. Mechanical properties of concrete depends on source, weight, size, shape, angularity index, surface texture, modulus of elasticity, bulk density, specific gravity, absorption, moisture content, cleanliness, soundness, thermal properties and, grading of aggregates (Muhit et al. 2013).

2.3.1 Compressive Strength

Compressive strength of concrete is determined according to the specifications of ASTM C39. Hardened concrete cylinders are tested using compression testing machine under continuously applied load over until failure occurs.

The compressive strength of concrete indicates its ability to withstand the load in compression and can be related to other types of concrete’s mechanical properties. Though the compressive strength of concrete is mainly controlled by the water to binder ratio, other components such as aggregate also play a significant role. The compressive strength of RAC has been reported to be lower than that of NAC (Adesina, 2018). Study of Rahal (2007) shows that compressive strength of recycled concrete aggregates at 28 days of curing is about 90% than that of NAC.

However, RA obtained from higher strength concrete waste show higher strength of RAC compared to RA processed from the waste concrete of low strength (Etxeberria et al. 2007b). The reduction in compressive strength after 28 days is about 20% when 100% recycled aggregates are used (Elhakam et al. 2012).

Several studies show that aggregate size has effect on the compressive strength on concrete. Higher strength ratio is observed for the larger nominal maximum aggregate size concrete at each testing date. Coefficient of variation increases as the nominal maximum aggregate size increases (Issa et al. 2000). The compressive strength of RAC increases with an increase of aggregate size due to the lower adhered mortar content of the bigger aggregate size comparative to the smaller aggregate size (Kang and Weibin, 2018).

2.3.2 Modulus of Elasticity of Concrete

Modulus of elasticity can be defined as the change of stress with respect to strain in the elastic range of a material. In case of concrete, it is the slope of the initial straight portion of the stress-strain curve. Modulus of elasticity (MOE) is a measure of stiffness or the resistance of the concrete to deformation. The modulus of elasticity is an essential parameter in the determination of the stress and strain distributions and displacements, especially when the elasticity considerations governed the concrete structure design (Vakhshouri, 2018).

Modulus of elasticity, E_c is necessary for calculating the static and dynamic behavior of structural elements. Furthermore, E_c is a good indicator of degree of concrete deterioration: more degradation results in lower E_c. Elastic modulus has importance in designing structures for the serviceability limit state, in which the main focus is the control of crack widths and the limitation of deflections (Silva et al. 2016).

The cement content, as paste material to bond the aggregates, is also an important parameter in the mechanical properties and modulus of elasticity of concrete. Increasing the paste content decreased the void content of the mixture, which in turn, increased the modulus of elasticity of the hardened concrete (Vakhshouri, 2018).

Generaally, modulus of elasticity generally strongly decreases with increasing recycled aggregate (RA) content. Even when the compressive strength of RAC is equivalent to that of a conventional concrete, its modulus of elasticity is generally lower, and therefore the deformations are higher, which is a source of distrust and an effective barrier to using RA in concrete (Silva et al. 2016). 10% reduction in modulus of elasticity is observed for RAC compared to NAC (Etxeberria et al. 2007a).

Studies on mechanical properties particularly stress-strain curve of RAC is similar to NAC. Experimental studies show that with increase in amount of recycled aggregate, the values of compressive strength, peak strain, toughness, plastic energy capacity and elastic energy and elastic modulus decreases, which becomes barrier for the application of RAC structures (Nandhini et al. 2016).

2.3.3 Splitting Tensile Strength

Factors affecting the relationship between tensile strength and compressive strength are: aggregate type, the presence of compressive stresses transverse to the tensile stresses, and the magnitude of compressive strength. Relationship varies with the procedure of testing tensile strength. The most common tests of tensile strength - the direct tension test, flexure test, and splitting test. Splitting test is simple, reliable, and convenient method for approximating the tensile strength of concrete. ASTM C496 and BS 1881:117-83 prescribe standard procedures for conducting the splitting test. Cylindrical samples are usually used to evaluate the splitting tensile strength of concrete. The splitting tensile strength test induce transverse tension. Compressive stress in two diametrically opposite points on the cylinder diameter develops of high tensile stresses that cause rupture of the specimen along the vertical plane. Traditionally, tensile strength of NAC is 8-15 percent of the compressive strength (Mohamed et al. 2016).

A reduction of over 20% in split tensile strength has been reported when RCA is used to make concrete (Adesina, 2018). The splitting tensile strengths of concrete made with recycled coarse aggregate depend on the mix proportions. The strength of recycled concrete can be 10–25% lower than that of NAC (Tabsh and Abdelfatah, 2009).

2.3.4 Modulus of Rupture and Flexural Toughness

Modulus of rupture (MOR) is determined from third point loading on a simply supported beam. Increasing flexural load increases deflection which is generally maximum at the mid span. The load-deflection curve found from the flexural test provide the toughness. Toughness indexes are calculated using the load-deflection data. Flexural strength indirectly measure the tensile strength of concrete, and can be determined from a third-point loading (Dhir et al. 2019). Many factors have been shown to influence the flexural tensile strength of concrete, particularly the level of stress, size, age and confinement to concrete flexure member, etc. (Ahmed et al. 2014).

Besides, flexural toughness is a measure of energy absorption capacity and characterization of material’s ability to resist fracture under flexure loads. Flexural behavior of concrete particularly the post-peak performance is rather weak and brittle (Chin and Xiao, 2013). Study of Nandhini et al. (2016) showed that beams using 100% of RCA undergoes 3.57% higher deflection than NAC.

Flexural strength of concrete shows the ability of a concrete to resist deformation when subjected to bending. The flexural strength of concrete decreases with the incorporation of RA as an aggregate and the trend in strength reduction continues with an increase in the amount RA used (Adesina, 2018). However, Arezoumandi et al. (2015) showed that RAC exhibited similar flexural strength compared to NAC. The crack pattern of the RCA beams is similar to that of the NA beams. However, the RCA beams exhibits smaller crack spacing than the NA beams. The flexural strength is slightly affected by the RCA content. However, the ductility of the beam is not significantly influenced by the RCA content (Yang et al. 2020).

2.3.5 Non-destructive Test Using Elastic Rebound Hammer

Hardness is considered as an important property of concrete and used to predict compressive strength of concrete non-destructively. The classic Schmidt rebound hammer is the most popular nondestructive method in this regard. The simple linear correlation between rebound numbers and concrete compressive strength are proposed by several scholars. Schmidt rebound number is correlated with compressive strength for concretes with different water-cement ratios. The classic Schmidt rebound hammer is not recommended to be used on the concrete specimens at early age i.e. less than 3 days (Kovler et al. 2018).

The rebound hammer test is described in ASTM C805 and BS 1881:202-86. Schmidt hammer test is most useful for rapidly surveying large areas of similar types of concrete in the construction being considered (Aydin and Saribiyik, 2016).

RAC tends to be more porous, have higher absorption and relatively lower specific gravity than NAC (Highways Agency Standards, 2007) and hence the rebound number of RAC is less than that of NAC. Around 95% prediction band should be used to estimate the compressive strength of concrete (Saha and Amanat, 2021). The old mortar having higher air content, leading to decreasing the compressive strength of RAC (Das et al. 2018).

Rebound hammer test can be applicable directly on the curved surface of molded cylindrical specimens. Each cylindrical specimen can be labeled in three parts of 120° where in each one three readings were performed, one in the center, one in the upper end and another at the lower end of the specimen (Figure 2.3) (Pereira and Medeiros, 2012).

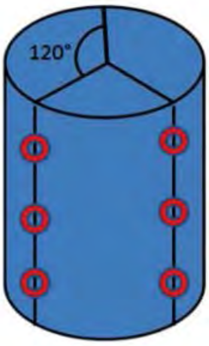


Figure 2.3 Measurement points Rebound hammer test in the cylindrical specimens (Pereira and Medeiros 2012)

2.4 Fiber Reinforced Concrete

Fiber Reinforced Concrete (FRC) is concrete containing fibrous material which impart structural integrity. The most famous advantage of concrete is its high compressive strength. However, there are many defects for concrete materials, such as low anti-cracking performance, bad toughness, low tensile strength, and so on (Zhang et al. 2018). Therefore, concrete requires reinforcement. The most known method is to use ordinary continuous reinforcing bars in order to increase the load carrying capacity in the tensile and shear zones.

Fibers are generally used as resistance to cracking and strengthening of concrete (Nishane and Thakare, 2017). Fibers that are short materials randomly spread in the concrete mix, are however discontinuous. Fibers' distribution in different directions in concrete greatly affects its reinforcement efficiency in the concrete matrix (Li et al. 2018). They do not enhance the (tensile) strength remarkably, but due to their random distribution in the mix, they are very effective and useful when it comes to controlling cracks. As a result, the ductility of fiber reinforced members is increased (Najafiyan et al. 2013). The concept behind FRC is that the deformation of the matrix under stress will transfer the load to the fibers (Parameswaran et al. 1989). Fiber enhances the toughness of concrete, and hence FRC is used on large scale for structural purposes (Nishane and Thakare, 2017).

Fibers work with concrete utilizing two mechanisms: the spacing mechanism and the crack bridging mechanism. The spacing mechanism requires a large number of fibers well distributed within the concrete matrix to arrest any existing micro-crack that could potentially expand and create a sound crack. For typical volume fractions of fibers, utilizing small diameter fibers or micro fibers can ensure the required number of fibers for micro crack arrest. The second mechanism, termed crack bridging, requires larger straight fibers with adequate bond to concrete (Joshi, 2016).

Reducing the disintegration, fibers consequently control cracking due to plastic shrinkage and to drying shrinkage. Besides, FRC has greater strain capacity and impact strength by furnishing energy dissipating mechanisms (Silawat and Kumar, 2016).

Fibers increase the tensile and flexural strength by diminishing and arresting development of cracks in concrete and improve toughness. In fact, fibers are usually used in concrete to control cracking due to both plastic shrinkage and drying shrinkage. They also reduce the permeability of concrete and thus reduce bleeding of water (Silawat and Kumar, 2016).

2.4.1 Effect of Fibers in Concrete

Fibers are usually used in concrete to control cracking due to plastic shrinkage and to drying shrinkage. Some types of fibers produce greater impact on concrete. The amount of fibers added to a concrete mix is expressed as a percentage of the total volume of the composite (concrete and fibers), termed "volume fraction" (V_f). V_f typically ranges from 0.1 to 3%. The aspect ratio (l/d) is calculated by dividing fiber length (l) by its diameter (d) (Rao, 2013). Fibers with a non-circular cross section use an equivalent diameter for the calculation of aspect ratio. Increasing the aspect ratio of the fiber usually segments the flexural strength and toughness of the matrix. However, fibers that are too long tend to “ball” in the mix and create workability problems (Ravikumar et al. 2015).

Fibers help to improve the compressive strength, tensile strength, flexural strength, post peak ductility performance, pre-crack tensile strength, fatigue strength, impact strength and eliminate temperature and shrinkage cracks. Essentially, fibers act as crack arrester restricting the development of cracks and thus transforming an inherently brittle matrix, i.e. cement concrete with its low tensile and impact resistances, into a strong composite with superior crack resistance, improved ductility and distinctive post- cracking behavior prior to failure (Lakshmi and Thaarani, 2015).

About 1% addition of synthetic fibers give higher compressive strength, flexural strength and tensile strength (Choudhary, 2017). Addition of fibers to concrete increased the splitting tensile strength of concrete by approximately 20–50% (Choi and Yuan, 2005). Also, ductility of concrete is found to increase with inclusion of fibers at higher fiber content (Ghaffar al. 2014). Most notable among the improved mechanical characteristics of Fiber Reinforced Concrete (FRC) are its superior fracture strength, toughness, impact resistance, flexural strength resistance to fatigue (Ragavendra et al. 2017).

If the fibers are sufficiently strong, sufficiently bonded to material, and permit the FRC to carry significant stresses over a relatively large strain capacity in the post-cracking stage. The real contribution of the fibers is to increase the toughness of the concrete (defined as some function of the area under the load vs. deflection curve), under any type of loading. That is, the fibers tend to increase the strain at peak load, and provide a great deal of energy absorption in post-peak portion of the load-deflection curve

(Joshi, 2016). The character and performance of FRC changes with varying concrete binder formulation as well as the fiber material type, fiber geometry, fiber distribution, fiber orientation and fiber concentration (Zollo, 1997).

The behavior of FRC under loading can be understood from the Figure 2.4. The plain concrete structure cracks into two pitches when the structure is subjected to the peak compressive strength and cannot withstand further load or deformation. The fiber reinforced concrete structure does not crack at the same peak compressive load. The area under the curve shows the energy absorbed by the FRC when subjected to compressive load (Hossain et al. 2012).

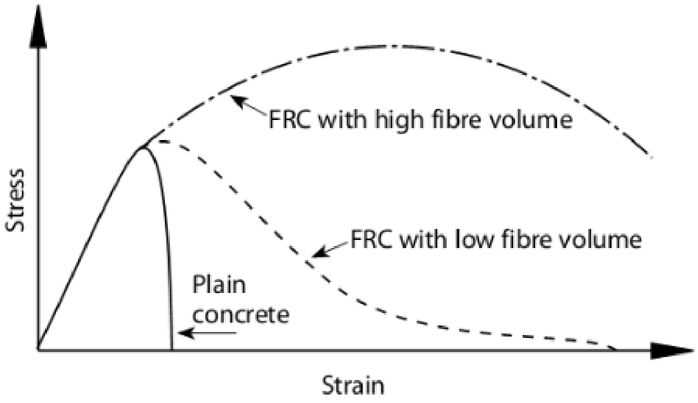


Figure 2.4 Typical stress-strain curves for fiber-reinforced concrete (Hossain et al. 2012)

2.4.2 Types of Fiber Used in Concrete

A wide variety of fibers have been used in concrete. For each application it needs to be determined which type of fiber is optimal in satisfying the concrete application. Fibers are typically classified as either natural fibers or synthetic fibers. According to terminology adopted by the American Concrete Institute (ACI) Committee 544, Fiber Reinforced Concrete, there are four categories of FRC based on fiber material type. These are SFRC, for steel fiber FRC; GFRC, for glass fiber FRC; SNFRC, for synthetic fiber FRC including carbon fibers; and NFRC, for natural fiber FRC (Zollo, 1997).

2.4.2.1 Natural Fiber Reinforced Concrete

Natural fibers include coconut (coir), sisal, palm, jute, flax, straw, bamboo, cane, and many more. The use of natural fibers has a long history. They are readily available, abundant and can be extracted from waste material. So natural fibers are economical and low in cost, and can reduce the environmental impact when used in the construction industry. However, the main disadvantage to these fibers is poor durability and degradability (Mohajerani et al. 2019).

2.4.2.2 Synthetic Fiber Reinforced Concrete

Synthetic fibers are manufactured and produced for a purpose. These include steel fibers glass fibers, plastic fibers, both macro plastic fibers and micro plastic fibers, and carbon fibers. Synthetic fibers can be categorized into two types based on their geometry, these are micro synthetic fibers and macro synthetic fibers (Mohajerani et al. 2019). The fibers are categorized based on Table 2.1 (Yin et al. 2015).

Table 2.1 Geometry of micro and macro synthetic fibers (Yin et al. 2015)

Geometry	Micro Synthetic Fiber	Macro Synthetic Fiber
Diameter or cross-section	5–100 μm	0.6–1 mm^2
Length	5–30 mm	30–60 mm

With the continuous enhancement of technology, and as further knowledge about synthetic fibers is studied, the types of synthetic fibers and their properties have continually improved (Mohajerani et al. 2019).

2.4.2.3 Steel fiber-reinforced concrete

Steel fiber-reinforced concrete is basically a cheaper and easier to use. Steel fiber-reinforced concrete uses thin steel wires mixed in with the cement. This imparts the concrete with greater structural strength, reduces cracking and helps protect against extreme cold. Steel fiber is often used in conjunction with rebar or one of the other fiber types (Mohajerani et al. 2019). With the addition of steel fiber the toughness, of the recycled concretes increased and their behavior under compression is similar to that of fiber-reinforced natural aggregate concrete (Carneiro et al. 2014).

2.4.2.4 Glass Fiber Reinforced Concrete

Glass fiber-reinforced concrete uses fiber glass, much like found in fiber glass insulation, to reinforce the concrete. The glass fiber helps insulate the concrete in addition to making it stronger. Glass fiber also helps prevent the concrete from cracking over time due to mechanical or thermal stress. In addition, the glass fiber does not interfere with radio signals like the steel fiber reinforcement does (Mohajerani et al. 2019). The addition of 0.1% glass fibers into the concrete shows better result in compressive strength, flexural strength and splitting tensile strength (Deshmukh et al. 2012).

2.4.2.5 Polymeric Fibers

There are different types of polymeric fibers including polypropylene, nylon, and polyethylene. There are three main types of macro synthetic fibers: polypropylene fibers (PP), high-density polyethylene fibers (HDPE), and polyethylene terephthalate fibers (PET). The type of fiber, and the mechanical and physical properties it possesses, is related to the technique used to manufacture the material. Some methods of manufacturing include melt spinning techniques, the film sheet technique, and manual cutting (Mohajerani et al. 2019).

2.4.3 Nylon Fiber

Nylon is a generic name that identifies a family of polymers. Nylon fiber is a textile fiber invented in 1938 by Wallace Carothers to compete with the strength of silk fiber. The tensile strength of nylon fiber was claimed to be 750-1000 MPa (Ahmad et al. 2021b). Nylon fiber's properties are imparted by the base polymer type, addition of different levels of additive, manufacturing conditions and fiber dimensions. Currently only two types of nylon fiber are marketed for concrete. Nylon is heat stable (melting temperature of 256^0C/450^0F), hydrophilic, relatively inert and resistant to a wide variety of materials. Nylon is particularly effective in imparting impact resistance and flexural toughness and sustaining and increasing the load carrying capacity of concrete following first crack (Saxena and Saxena, 2015).

2.4.3.1 Effect of Nylon Fiber on the Mechanical Properties Concrete

Song et al. (2005) used non-fibrous control concrete mixture consisted of the normal Type I Portland cement, the gravel having a maximum size of 2.54 cm, and the river sand having a fineness modulus of 2.9. Approximately 300 kg/m^3 of cement and 194 kg/m^3 of mixing water were used with 1050 kg/m^3 gravel and 850 kg/m^3 sand for the non-fibrous concrete mixture. Nylon fibers was added at the concentration of 0.6 kg/m^3

for the nylon-fiber-reinforced concretes. The properties of the two types of concrete was observed.

(a) Compressive Strength: The compressive strength of the nylon-fiber-reinforced concrete improved by 12.4% over the non-fibrous control counterpart (Song et al. 2005). The improvements came principally from the fibers interacting with the advancing cracks. When withstanding an increasing compression load, the fibrous concrete cylinders may develop lateral tension, thus initiating cracks and advancing those cracks. As the advancing crack approached a fiber, the de-bonding at the fiber–matrix interface began due to the tensile stresses perpendicular to the expected path of the advancing crack. As the advancing crack finally reached the interface, the tip of the crack encountered a process of blunting because of the already present de-bonding crack (Song et al. 2005). The blunting process reduced the crack-tip stress concentration, thus blocking the forward propagation of the crack and even diverting the path of the crack. The blunting, blocking, and even diverting of the crack allowed the fibrous concrete cylinders to withstand additional compressive load, thus upgrading its compressive strength over the non-fibrous control concrete (Song et al. 2005).

Compressive strength of the composites with micro nylon fibers (micro straight fiber: Length - 12 mm, Diameter - 0.05 mm) were higher than those with macro fibers (macro straight fiber: Length - 54 mm, Diameter - 0.55 mm), while the fracture energies were found significantly higher when the macro nylon fibers were used (Ozsar et al. 2018).

The use of nylon fiber as an ingredient in cement concrete is promising as it provided an alternative method of disposal and fibers, owing to this also improve strength and durability of concrete. The addition of nylon fiber has also been reported to improve the durability of concrete. Fibers protect the concrete cover from spalling due to good bonding character (Ahmad et al. 2021b). Studies showed that compressive strength of concrete increases as nylon fiber concentration is increased. But this increase is only for amount of fiber near 1% beyond which the strength starts to decrease. This decrease in strength is chiefly due to lower workability of concrete leading to segregation and uneven mixing (Swami and Gupta, 2016).

(b) Modulus of Elasticity: When the ratio of coarse aggregate and fine aggregate is greater than one, the fibers do not influence its elastic properties. If CA/FA ≤ 1, the elastic modulus of FRC decreases with an average reduction of 20% compare to NAC (Suksawang et al. 2018). This could be attributed to extra voids brought on by the addition of fiber. Existing elastic modulus equations from the codes would not provide a good estimation of the reduction in elastic modulus (Suksawang et al. 2018). The addition of fiber and recycled aggregate increases most of the mechanical properties. The fiber is useful to control the post-crack regime of the stress–strain curve of the recycled concrete mixtures. Studies showed an improved peak stress, ductility and energy dissipation capacity with the increase in fiber dosage for both in RAC and NAC. Moreover, adverse effect of increasing replacement ratio of RA can be reduced by increasing the dosage of fibers (Kazmi et al. 2019).

(c) Modulus of Rupture: The modulus of rupture of the nylon fiber concrete posted a 5.9% increase over the non-fibrous control concrete. The increase resulted primarily from the fibers intersecting the cracks in the tension half of the reinforced beam. These fibers accommodated the crack face separation by stretching themselves, thus providing an additional energy-absorbing mechanism and also stress relaxing the micro-cracked region neighboring the crack-tip (Song et al. 2005).

With addition of 1.5% volume fraction of nylon fibers in M30 concrete there was an increment of the flexural strength up to 18% at 28 days strength (Nitin and Verma, 2016). The influence of fibers on flexural response of concrete is much greater than on compressive response. Two types of flexural strength values are commonly reported. One is termed as first-peak strength (first-crack flexural strength), corresponds to the load at which the load-deformation curve departs from linearity. This is when concrete matrix cracks. The other corresponds to the maximum load achieved, commonly called the ultimate flexural strength, peak strength, or modulus of rupture (ACI 544.4R-18).

Ummahat et al. (2021) studied on flexural strength of nylon fiber reinforced concrete. Studied showed that flexural strength increases while using 25 mm fiber length for 25% of fiber volume. After that increase of fiber percentages, the strength decreases. But for 0.5% volume of fiber content shows increasing strength with increasing aspect ratio. PCC (Portland Composite Cement) sample with higher nylon content shows better performance on flexural rigidity (Samrose et al. 2019). In the flexural strength test after the cracking of the specimens, the parts of the specimen of the nylon fiber reinforced concrete were holding together by nylon fiber. In case of the mixes without fiber, samples were broken into two distinct parts. It was found that with 0.5% fiber dosage a significant residual strength was demonstrated by those samples (Ummahat, 2021).

(d) Durability: A durable condition arises with increment of nylon fiber content within the optimum limit. For 0.45 water-cement ratio, PCC reinforced with 0.25% nylon fiber content is the optimum limit and makes structure more durable (Samrose and Mutsuddy 2019). Moreover, using 0.25% nylon fiber, structure can withstand any hazardous situation as well as increases its service life. Also, OPC reveals less durability than PCC due to its chemical formation in Rapid Chloride Penetration Test (RCPT) and Rapid Migration Test (RMT) (Samrose and Mutsuddy, 2019).

(e) Splitting Tensile Strength: The splitting tensile strength of the nylon fiber reinforced concrete is 17.1% higher than that of the unreinforced control concrete (Song et al. 2005). Once the splitting occurred and continued, the fibers bridging across the split portions of the matrix acted through the stress transfer from the matrix to the fibers and, thus, gradually supported the entire load. The stress transfer improved the tensile strain capacity and, therefore, increased the splitting strength (Song et al. 2005).

(f) Rebound Hammer: Insertion of nylon fiber results in increasing the rebound number of concrete mixes up to 3.5% (Kazemi et al. 2020).

Increased fiber content from 2% to 3% decreases the crack surface of polyolefin shrinkage. Higher fiber content decrease the crack width and increases the time required for crack generation on the concrete surface (Saradar et al. 2018).

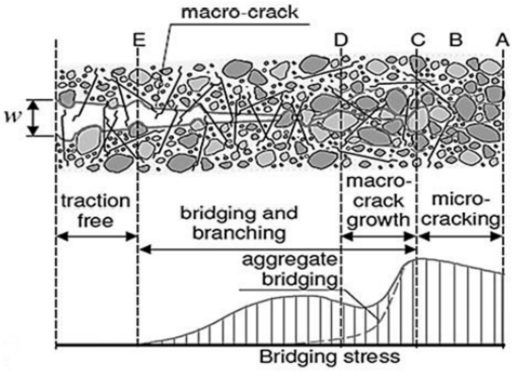


Figure 2.5 Schematic description of the effect of fiber on the fracture process of concrete in tensile loading (Löfgren, 2005)

The stress-crack opening relationship, in Figure 2.5, depends on the fracture properties of the concrete, and in most cases it will start with a steep descending part (C-D) for small crack openings (width < 0.1 mm). The contribution from fiber bridging comes gradually, and it is not until crack openings of at least 0.05 mm that it has any major influence. Depending on the characteristics of the fiber, the curve will level out and slowly decrease for increasing fiber slip (or crack opening) until it becomes zero (D-E); for some types of fibers the curve will enter an ascending part for which the stress increases as the fiber is deformed during the fiber pull-out, but eventually the stress will start to decrease until it becomes zero (Löfgren, 2005).

2.4.3.2 Effect of Size and Doses of Nylon Fiber

Inclusion of nylon fibers to the concrete mix strongly increased the compressive strength. The increment is 37.21% for fiber volume fraction equal to 0.3% in case of 30 mm size fiber. The use of nylon fibers will increase the split tensile strength of concrete. The maximum increment is for fiber ratio 0.6% in case of 30 mm long fibers, which increases by 34.98% strength of control specimen (Dewangan et al. 2019).

Small dosage of nylon fiber (NF) (below 5 kg/m^3) shows some increase in strengths but the effect is not remarkable. Medium dosage of NF (5-10 kg/m^3) is seems to have the highest potential of increase in strength and can be effectively used without much of workmanship. High dosage of NF (Above 10 kg/m^3) shows some great increase in strengths but from the practical point of view, this requires the lot of labor, casting becomes tedious and the effect of ball formation becomes the most prominent issue (Dewangan et al. 2019).

Micro-synthetic fiber are typically range in length from 0.5 inches to 0.75 inches are dosed at rates ranging from 0.5 to 3 lb/yd^3 (Ghadban et al. 2017). Utilizing 0.5% nylon fiber has a positive effect on the compressive and tensile strength of cement based mortar. Higher quantity of nylon fiber, the compressive and tensile strength of cement based mortar decreases. (Hanif et al. 2017)

Bakliwal and Bakliwal (2018) added 1%, 2% and 3% of nylon fiber by volume to concrete. Experiment showed that for 2% of dose of nylon fiber, the specimen showed highest compressive and tensile strength. (Bakliwal and Bakliwal, 2018)

Thamizharasan et al. (2016) tested on compressive strength of cubes for different volume fraction of 0.5, 1, 1.5 and 2% of nylon fiber in concrete. The split tensile strength was maximum at 0.5% and flexural strength was maximum at 1.5% dose.

Saxena and Saxena (2015) used the nylon fiber in conventional concrete in various proportions 0.2%, 0.25% and 0.3% of volume of concrete resulting increase of compressive strength.

Dewangan et al. (2019) conducted study and showed that two type of fiber length i.e. 30 mm and 50 mm showed increase in strengths in a very competitive manner to each other. 30 mm is better in compressive strength and the other is better in split tensile strength. Again it is seen that 50 mm fiber at higher doses are more prone to ball formation as compared to 30 mm fiber. So, both lengths are susceptible to ball formation and hence utter care should be taken during mixing operation. This could be the cause for 0.1% nylon fiber reinforced concrete (NFRC) of 50 mm showing negative results. From previous researches it is seen that NF having length less than 30 mm, have very least reinforcing ability and also fibers more than 50 mm fiber shows high degree of ball formation (Dewangan et al. 2019).

Nylon fiber reinforced concrete remains intact even after the development of crack once formed, which is not always true for non-fiber reinforced concrete as the spalling and shuttering of these concrete may immediately be seen. While nylon fiber reinforced concrete has some residual compressive strengths about 85% - 95 % of their un-cracked strength, hence they will prove to be live saving at conditions of earthquakes and other accidents (Dewangan et al. 2019).

Nylon fiber tends to increase the strengths if the volume fraction is kept lower and if shorter length of nylon fiber is used. But it decreases at higher fiber percentage and longer length (Ummahat, 2021).

2.5 Recycled Aggregate Concrete Reinforced with Nylon Fiber

Fiber reinforced materials are unconventional materials, which utilize substances such as Fiber as bonding agents. With every increase in material waste, the utilization of such bonding agents can also further reduce the impact of recycling requirements. More importantly, such innovative materials, can withstand the required loads (stress and strain) as per more conventional methods of material engineering (Gharehbaghi and Chenery, 2017).

There are many solutions to improve the properties of Recycled Aggregate Concrete (RAC), such as adding admixture, increasing the amount of cement, using fiber, removing adhered mortar, and strengthening adhered mortar. Among these solutions, using fiber may be the most effective one (Yin, 2021).

Experimental works of Lee (2019) with the additions of 0, 0.6 and 1.2 kg/m^3 of NF (Nylon Fiber) in both NA and RAC mixes provided comparative findings. Due to the adhered mortar in RA, the compressive strength values of the RAC mixes are relatively lower than those of the NAC mixes. However, the addition of NF leads to an increase in compressive strength of both the NA and RAC mixes. In particular, this trend is more remarkable in the RAC mixes with a high content of NF. There is a beneficial effect of NF on the increase in compressive strength.

Similar to compressive strength, there is a significant increase in the split strength, especially with the addition of 1.2 kg/m^3 NF, regardless of concrete types (Lee, 2019). Based on the results of RCPT, the addition of NF in the NAC mixes reduces the total charge and the reduction of the total charge was more remarkable in the concrete mixes with RA. This implies that the usage of NF in the RAC mixes can mitigate the possibility of steel corrosion oriented from external chlorides due to the reduction of micro-cracks in the cement matrix (Lee, 2019).

The microstructural observation of concrete reveals that the micro-cracks propagates along the interfacial transition zone (ITZ) between old mortar and aggregate, especially in the RAC mixes. However, for RAC mix with an addition of NF, the NF plays an important role in crack bridging, resulting in a higher strength and lower permeability in concrete. The addition of nylon fiber enhanced the permeability as well as the mechanical properties, especially in concrete incorporating RA. The enhancement is primarily attributed to the bridge effect of NF, which allowed for a higher development of strength and concrete density (Lee, 2019). By mixing the nylon with RAC at 0%, 0.5%, 1%, and 1.5% respectively by weight, the maximum compressive strength was observed for 1.5% nylon fiber in recycled concrete in the study of Bright et.al (2017).

2.6 Supplementary Cementitious Material

The most often used mineral admixture in the modem concrete industry is the pozzolan. A pozzolan, and there are many of them, is defined as “siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide possessing cementitious properties” (Dodson, 1990).

This chemical reaction between the siliceous and/or siliceous-alumina components in the pozzolan, calcium hydroxide and water is called the pozzolanic reaction. Two types of pozzolanic materials are readily available. There are the natural pozzolans which are of volcanic origin. Since the best of the many varieties of volcanic ash was found near Pozzoli, Italy, the material was called Pozzolana or Pozzolan (in English) and this name has since been extended to cover the entire class of mineral admixtures of which it is a member. Those of the second type are man-made pozzolans which include such by products as fly ash (the burning of coal), blast furnace slag (steel industry), and silica fume (silicon and ferrosilicon manufacture) (Dodson, 1990).

Mineral admixtures are usually added to concrete in large amounts to reduce cost and enhance workability of fresh concrete. Industrial by-products like slag are commonly used mineral admixtures. Due to their cementitious property, they are also known as supplementary cementing materials. Supplementary cementitious materials (SCMs) include cupola furnace slag powder, blast furnace slag powder, silica fume, fly ash, rice husk ash, metakaolin, coconut husk ash, palm oil fuel ash, wood waste ash, sugar cane bagasse ash, and bamboo leaf ash. They are added to cement either through inter-grinding with cement clinker, or by blending with cement after grinding, or can be added during concrete batching to supplement the cement (Mark et al. 2019).

As per rapid industrialization, steel producing industries increasing year and year. These industries produced steel waste and gases which are very harmful to the environment. In India steel waste generated from steel industry is very high. This waste may be dumped in to the barren land and other disposal places. Recycling of steel waste reduces the steel waste but recycling steel has low quality and recycling cost is high. However recycled steel is not used in construction, so we are using steel scrap waste in concrete which reduces the consumption of reinforcement and cost of structure (Jaral and Firdous, 2018).

Fly ash (25% - 35%), silica fume (10%) and ground-granulated blast-furnace slag (up to 65%) are the most commonly SCM which are used to improve concrete strength and durability properties (Yehia et al. 2015). Among several available types, the most commonly used mineral admixtures are fly ash (FA), silica fume, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash (Ayub et al. 2014). The continuous increase in the price of Ordinary Portland Cement (OPC) globally is partly attributed to the insufficient production rate when compared to its demand rate in the construction industries. Considerable efforts have been made worldwide to utilize natural waste or by-product as supplementary cementatious materials (SCMs) to improve on the properties of concrete and other cement products (Samson et. al. 2016).

2.6.1 Ground Granulated Blast-Furnace Slag

GGBS is a by-product from the blast furnaces used to make iron. These operate at a temperature of about 1500 degrees centigrade and are fed with a carefully controlled mixture of iron ore, coke and limestone. The iron ore is reduced to iron and the remaining materials from a slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid and if it is to be used for the manufacture of GGBS it has to be rapidly quenched in large volumes of water. The quenching optimizes the cementitious properties and produces granules similar to coarse sand. This granulated slag is then dried and ground to a fine powder (Suresh and Nagaraju, 2015). Molten slag diverted from the iron blast furnace is rapidly chilled, producing glassy granules that yield desired reactive cementitious characteristics when grounded into cement fineness. Once the slag has been cooled and grounded to a usable fineness it is stored and shipped to suppliers. Slag cement is commonly found in ready-mixed concrete, precast concrete, masonry, soil cement and high temperature resistant building products (Kondraivendhan and Bhattacharjee, 2015).

Slag cement is hydraulic cement formed when granulated blast furnace slag (GGBS) is grounded to suitable fineness and is used to replace a portion of Portland cement. Ground granulated slag is often used in concrete in combination with Portland cement as part of a blended cement. Ground granulated slag reacts with water to produce cementitious properties. Pozzolana from power plant residue improve the properties of the blended cement concrete, the cost and the reduction of negative environmental effects (Kondraivendhan and Bhattacharjee, 2015).

The physical properties of GGBS vary significantly from source to source and region to region as there is no standardized manufacturing process. Hence, its effects on the properties of concrete in fresh and hardened form also change significantly (Suresh and Nagaraju, 2015). The chemical composition of a slag varies considerably depending on the composition of the raw materials in the iron production process. Silicate and aluminate impurities from the ore and coke are combined in the blast furnace with a flux which lowers the viscosity of the slag. In the case of pig iron production the flux consists mostly of a mixture of limestone and forsterite or in some cases dolomite. In the blast furnace the slag floats on top of the iron and is decanted for separation. Table 2.2 shows the typical chemical composition of GGBS (Suresh and Nagaraju, 2015).

Table 2.2 Chemical composition of GGBS (Suresh and Nagaraju, 2015)

Analyte	**Mass%**
Calcium Oxide, CaO	40
Silica, SiO_2	35
Alumina, Al_2O_3	13
Magnesia, $Mg(OH)_2$	8

The compressive strength of concrete varies with the fineness of GGBS (Raju and Dadapeer, 2017). The Slag Cement Association estimated that the use of slag cement as a cement substitute in concrete has the potential to eliminate 3 million metric tons of carbon dioxide emissions annually (Neville, 2011). The slag cement comprises of calcium-bearing siliceous and alumino-siliceous materials. The relative density of the slag cement ranges from 2.85-2.95. This has been in use as an SCM since 1900. Slag cement tends to prolong the initial setting time. This is advantageous when the weather is warm. When the weather is cold, accelerators can be used or the proportion of the slag cement can be reduced in order to reduce the initial time of setting. Its compressive strength from 7 to 14 days of curing is low but its strength at 28 days of curing and above is high (Neville, 2011).

The curing process also affects the properties of concrete made from ordinary or blended cement incorporating GGBS. Concrete made with slag cement has higher long-term strengths compared to Portland cement concrete and it varies for different curing conditions, mix proportions and age of testing. When Portland cement reacts with water, it forms calcium silicate hydrate (C-S-H) and calcium hydroxide $Ca(OH)_2$. C-S-H is a glue that provides strength to the concrete and hold sit, while $Ca(OH)_2$ is a by-product and does not contribute to the strength of concrete (Figure 2.5). When slag is used as part of the cementitious constituent in concrete, it reacts with water and $Ca(OH)_2$ to form more C-S-H gel and increases the strength (SCA, 2003). Mineral admixture reacts with lime and reduce void content (Figure 2.6).

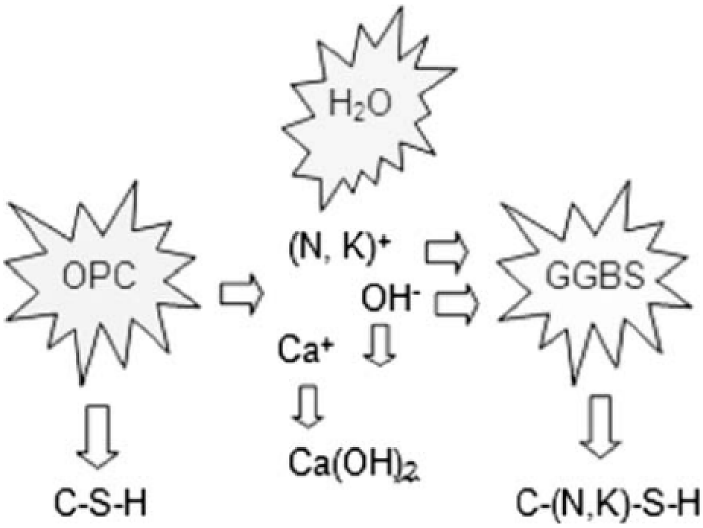
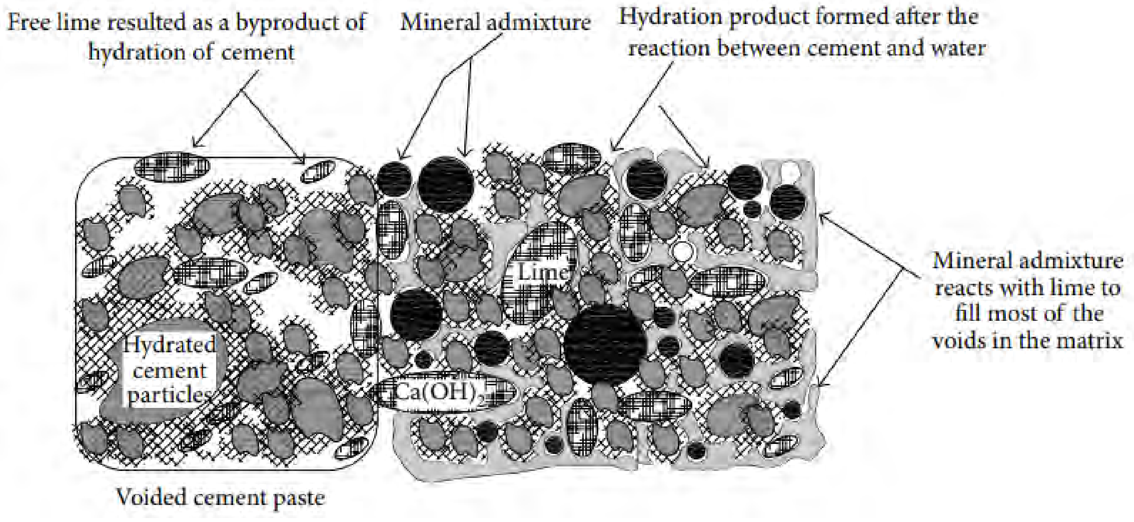


Figure 2.6 Hydration model for mix OPC-GGBS (Lizarazo-Marriaga et al. 2011)



(a) (b)

Figure 2.7 Pore refinement (a) Formation of lime (b) Pozzolanic reaction between lime and mineral admixture to fill the interstitial spaces (Ayub et al. 2014).

2.7 Effect of Partial Replacement of Cement with GGBS

The partial replacement of OPC with GGBS improves the workability and decreases plastic density of the concrete. The compressive and tensile splitting strengths, flexure and modulus of elasticity increases with increasing GGBS content. The drying shrinkage shows a slight increment with GGBS. If GGBS content increases to 30% and 50%, the tensile splitting strength increases by 12% and 17% respectively compared to the 100% OPC mix (Rughooputh and Rana, 2014). When GGBS is added to the concrete, stronger bonds develop between the GGBS cement paste and the aggregate which leads to a rise in the tensile splitting strength of the test specimens. OPC is partially replaced by 30% and 50% of GGBS, the flexural strength increases by 22% and 24% respectively. This is due to the formation of more cement gel upon addition of GGBS, thus resulting in stronger bonds between cement paste and aggregate (Rughooputh and Rana, 2014).

The workability of fresh concrete decreased as the percentage of RCA increased due to the porous nature of RCA, which absorbs more water. GGBS improves the workability of RAC by filling the voids of the recycled aggregate and hence more free water is available for workability (Ahmad et al. 2021a). At 28 and 56 days; however, the concretes incorporating slag had higher strengths than OPC (Lee and Yoon, 2015). Partial substitution of ordinary sand by slag gives better results compared with the ordinary concrete, the total substitution of natural gravels by crystallized slag improves the strength, but the full replacement of fine and coarse aggregates by slag products affect negatively the strength of concrete (Zeghichi, 2006).

With the blast furnace slag mixed in cement, the porosity and pore size of cement pastes was decreased. Compressive strength of mortars was closely related to the content of pore in the sizes (Song et al. 2010). Concrete containing GGBS up to 50% have higher values of flexural strength (Samad et al. 2017). The 28-day flexural strength of 30%, 40% and 50% GGBS concrete mixes are 3.3%, 8.2% and 4.9% higher, respectively, than the control mix (Samad et al. 2017).

Study of Jalil et al. 2019 showed that compressive strength, tensile strength and flexure strength of concrete reduces for 10% replacement of OPC with GGBS. Split tensile strength of concrete was found maximum at 30% replacement of OPC with GGBS (Jonalagadda et al. 2020).

Researches showed betterment of strength, durability and workability than a normal conventional concrete for the replacement of 20% of OPC with GGBS (Seetharam et al. 2017). Deboucha et al. (2015) showed that it is possible to obtain the same or better strength grades by replacing cement with BFS up to 30% in concrete.

2.8 Effect of SCM on the Mechanical Properties of FRC

Using 7.5% GGBS with 0.2% fiber percentage the 28 days compressive strength increases 7% more than NAC with 0.2% fiber only. 28 days split tensile and flexural strength increases further, about 12% and 10% that of NAC (Raju and Dadapeer, 2017). Concrete with silica fume and fly ash have a reduction in permeability when reinforced with polypropylene fibers (Zhang and Li, 2013). The splitting tensile strength increases about 15% at 5% GGBS and constant 0.2% nylon fiber, then decreases with increasing the GGBS percentage (Raju and Dadapeer, 2017). Compressive strength is increasing as the percentage of GGBS increases from 0% - 10% and 0.2% fiber and it is about 20% more than strength of NAC with OPC (Raju and Dadapeer, 2017). The Addition of fibers with additional supplementary cementations materials have better performance by improving workability of concrete and inherent properties of concrete (Gupta and Rashid, 2020). With 20% to 30% replacement of cement with GGBS, the compressive strength increases and tensile strength decrease with the addition of 0.1% synthetic fiber. Flexural strength increase at 20% of GGBS and 0.2% of fiber in NAC (Bhosale and Kawade, 2013). Mechanical properties of NAC containing silica fume, metakaolin (MK), fly ash as cement replacement material and steel fiber was better than NAC containing only mineral admixture (Zoe et al. 2020).

Saxena and Saxena (2015) studied on using nylon fiber in various proportions 0.2%, 0.25%, and 0.3% to volume of concrete and replacing cement by percentages of (10%, 20%, and 30%) with fly ash. Addition of 10% fly ash to cement, and 0.2, 0.25, and 0.3 percentages of nylon fiber the performance of concrete increased (Saxena and Saxena, 2015). Addition of fibers alone to the concrete mix increases toughness, ductility and tensile properties, but increment in fiber content decreases workability of the concrete. When fly ash is added to concrete workability increases but it effects the setting time of concrete (Kamal and Dash, 2019).

2.9 Effect of GGBS on the Mechanical Properties of RAC

With the addition of ground granulated blast furnace slag as a partial replacement of cement weight by 5%, it is possible to replace natural coarse aggregates by recycled aggregates up to 20%, without affecting strength and durability properties of concrete (Jaldhari and Nagar, 2017).

On the replacement of 40% natural aggregate with recycled aggregate, slight decrease in compressive strength is observed and this decrease was compensated on the replacement of cement with GGBS. With 30% replacement of cement with GGBS, the compressive strength is increased by 5.05% increase compared to NAC. Split tensile strength increases on the addition of GGBS up to 30% and then decreases in RAC. Flexural strength continued to increase with the increase in GGBS percentage at 28 days with 30% replacement in RAC (Krishnan and Subhash, 2020).

Nandanam et al. (2021) studied on effect of GGBS, metakaolin and fly ash in RAC. Good mechanical strength is exhibited by GGBS with 30% and 50% replacement of OPC. GGBS in RAC may provide higher slump value than OPC concrete with same w/c ratio (Xie et al. 2019b). Elastic modulus, Poisson’s ratio and toughness of RAC increases with GGBS content. Replacing OPC matrix by GGBS can improve the mechanical strength of RAC (Xie et al. 2019b). Flexural behaviour of reinforced concrete beam containing GGBS and RCA is similar to that of NA (Deepa and Anup, 2016). Though increasing the percentage of recycled aggregate the compressive strength decreases replacing OPC with 20% GGBS and replacing NA with 20% RCA gives maximum compressive strength (Deepa and Anup, 2016).

RAC is inferior to normal concrete in mechanical and durability properties since it inherently has high porosity, high water absorption, and low strength. Addition of GGBS could improve the performance of the RAC (Xie et al. 2019a). Use of mineral admixtures like fly ash and GGBS has improved the performance of recycled aggregate concrete. GGBS in concrete increase the compressive strength 20% to 25% higher than fly ash at 28 day (Pramod et al. 2018). Compressive strengths of RAC (after 28 days) are less than that of NAC and maybe improved using 25% GGBS (El-Hawary et al. 2021). GGBS improves the workability of RAC by filling the voids of the RA and hence more free water is available for work (Ahmad et al. 2021).

2.10 Combined Effect of Fiber and SCM on the Mechanical Properties of RAC

Addition of steel fibers improves the concrete mechanical and durability performance with the composite addition of GGBS and recycled aggregate. Therefore, concrete production can be made sustainable by the incorporation of recycled aggregate, GGBS, and steel fibers (Ahmad et al. 2021a).

Nylon fibers are also observed to be effective in enhancing the mechanical, microstructural, and durability properties of concretes prepared with recycled aggregates. The nylon fibers is also useful in concrete composites along with fly ash for prominent growth in strength values (Ahmad et al. 2021b).

Several studies were conducted on nylon fiber reinforced RAC, effect of supplementary cemetitious material in RAC, but very few studies were focused on the combined effect of the GGBS and nylon fiber in RAC. Hence, the main focus of this study to observe the effect of GGBS as partial replacement of OPC in nylon fiber incorporated RAC on the basis of mechanical properties i.e. compressive strength, splitting tensile strength, flexural strength, modulus of elasticity and Poisson’s ratio.

Chapter 3

EXPERIMENTAL PROGRAMME

3.1 Introduction

This study involved determining the various mechanical properties of concrete viz. compressive strength, splitting tensile strength, modulus of rupture, modulus of toughness, modulus of elasticity, and Poisson's Ratio. Besides, non-destructive test of concrete using elastic rebound hammer was conducted to compare with the compressive strength. A total of 18 concrete mixes were prepared and tested.

Starting from the collection of test materials, through preparation and routine aggregate and cement tests, casting of concrete specimens and their curing, and finally the testing of concrete is briefly outlined in this chapter.

3.2 Collection of Materials

Ordinary Portland Cement (CEM I cement) is the main cementitious material for all concrete mixes in this study. GGBS was also used in 12 mixes as a partial replacement for the cement. The fine aggregates (Sylhet sand) and coarse aggregates (stone chips) were obtained from the local market. Concrete debris was collected from the premises of the concrete laboratory in BUET. Concrete debris was used as recycled concrete stone chips i.e. RCA in this study. Concrete cylinders tested in the laboratory for other purposes were collected from the disposal and were crushed mechanically to produce recycled stone concrete aggregates. Nylon fiber was obtained from the nylon rope available in the local market. The fiber was then extracted from the rope and cut into the required length.

3.3 Preparation of Aggregates

The maximum size of coarse aggregates was limited to 19 mm. The crushed aggregates were screened for impurities and sieved to produce aggregate particles in the required size range. As for the fine aggregates, all the sand was sieved through the No. 4 sieve. After sieving, all aggregates were washed properly with water to clear off any dusts and unwanted materials which might affect the results.

3.4 Properties of Aggregates

Aggregate as an inert filler in the concrete providing improved volume stability. Tests were conducted on the coarse aggregates (viz. natural stone aggregates, recycled concrete stone aggregates) and on the fine aggregates (Sylhet Sand).

RCA compared to NA has following properties (Malešev et al. 2010): increased water absorption, decreased bulk density, decreased specific gravity, increased abrasion loss, increased crushability, increased quantity of dust particles, increased quantity of organic impurities if concrete is mixed with earth during building demolition, and possible content of chemically harmful substances, depending on service conditions in building from which the demolition and crushing recycled aggregate is obtained.

3.4.1 Sieve Analysis of Coarse Aggregate and Fine Aggregate

Sieve analysis conforms to the specification of ASTM C136/C136M-14. In concrete, gradation influences shrinkage and shrinkage cracking, permeability, and other characteristics. After sieving, the samples retained in each sieve were collected separately and their weight was measured. The fine aggregates, we used the mechanical sieve to separate the various particle sizes into certain groups. The sieve sizes used were 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm and 0.075 mm. The gradation curve for coarse aggregates and sand are shown in Appendix A.1.1.

3.4.2 Fineness Modulus

The term fineness modulus (F.M.) is a ready index of coarseness or fineness of the material. This test method conforms to specification of ASTM C136/C136M-14.

3.4.3 Specific Gravity and Absorption Capacity

Specific gravity, a dimensionless quantity, is expressed as OD, SSD, or as apparent specific gravity. Absorption is the increase in mass of aggregate due to water penetration into the pores of the particles during a prescribed period of time, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry mass. For coarse and fine aggregate the test methods conform to the requirements of ASTM C127-15 and ASTM C128-15 respectively.

3.4.4 Los Angeles Abrasion Test

Abrasion test is carried out to test the hardness property of aggregates. The principle of Los Angeles abrasion test is to find the percentage wear due to relative rubbing action between the aggregate and steel balls used as abrasive charge. The test method conforms to the specification of ASTM C131/C131M-14. The grading of the aggregate sample was B. Therefore, 2500 gm of aggregate passing 19 mm sieve and retained on 12.5 mm sieve and another 2500 gm of aggregate passing 12.5 mm sieve and retained on 9.5 mm sieve was required as specified by the code. Detailed calculation is given in Appendix A.1.2.

3.4.5 Unit Weight of Aggregate

Natural stone aggregate, recycled concrete stone aggregate, and fine aggregate were used in this study. For all the cases, aggregates were mixed properly to get a homogenous mixture of all sizes of particles so that the unit weight calculated is representative enough. This test method conforms to the specification of ASTM C29/C29M-16.

3.5 Properties of Cement and GGBS

Ordinary Portland Cement (OPC) type CEM-I 52.5 N conforming to the Standards of BDS EN 197-1:2003 have been used in this research. Properties of cement have been determined in the concrete laboratory of the Department of Civil Engineering, BUET.

Preparation of hydraulic cement mortars using 2 inch cube specimens and the determination of compressive strength of mortar have been conducted in accordance with ASTM C109-13 and the setting time has been determined in accordance with ASTM C191-08a, the normal consistency has been determined in accordance with ASTM C187-11, the fineness has been determined in accordance with ASTM C204-11, and the specific gravity has been determined in accordance with ASTM C188-09.

3.6 Properties of Nylon Fiber

Nylon fiber is locally available in Bangladesh. In this study the fiber was cut from a rope. The length of the fiber was maintained at 20 mm. Fiber was added in the mixture with the volume fraction of 0%, 0.1%, 0.2%, 0.35%, and 0.5%.

3.6.1 Test on Nylon Fiber

Density of nylon is very important to calculate the required doses to maintain the estimated volume fraction according to ASTM D1577–01. Forty samples were observed in a digital microscope with a calibration ruler to measure the diameter of the fiber. The average diameter was found as 0.1 mm. Then the average diameter is used to calculate the cross-sectional area and corresponding volume from the fixed length of the fiber. Then 60 samples were weighted and density was measured. Detailed calculations are provided in Appendix A.1.3.

3.7 Mold Preparation

Concrete specimen molds (cylinders, prisms) were prepared according to ASTM C 192/C 192M-16a. According to ASTM C 192, diameter of a cylindrical specimen and minimum cross-sectional dimension of a rectangular section shall be at least three times the nominal maximum size of the coarse aggregate in the concrete. Cylindrical specimens (100 by 200 mm) were used for compressive strength, split tensile test, and for determining the modulus of elasticity and Poisson's ratio. Prisms (285 mm x 75 mm x 75 mm) were used for the determination of modulus of rupture and flexural toughness.

3.8 Mix Design

The target strength is 35 MPa (5080 psi) for this experimental purpose. Two types of coarse aggregates have been used. Mix composition was adopted from the study of Saha (2019). He followed the mix design according to ACI 211.1-91 and conducted tests on the mechanical properties of RAC. The mix proportion for both NAC and RAC with a target strength of 35 MPa (5080 psi) is given in Table 3.1.

Table 3.1 Mix proportions for 35 MPa (5080 psi) concrete using NA and RCA

Mix proportion for 1 m^3 concrete		
Constituents	**NAC**	**RAC**
Water	227.36kg	227.50 kg
Cement	568.40 kg	568.43 kg
Sand(SSD)	565.00kg	518.52 kg
Stone(SSD)	971.00kg	904.23

3.9 Casting of Concrete

This study includes the preparation and testing of 18 concrete mixes. The specimens were cured for 28 days. Concrete cylinders and prisms were tested at the age of 28 days. The number of cylinders, prisms to be tested in this whole scheme of study is summarized in Table 3.2. The designations of the mixes are shown in Table 3.3. Amount of materials required for each batch are listed in Table 3.4.

Table 3.2 Scheme of the study

Type of Specimens	**Name of Test**	**Aggregate Type**	**No. of GGBS Percentage**	**No. of Volume Fractions of Nylon Fiber**	**No. of Specimens per mix**
Cylinder	Compressive Strength and Rebound Hammer	NA RCA	3 3	1 5	3 3
Cylinder	Splitting Tensile Strength	NA RCA	3 3	1 5	3 3
Cylinder	Modulus of Elasticity and Poisson’s ratio	NA RCA	3 3	1 5	3 3
Prisms	Flexural Strength	NA RCA	3 3	1 5	3 3

Total of 162 cylinders and 54 prisms were prepared for this study.

Table 3.3 Designation of the mixes

Mix	**Aggregate Type**	**Nylon Fiber V_f**	**Percentage of GGBS**	**Designation**
1.	NA	0	0	N-0-S0 (Control Mix)
2.	RCA	0	0	R-0-S0
3.	RCA	0.1	0	R-0.1-S0
4.	RCA	0.2	0	R-0.2-S0
5.	RCA	0.35	0	R-0.35-S0
6.	RCA	0.5	0	R-0.5-S0
7.	NA	0	10	N-0-S10
8.	RCA	0	10	R-0-S10
9.	RCA	0.1	10	R-0.1-S10
10.	RCA	0.2	10	R-0.2-S10
11.	RCA	0.35	10	R-0.35-S10
12.	RCA	0.5	10	R-0.5-S10
13.	NA	0	20	N-0-S20
14.	RCA	0	20	R-0-S20
15.	RCA	0.1	20	R-0.1-S20
16.	RCA	0.2	20	R-0.2-S20
17.	RCA	0.35	20	R-0.35-S20
18.	RCA	0.5	20	R-0.5-S20

N denotes natural aggregates and R is for RCA in the designation. The numerical value in the middle is for the volume fraction of nylon fiber and the last part of the designation indicates the percentage of partial replacement of OPC with GGBS.

Table 3.4 Amount of the materials in mix

Mix Designation	Binder Content (kg)		Amount of FA (kg)	Amount of CA (kg)
	OPC	GGBS		
N-0-S0 (Control Mix)	568.40	-	565.00	971.00
R-0-S0	568.43	-	518.52	904.23
R-0.1-S0				
R-0.2-S0				
R-0.35-S0				
R-0.5-S0				
N-0-S10	511.56	56.84	565.00	971.00
R-0-S10	511.59	56.84	518.52	904.23
R-0.1-S10				
R-0.2-S10				
R-0.35-S10				
R-0.5-S10				
N-0-S20	454.72	113.68	565.00	971.00
R-0-S20	454.75	113.68	518.52	904.23
R-0.1-S20				
R-0.2-S20				
R-0.35-S20				
R-0.5-S20				

3.9.1 Concrete Casting and Curing

Mixing of concrete requires the aggregates to be in SSD condition. According to the mix design, aggregates are gathered in the laboratory and sprinkled with water, so that it reaches SSD condition the next day during casting. The mix was done by concrete mixer machine Nylon fiber was added gradually while the drum was rotating.

Slump test was performed on fresh concrete to find out the slump value. The concrete slump test measures the consistency of fresh concrete before it sets. It is performed to check the workability of freshly made concrete, and therefore the ease with which concrete flows. The test is carried out using a metal mould in the shape of a conical frustum known as a slump cone that is open at both ends and has attached handles.

Freshly mixed concrete was poured into different molds as soon as possible, compacted using a vibrator and kept in open space for curing. After every few hours, the surface was smoothened. The cylinders and prisms were cured in a curing tank 24 hours after the casting. Concrete strength increase with age as moisture and a favorable temperature is present for hydration of cement.

3.10 Testing of Concrete

After the specimens have been cured for 28 days, they were ready to be tested. The compressive strength of concrete was determined by conducting tests on 100 mm by 200 mm cylinders and using an elastic rebound hammer on concrete cylinders. Splitting tensile strength of concrete was obtained by testing 100 mm by 200 mm cylinders and modulus of elasticity and Poisson’s ratio was determined using 100 mm by 200 mm cylinders. The flexural strength of concrete was determined by conducting tests on 285 mm x 75 mm x 75 mm prisms.

3.10.1 Compressive Strength Test of Cylinders

This test method consists of applying a compressive axial load to molded cylinders at a rate that is within a prescribed range until failure occurs (ASTM C39/C39M-15a). The compressive load was applied until the load indicator showed that the load is decreasing steadily and the specimen displayed a well-defined fracture curve (Figure 3.1). Cylinders were crushed for compressive strength using a compression testing machine. Three cylinders from each batch were tested for compressive strength.

Figure 3.1 Compression test set-up

When neoprene caps are used, the broken cylinder only rarely exhibits the conical fracture typical of capped cylinders. If requirements for perpendicularity of the cylinder end or vertical alignment during loading are not met, the load applied to the cylinder may be concentrated on one side of the specimen. This can cause a short shear failure. The platen restrains the lateral expansion of the concrete in parts of the specimen near its ends. This develops friction. With friction acting, the specimen is subjected to shearing stress as well as to compression. When shearing stress acts in addition to the uniaxial compression, failure is delayed, and it can, therefore, be inferred that it is not that principal compressive stress that induces cracking and failure, but probably the lateral strain (Neville, 1994). In our specimens, we have observed shear failure for the batches without any fiber content and shallower crack at the ends and to the outside surfaces for the specimens having nylon fiber reinforcement. The failure pattern in concrete with nylon fiber was not in a destructive manner which could be categorized as compression failure (Figure 3.2).

(a) (b)

Figure 3.2 Failure pattern under compressive load (a) concrete cylinder without fiber (b) concrete cylinder with nylon fiber

Usually, the compressive strength is calculated by averaging the crushing strength of all the specimens in the lot. The arithmetic mean value of the three test values is the strength of the test specimen. While the difference between the maximum or minimum value of the values and the intermediate values is above 15%, the intermediate value is taken as the compressive strength, and the maximum and minimum value should be discarded. While the differences between the maximum (and minimum) value of the three values and the intermediate values are above 15%, the group test results are invalid.

3.10.2 Testing and Data Collection for Modulus of Elasticity and Poisson’s Ratio

One day before testing, cylinders were taken out of the water tank and air-cured. The objective is to determine a stress-strain ratio value and a ratio of lateral to longitudinal strain for hardened concrete. Three compressometer were used the determination of the longitudinal and lateral deformation of the cylindrical sample. The arrangement of the apparatus is shown in Figure 3.3.

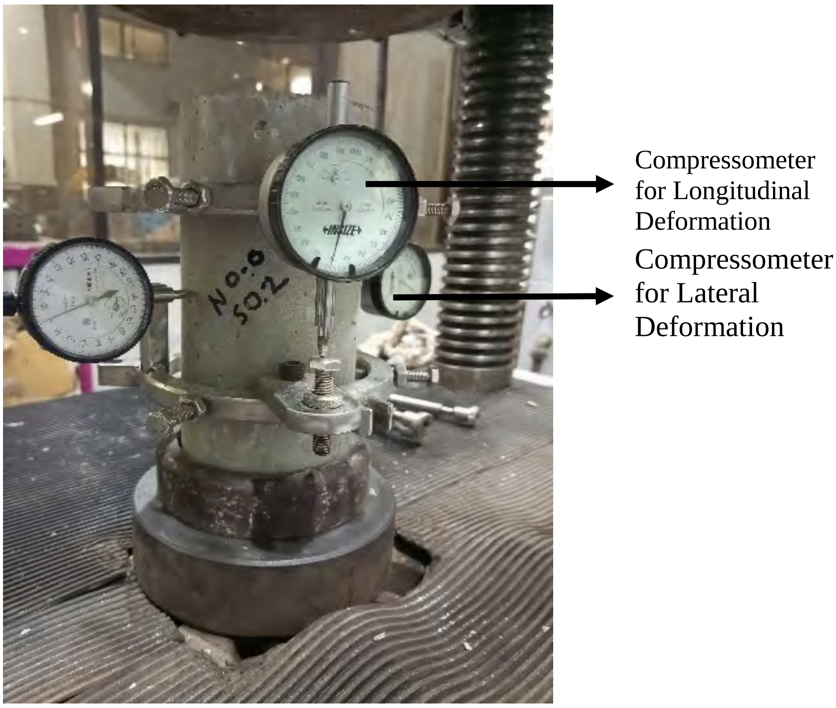


Figure 3.3 Sample fitted within a compressometer

Longitudinal displacement is measured at the opposite end using digital indicators with an accuracy of 0.001 mm. The lateral deformation is measured using a circular yoke which is placed at the mid-height of the specimen with a pivot at one end and the dial gauge (accuracy of 0.001 mm) at the diametrically opposite end. For the determination of elastic modulus, Poisson’s ratio and compressive strength of the cylinders, the load was applied using a Universal Testing Machine (UTM). Tests were performed at a loading rate of approximately 4 kN/s. Initially, the specimens were loaded to failure and the ultimate failure load was noted. In order to avoid damage to the dial indicator and according to code permissions, the samples were subjected to about 50% of their ultimate loads. Their actual ultimate loads were determined at a later time after removing the dial indicator from the samples and loading them to failure. The two dial indicators showed the values of longitudinal deflection and lateral deflection whereas the load cell showed the values of applied load at that moment. The longitudinal and lateral deflections were converted to successive longitudinal strains and lateral strains and the loads to compressive stresses.

According to the test method ASTM C469/C469M-14, the modulus of elasticity is calculated as,

$$E = (S_2 - S_1)/(\varepsilon_2 - 0.000050) \quad (3.1)$$

Where,

E = Modulus of elasticity, MPa

S_2 = Stress corresponding to 40% of ultimate load, MPa

S_1 = Stress corresponding to a longitudinal strain of 0.00005, MPa

ε_2 = Strain corresponding to stress S_2

According to the test method ASTM C469/C469M-14, Poisson’s ratio was calculated as,

$$\mu = (\varepsilon_{t2} - \varepsilon_{t1})/(\varepsilon_2 - 0.000050) \quad (3.2)$$

Where,

μ = Poisson’s ratio,

ε_{t2} = transverse strain at mid-height of the specimen produced by stress S_2,

ε_{t1} = transverse strain at mid-height of the specimen produced by stress S_1

Values of Poisson’s ratio and modulus of elasticity of all the tested samples are provided in Appendix A.2.4.

3.10.3 Splitting Tensile Strength Test

Determination of the splitting tensile strength conforms to the specifications of ASTM C496/C496M-11. The sample was placed in such a manner that the curved side surface of the cylinder lay between the platens of the testing machine. The sample was then simply loaded to failure and the ultimate load was noted down. The whole process is illustrated in Figure 3.4.

(a) (b)

Figure 3.4 Splitting tensile test (a) setup (b) failure pattern of nylon fiber reinforced concrete cylinder

Splitting tensile strength of the specimen was calculated as follows:

$$T = 2P/\pi ld \tag{3.3}$$

Where,

T = splitting tensile strength, MPa

P = maximum applied load indicated by the testing machine, N

l = length, mm

d = diameter, mm

3.10.4 Determination of Modulus of Rupture

The testing specimen for the flexural strength test was a simple beam having the dimensions 285 mm x 75 mm x 75 mm. The test was done in accordance with the standard test method of ASTM C78. The cured specimens were subjected to test shortly after removal from moist storage, as surface drying of the specimen would result in a reduction in the measured flexural strength. Then load was applied to the specimen continuously and without shock. The third point loading method was used in flexure tests of the concrete specimen, which ensured that forces applied to the beams were perpendicular to the face of the specimen and applied without eccentricity (Figure 3.5). Modulus of rupture of all the tested samples are shown in Appendix A.2.5.

Figure 3.5 Set-up for flexural strength test

As the fracture occurred in the tension surface within the middle third of the span length, the modulus of rupture was calculated by the following equation:

$$f = PL/bd^2 \tag{3.4}$$

Where,

f = modulus of rupture, MPa,
P = maximum applied load indicated by the testing machine, N,
L = span length, mm,
b = average width of the specimen at the fracture, mm,
d = average depth of the specimen at the fracture, mm,

3.10.5 Flexural Toughness

Toughness is a measure of the energy absorption capacity of a material and is used to characterize the material's ability to resist fracture when subjected to static strains or to dynamic or impact loads. The simpler flexural test is recommended for determining the toughness of fiber reinforced concrete. In addition to being simpler, the flexural test simulates the loading conditions for many practical applications of fiber reinforced concrete. The first-peak strength characterizes the flexural behavior of the fiber reinforced concrete up to the onset of cracking while residual strengths at specified deflections characterize the residual capacity after cracking. The appropriateness of each parameter depends on the level of acceptable cracking and deflection serviceability. Fiber reinforced concrete is influenced in different ways by the amount and type of fibers in the concrete. In some cases, fibers may increase the residual load and toughness capacity at specified deflections while producing a first peak strength equal to or only slightly greater than the flexural strength of the concrete without fibers. In other cases, fibers may significantly increase the first peak strengths while affecting a relatively small increase in residual load capacity and specimen toughness at specified deflection. The flexural toughness can be evaluated under third-point loading using the specified code ASTM C1609. Toughness (T) was calculated by the total area under the load-deflection curve up to a net deflection of $1/150$ of the span length.

3.10.6 Non-destructive Test of Concrete Using Rebound Hammer

The test method starts with the careful selection and preparation of the concrete surface to be tested. A fixed amount of energy is applied horizontally by pushing the hammer against the test surface according to the ASTM C805/C805M-13. It is necessary to take 10 to 12 readings over the area to be tested because the test is sensitive to the presence of aggregate and voids immediately beneath the plunger (Neville, 1994). In this study, the cylinders were clamped properly at a compressive testing machine (CTM) and the curved surface was marked with radially equal sides (Figure 3.6).

(a) (b) (c)

Figure 3.6 Rebound hammer test (a) radial distribution of surface points (b) Clamping of a cylinder (c) Rebound Hammer

The rebound hammer conversion graph gives the compressive strength of cylinders strength to compare with the actual compressive strength (Figure 3.7). The curve provides the strength for the concrete cylinder having diameter of 150 mm and height of 300 mm. In order to convert the strength for our concrete cylinder with diameter of 100 mm and height of 200 mm, shape factor (1.06) was multiplied with the compressive strength obtained from the conversion curve. Again, calibration factor (80/82 = 0.976) was also considered to get the exact result.

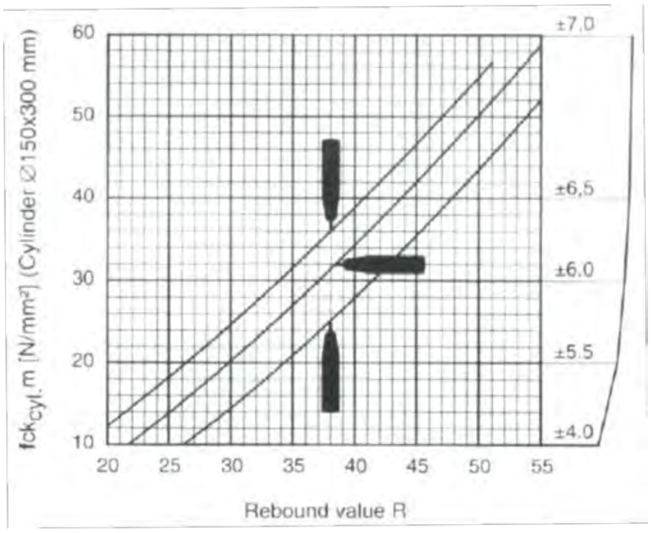


Figure 3.7 Rebound number to compressive strength conversion graph

Chapter 4
RESULTS AND ANALYSIS

This chapter lists and interprets the results of the test conducted on aggregate, cement and concrete. Compressive strength, flexural strength, splitting tensile strength, non-destructive test using elastic rebound hammer, modulus of elasticity and Poisson's ratio of nylon fiber reinforced recycled aggregate concrete with partial replacement of OPC with GGBS are discussed in this chapter.

4.1 Properties of Aggregates and Binder

Two types of coarse aggregate (natural stone aggregate and recycled concrete stone aggregate) were tested in the laboratory. RCA was found inferior to NA considering the mechanical properties. AIV, ACV and L.A.A. of RCA was about two times greater than that of NA. Moreover, due to the presence of porous layer of old concrete in ITZ, the water absorption capacity of RCA was about three times of that of NA. Specific gravity and unit weight of both the types of aggregate were similar. Properties of the aggregates are showed in Table 4.1.

Table 4.1 Properties of coarse and fine aggregate

Properties	**Type of Aggregate**		
	NA	**RCA**	**Sand**
FM	6.89	6.38	2.92
Apparent Specific Gravity	2.93	2.77	2.66
Bulk specific gravity (O-D)	2.77	2.33	2.57
Bulk specific gravity (S.S.D)	2.83	2.47	2.60
Absorption capacity,%	2.07	5.8	1.39
Unit Weight, kg/m^3	1576	1375	1478
Aggregate Impact Value, %	14.6	26.4	-
Aggregate Crushing Value, %	15.9	25.3	-
Los Angles Abrasion (L.A.A.) value, %	13.9	26.4	-

Mainly compressive strength of the mortar was observed at 3, 7 and 28 days. Moreover, fineness test was conducted for both OPC and GGBS. All the properties of cement and GGBS are shown in Table 4.2 and Table 4.3 respectively.

Table 4.2 Properties of cement used in this study

Physical properties	**Observed Value**	**Standard Value**
Fineness (m^2/kg)	272	≥225
Cement mortar compressive strength		
3 days (MPa)	23.9	≥12
7 days (MPa)	34.7	≥19
28 days (MPa)	45.2	≥28
Others		
Water for normal consistency (%)	26.5	22-30
Initial setting time (minutes)	135	≥45
Final setting time (minutes)	370	≤375

Table 4.3 Properties of GGBS used in this study

Physical properties	
Fineness (m^2/kg)	278

4.2 Workability of Fresh Concrete

The relationship between slump value and the fiber amount is presented in Figure 4.1 with standard deviation. Just one slump value was measured per mix in this study. It was found that the slump value decreased with the increase of fiber content in the mix. The reason for this occurrence might be clarified that the interfacial bond between fibers-cement pastes in concrete limits the scattering and motion of paste of cement and increase the viscosity of blends. Furthermore, 20% replacement of OPC with GGBS in RAC shows more workability. However, partial replacement of OPC with GGBS has no effect on the workability of NAC.

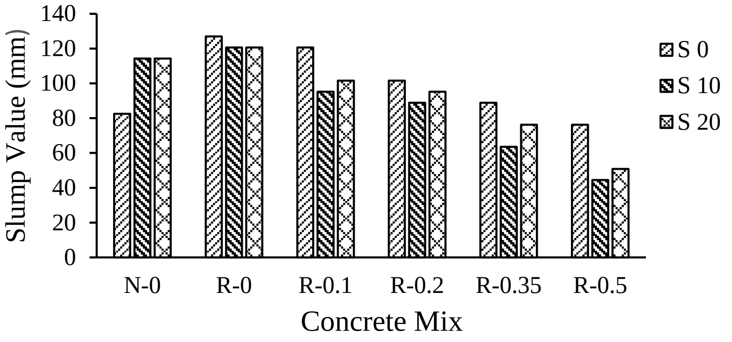


Figure 4.1 Slump values (mm) of fresh concrete

4.3 Compressive Strength

The compressive strength of cylinders for each mix was determined by taking the average strength of three cylinders. Table 4.4 shows the calculation of the compressive strength of a recycled aggregate concrete cylinder with 0.1% volume fraction of nylon fiber. Other results are given in Appendix A.2.1.

Table 4.4 Compressive strength test results

Sl. No.	Ultimate Load (kN)	Crushing Strength (MPa)	Average Crushing Strength (MPa)
1.	391	47.9	49.4
2.	408	51.1	
3.	403	49.2	

4.3.1 Effect of Partial Replacement of OPC with GGBS in NAC and RAC

Comparison of compressive strength for three different percentage of replacement of OPC with GGBS in NAC and RAC is showed in Figure 4.2. NAC shows better performance in each case. For both NAC and RAC, strength increases at 10% replacement of OPC with GGBS, but decreases for 20% replacement of OPC. We can observe that for 10% replacement of OPC with GGBS in RAC, the strength reaches the strength of N-0-S0 (control mix). RAC shows about 4.5% lower compressive strength compared to that of NAC.

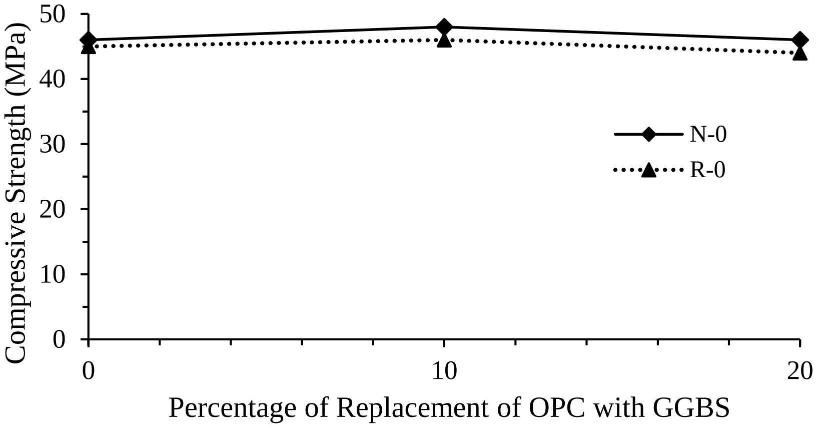


Figure 4.2 Effect of GGBS on the compressive strength of NAC and RAC

4.3.2 Effect of NF in RAC

Incorporation of nylon fiber in recycled aggregate concrete can increase the compressive strength (Figure 4.3). For 0.1% volume fraction of NF in RAC the compressive strength increases about 9% and up to 0.35% of volume fraction, the compressive strength is higher than that of R-0-S0. Furthermore, maximum compressive strength achieved from 0.1% V_f of NF in RAC, is about 6.5% greater than that of N-0-S0 or control mix.

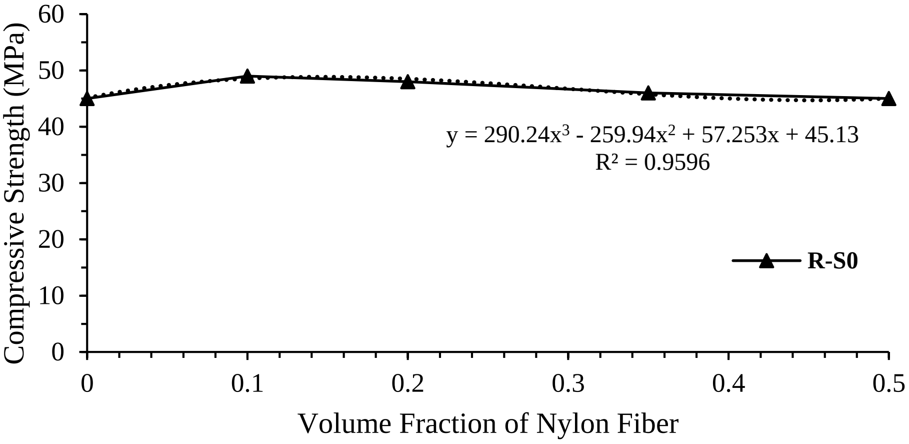


Figure 4.3 Effect of NF on the compressive strength of RAC

4.3.3 Combined Effect of NF and GGBS in RAC

The effect of volume fraction of nylon fiber in recycled aggregate concrete for 10% and 20% partial replacement of OPC with GGBS is shown in Figure 4.4. At 10% replacement of OPC with GGBS, recycled aggregate concrete with any combination of NF doses, the strength reaches or exceeds the compressive strength of the control mix.

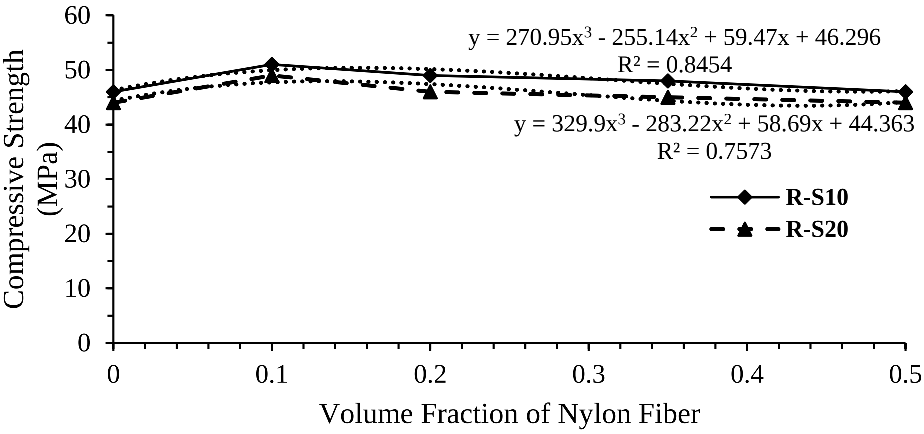


Figure 4.4 Effect of GGBS on the compressive strength of NF reinforced RAC

It can be clearly observed from Figure 4.5 that for the incorporation of nylon fiber in RAC, the compressive strength starts increasing up to the volume fraction of 0.1% and further incorporation of nylon fiber reduces the strength of the RAC. In all cases, the strength is maximum for 10% partial replacement of OPC with GGBS.

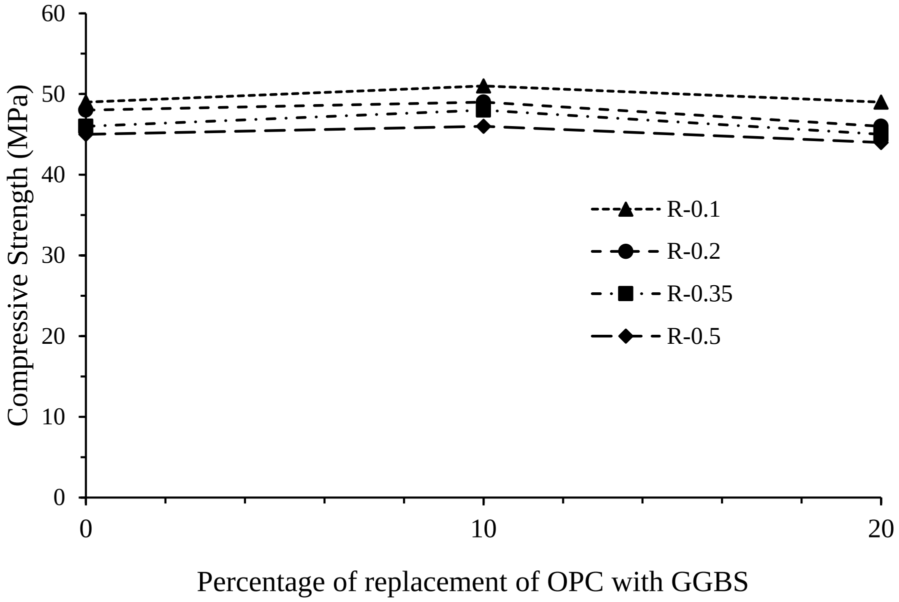


Figure 4.5 Combined effect of GGBS and NF on the compressive strength of RAC

From Figure 4.6 in a bar diagram, we can compare the compressive strength of all the mixes in this study. Standard deviation as error bar is also shown in Figure 4.6.

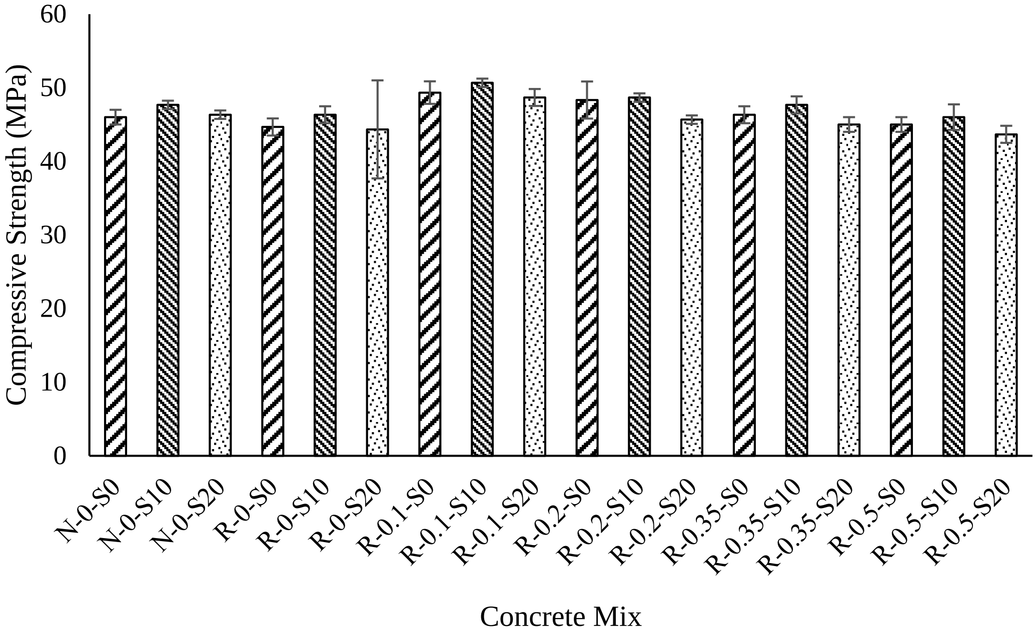


Figure 4.6 Compressive strength of all the mixes

Natural aggregate concrete has higher strength than recycled aggregate concrete. The lower compressive strength of concrete made with recycled concrete aggregate is probably due to the presence of two types of interfacial transition zones (ITZ) in the matrix. The ITZ represents the bond between the aggregate and paste and is normally weaker than either the aggregate or hydrated cement paste. In concrete made with natural stone aggregate, the ITZ occurs between the aggregate and mortar while in concrete containing recycled concrete, the ITZ takes place between the original aggregate and old mortar and new mortar. The presence of old mortar on the surfaces of recycled concrete also contributes to the lower compressive strength of recycled concrete as it possesses lower density.

From the results, it can be observed that the compressive strength value is increased with the incorporation of the fiber into the mix. The explanation for this is that, under axial loads, cracks occur in the microstructure of concrete and fibers arrest the crack formation and progression. Thus, the compressive strength of concrete increases. When withstanding an increasing compression load, the fibrous concrete specimens may develop lateral tension, and then it initiates those cracks and advances them. As the advancing crack approaches a fiber, the de-bonding at the fiber–matrix interface begins due to the tensile stresses perpendicular to the expected path of the advancing crack. As the advancing crack finally reaches the interface, the tip of the crack encounters a process of blunting because of the already present de-bonding crack. The blunting process reduces the crack-tip stress concentration, thus blocking the forward propagation of the crack and even diverting the path of the crack. The blunting, blocking, and even diverting of the crack allow the fibrous concrete specimen to withstand the additional compressive load, thus upgrading its compressive strength over the non-fibrous control concrete.

According to Spadea et al. (2015) and Campello et al. (2014) adding more nylon fiber creates higher porosity or cavity between the mortar matrixes which causes the compressive strength of cement-based mortar to decrease. Therefore, the incorporation of fiber up to a certain volume fraction increases the compressive strength over natural stone concrete. The optimum dose of nylon fiber was found 0.1%.

From Figure 4.7 we can observe the failure pattern of the cylinders. For NAC and RAC without concrete, it was observed that the cracks were randomly separated in different directions with deeper cracks in the middle of the cylinder along the longitudinal axis. The propagation of the cracks allowed the cylinders to easily split into two halves which led to longitudinal splitting failure. On the other hand, for any volume fraction on fiber incorporated into concrete the cylinder had fewer and shallower cracks that was separated away from the center occurring mainly at the ends and to the outside surfaces. These cracks did not severely damage the cylinder and the failure was not in a destructive manner which could be categorized as compression failure.


(a) (b)

Figure 4.7 Failure pattern of concrete cylinder under compressive load (a) RAC without any fiber (b) RAC with 0.5% nylon fiber

Replacement of OPC with GGBS shows small changes in compressive strength. 10% replacement has better results than 20% replacement. 10% partial replacement of OPC with GGBS shows 10.8% increase of compressive strength over control mix.

4.4 Modulus of Elasticity

The modulus of elasticity was determined using equation no. 3.1 for concrete cylinder made of natural and recycled coarse aggregates with the incorporation of nylon fiber in only recycled aggregate concrete and also with the partial replacement of OPC with GGBS. Test results of three samples were analyzed for each mix. Figure 4.8 illustrates the value of modulus of elasticity with standard deviation. Detailed results are provided in Appendix A.2.4.

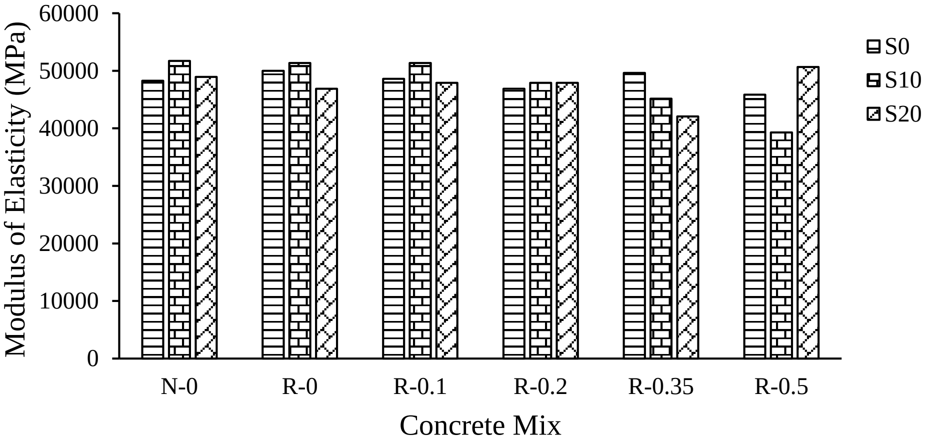


Figure 4.8 Modulus of elasticity of all the mixes

Partial replacement of OPC with GGBS and incorporation of nylon fiber has little effect on the modulus of elasticity. With the increase in volume fraction of nylon fiber the modulus of elasticity reduces with for the samples with 10% partial replacement of OPC and at this level of replacement comparatively modulus of elasticity is higher.

4.5 Poisson's Ratio of Concrete

Poisson's ratio of concrete was determined from equation no. 3.2 and also by finding the slope of lateral strain versus longitudinal strain graph. Three samples were tested for each batch and the average value is considered. The bar chart with the standard deviation (Figure 4.9) shows the variation of Poisson's ratio for all the mixes. Detailed results are provided in Appendix A.2.4. It is obvious from the results that for the 0.2% volume fraction of nylon fiber in RAC, the Poisson's ratio is higher than that of all other mixes. Partial replacement of OPC has a comparatively lower effect.

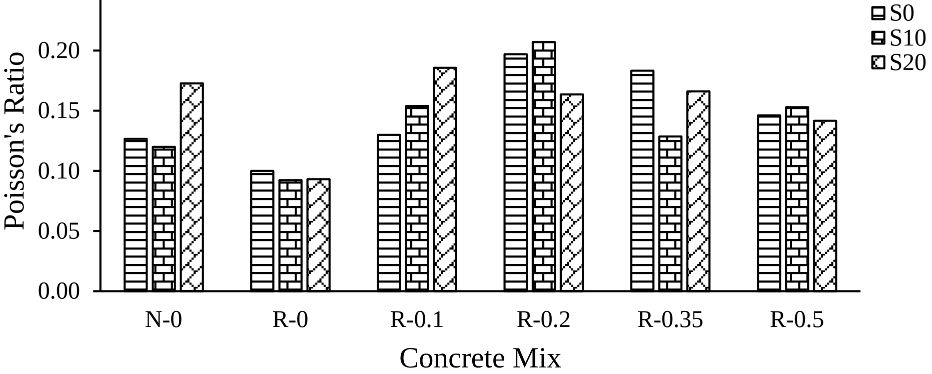


Figure 4.9 Poisson's ratio of all the mixes

4.6 Splitting Tensile Strength of Concrete Cylinders

The splitting tensile strength was determined using equation no. 3.3 for concrete made with two different types of coarse aggregates and different doses of nylon fibers and partial replacement of OPC with GGBS. Three samples from each mix were tested for determining the splitting tensile strength. Table 4.5 shows the result of splitting tensile strength of a concrete cylinder sample (0.1% NF incorporation and 10% partial replacement of OPC with GGBS). Other results are given in Appendix A.2.2.

Table 4.5 Splitting tensile strength test result

Sl. No.	Ultimate Load (kN)	Splitting Tensile Strength (MPa)	Average Splitting Tensile Strength (MPa)
1.	75.56	2.35	2.29
2.	72.49	2.23	
3.	74.54	2.30	

4.6.1 Effect Partial Replacement of OPC with GGBS in NAC and RAC

10% partial replacement of OPC with GGBS in both NAC and RAC reduces the splitting tensile strength (Figure 4.10). Splitting strength starts increasing for further replacement of OPC in GGBS. 20% replacement of OPC in RAC shows better performance comparatively. In no case the splitting strength of RAC can reach that of the control mix.

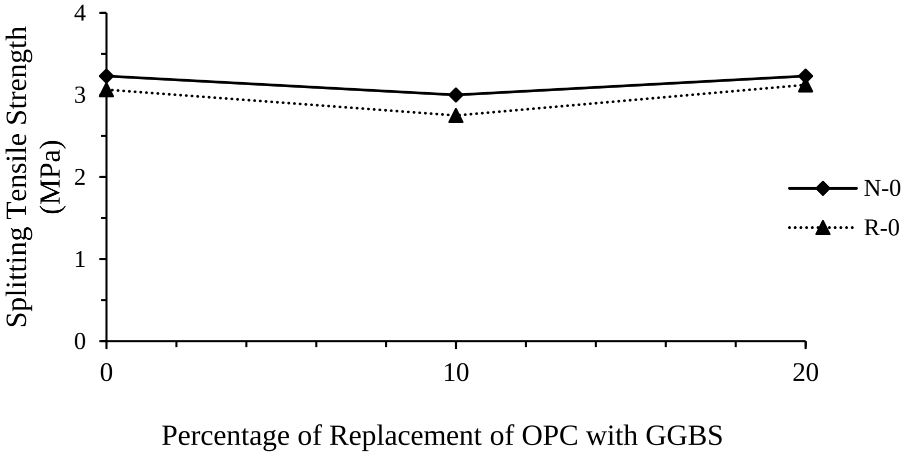


Figure 4.10 Effect of GGBS on the splitting tensile strength of NAC and RAC

4.6.2 Effect of NF in RAC

Addition of nylon fiber in recycled aggregate concrete imparts insignificant effect on the splitting tensile strength. For 10% V_f of NF, the splitting tensile strength reduces about 25% compared to RAC without any fiber and GGBS (Figure 4.11). Further incorporation of NF increases the splitting tensile strength, but cannot reach the strength of control mix.

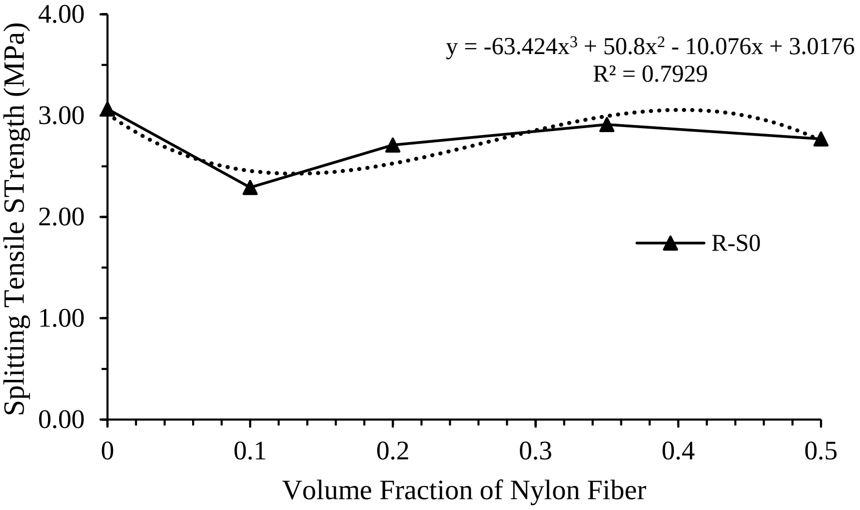


Figure 4.11 Effect of NF on the splitting tensile strength of RAC

4.6.3 Combined Effect of NF and GGBS in RAC

20% partial replacement of OPC with GGBS in recycled aggregate concrete shows better performance than that of 10% partial replacement. But in both cases, the strength is relatively lower than the splitting tensile strength of the control mix (Figure 4.12). For any combination of nylon fiber volume fraction and partial replacement of OPC with GGBS in RAC, cannot improve the splitting tensile strength (Figure 4.13).

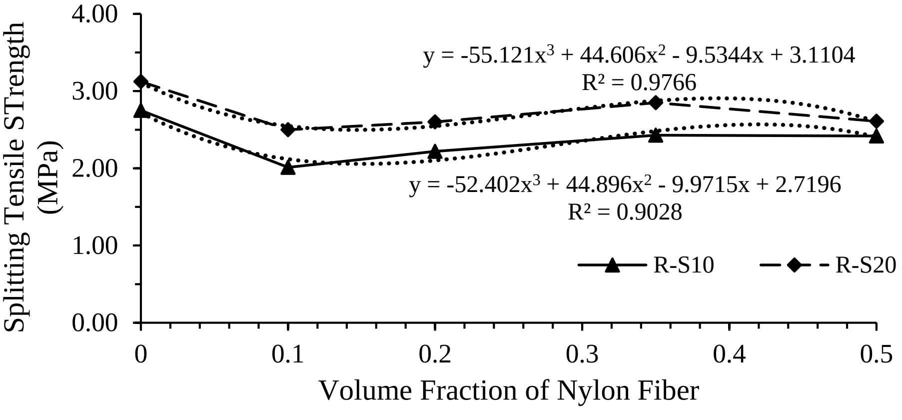


Figure 4.12 Effect of GGBS on the splitting tensile strength of NF reinforced RAC

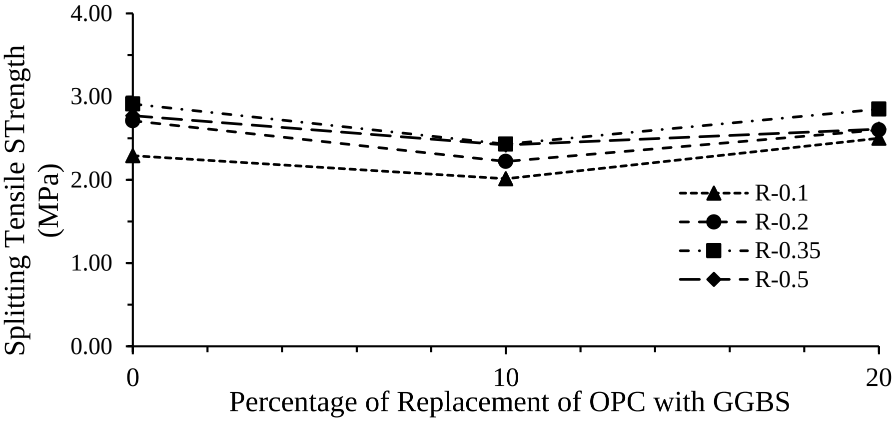


Figure 4.13 Combined effect of GGBS and NF on the tensile strength of RAC

Figure 4.14 shows the average splitting tensile strength of each mix of concrete. The standard deviation as error bar is also shown in the figure. It can be observed that the incorporation of nylon fiber in recycled aggregate concrete reduces the tensile strength of recycled concrete compared to the control batch.

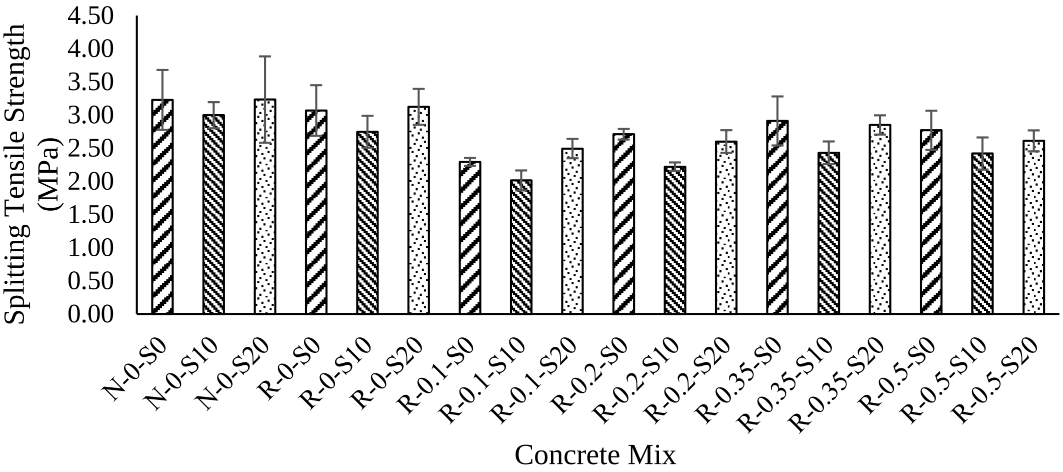


Figure 4.14 Splitting tensile strength of all the mixes

In general, natural aggregate concrete provides higher tensile splitting strength than recycled aggregate concrete. The incorporation of nylon fiber increases the tensile strength for higher volume fraction but does not exceed the strength of control mix. For 0.1% volume fraction of nylon fiber in recycled aggregate concrete, the tensile strength reduces. For all cases of nylon fiber reinforced recycled aggregate concrete, the cylinders do not fall apart, rather the two parts are bonded for the fibers (Figure 4.15). Replacement of OPC with GGBS draws small changes in the spitting strength. For 10% replacement of OPC with GGBS, cylinder provides lower splitting tensile strength.

(a) (b)

Figure 4.15 Failure pattern of cylinder under splitting tensile test (a) RAC with no fiber content (RAC with 0.1% nylon fiber)

Once the splitting occurred and continues, the fibers bridging across the split portions of the matrix acted through the stress transfer from the matrix to the fibers and, thus, gradually supported the entire load. The stress transfer improved the tensile strain capacity of the two fiber-reinforced concretes and, therefore, increased the energy absorbing capacity after the splitting tensile failure of the reinforced concretes over the unreinforced control counterpart. The resistance to crack propagation increase in splitting tensile test is due to the incorporation of using nylon fiber. Nylon fibers make the concrete less brittle and more ductile.

4.7 Modulus of Rupture

Flexural strength was determined under third-point loading using ASTM C78 standard. Three prisms of equal depth and width were prepared and tested for each result. The experimental data calculation for RAC with 0.1% volume fraction of nylon fiber has been shown in Table 4.6. Other data are provided in Appendix A.2.5.

Table 4.6 Flexural strength test result of concrete prisms

Sl. No.	Ultimate Load (kN)	Modulus of Rupture (MPa)	Average Modulus of Rupture (MPa)
1.	9.24	4.82	4.84
2.	9.35	4.92	
3.	9.24	4.78	

4.7.1 Effect of Partial Replacement of OPC with GGBS in NAC and RAC

For flexural strength addition of GGBS as partial replacement of OPC has insignificant effect on NAC, but for RAC the flexural strength gradually reduces (Figure 4.16). RAC has lower flexural strength compared to that of NAC. Hardened prism of control mix has shown even more flexural strength than RAC without any fiber and GGBS.

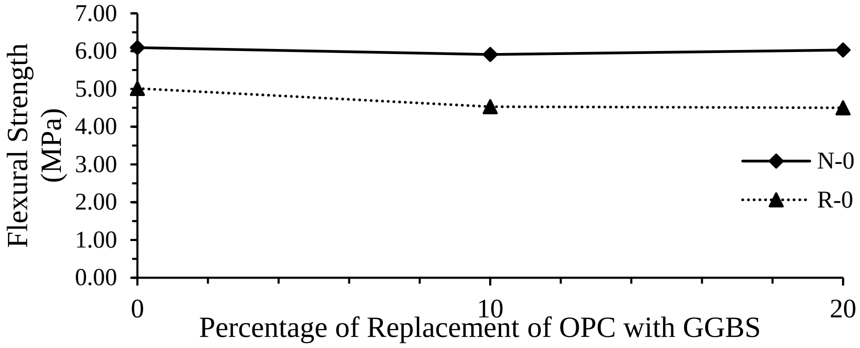


Figure 4.16 Effect of GGBS on the modulus of rupture of NAC and RAC

4.7.2 Effect of NF in RAC

Incorporation of nylon fiber in RAC does not improve the flexural strength. For any volume fraction of NF in RAC, the flexural strength is quite lower than the flexural strength of NAC (Figure 4.17).

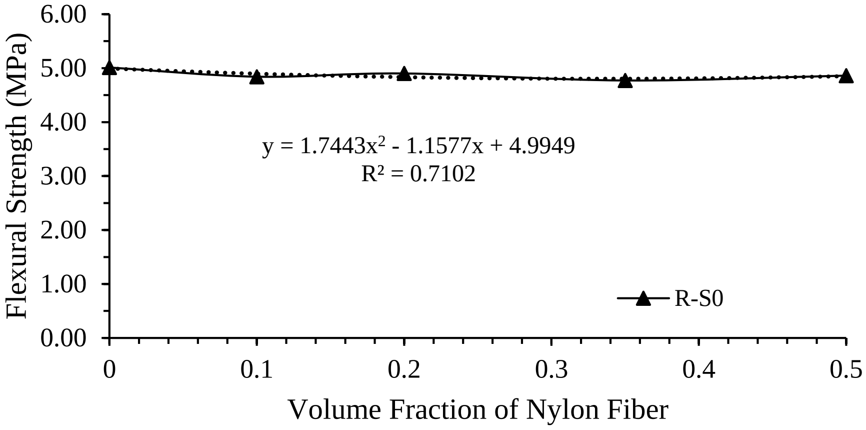


Figure 4.17 Effect of NF on the flexural strength of RAC

4.7.3 Combined Effect of NF and GGBS in RAC

For 20% replacement of OPC with GGBS in nylon fiber reinforced recycled aggregate concrete, the performance of the prism specimen in flexural load is comparatively better. Regarding the effect of NF, for 0.1%-0.2% volume fraction, the flexural strength increases for 20% replacement of OPC with GGBS whereas it reduces for 10% replacement, rather the increment of the flexural strength is observed within the range of 0.2%-0.35% volume fraction of NF in RAC of 10% replacement of OPC with GGBS (Figure 4.18).

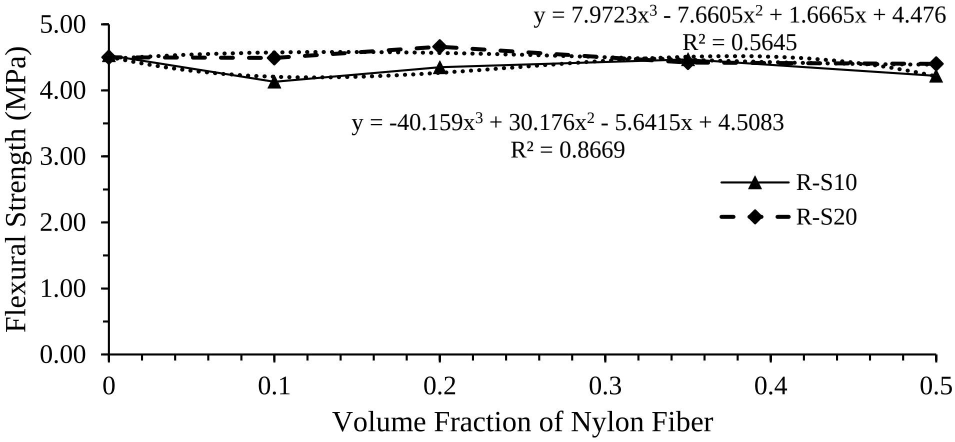


Figure 4.18 Effect of GGBS on the flexural strength of NF reinforced RAC

For all the volume fraction of NF added in RAC, the flexural strength reduces for the 10% partial replacement of OPC with GGBS (Figure 4.19).

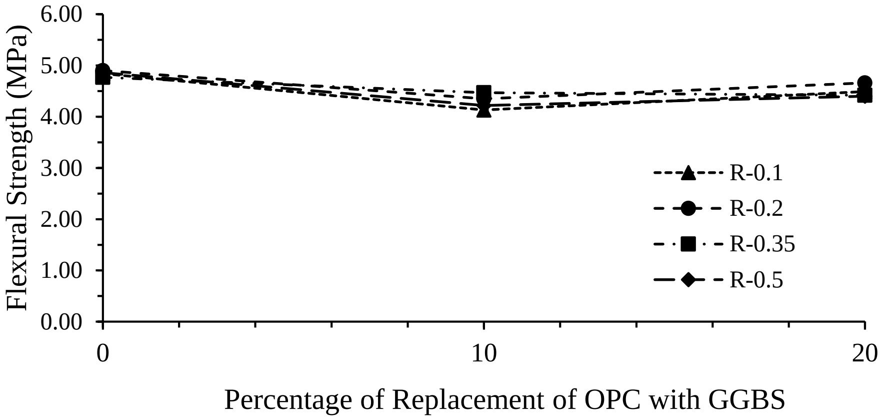


Figure 4.19 Combined effect of GGBS and NF on the flexural strength of RAC

Flexural strength decreases with the incorporation of nylon fiber in RAC. The bar chart with standard deviation (Figure 4.20) shows the variation of flexural strength for different percentages of nylon fiber in recycled aggregate concrete. It is observed that partial replacement of OPC with slag also reduces the flexural strength of RAC, though 20% replacement of OPC provides more strength than that of RAC with 10% replacement of OPC with GGBS. Due to incorporation of nylon fiber the cracks did not propagate easily and fiber held the broken parts together and absorbed more energy for the tension capacity of nylon fiber.

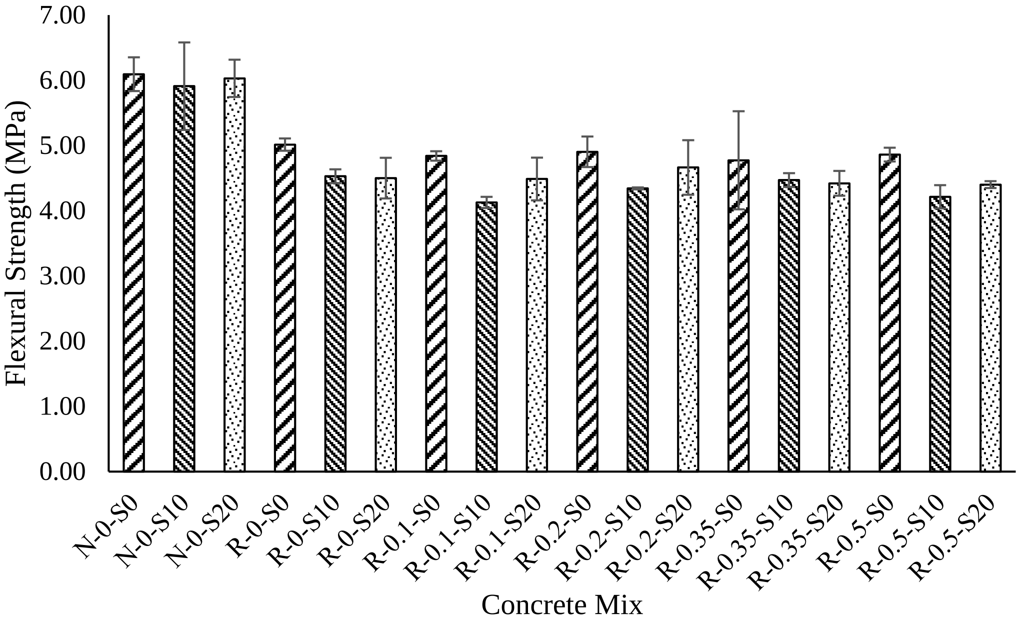


Figure 4.20 Flexural strength of all the mixes

4.7.4 Flexural Crack Behavior

After the flexural strength test, the cracking patterns were observed and found that the parts of the specimen of the nylon fiber reinforced concrete were held together by nylon fiber (Figure 4.21). In the case of the mixes without fiber, samples were broken into two distinct parts. With the increase in fiber dosage, the failure of the concrete prisms was ductile and a significant residual strength was demonstrated by those samples. The control mix beam was completely broken when subjected to the maximum load while nylon fiber reinforced beams did not fully break as a result of the bonding of nylon fibers with mortar.

(a) (b)

Figure 4.21 Flexural behavior of the specimen (a) without fiber (b) with 0.5% fiber

4.8 Flexural Toughness

With the addition of fiber the toughness of the RAC improved and energy absorption capacity was found higher than that of the sample without any fiber. According to ASTM C-1609 toughness was calculated from the recorded mid-point deflection of the prism under the flexural strength test. The load-deflection curve for 0.35% fiber in RAC without any replacement of OPC with GGBS is shown in Figure 4.22.

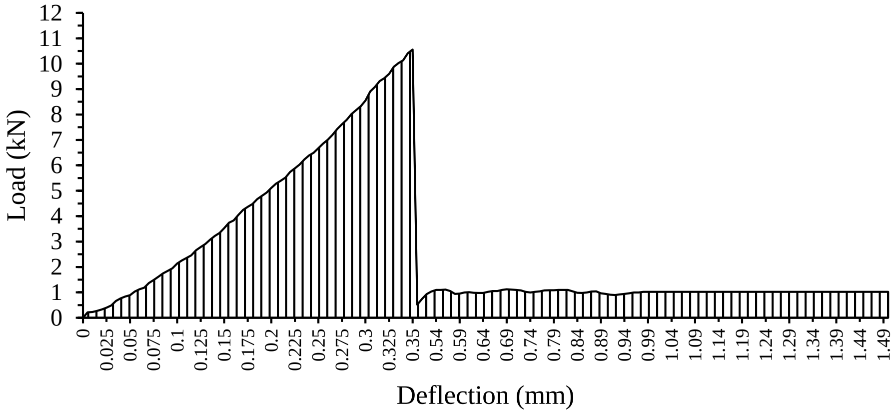


Figure 4.22 Load-deflection curve under flexural load

Using the trapezoidal formula, area up to the midpoint deflection of 1/150 of total span length was calculated from the available data. The area represents the value of the toughness, (T) = 3.455 J/volume or 3.455 kN/mm^2. As all the prisms have the same dimensions and hence have same volume, toughness of the specimens was compared instead of modulus of toughness.

4.8.1 Effect of Partial Replacement of OPC with GGBS in NAC and RAC

From the observation of flexural toughness on NAC and RAC, for both type of specimens, the toughness decreases with the 10% partial replacement of OPC with GGBS, But for 20% partial replacement, the toughness increases for NAC, on the contrary, the toughness continues to decrease for RAC (Figure 4.23). Addition of GGBS cannot improve the flexural toughness of RAC over NAC.

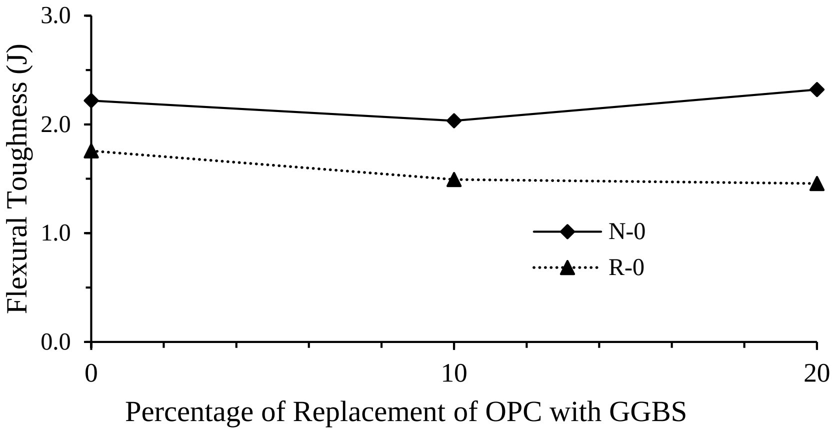


Figure 4.23 Effect of GGBS on the flexural toughness of NAC and RAC

4.8.2 Effect of NF in RAC

Flexural toughness increases with the addition of NF up to 0.2% volume fraction, but further addition causes reduction in toughness (Figure 4.24). For all the doses of NF the toughness is higher than that the control mix. RAC with 0.2% volume fraction of nylon fiber has nearly two times toughness compared to the control mix. RAC with NF can impart more ductility and energy absorption capacity.

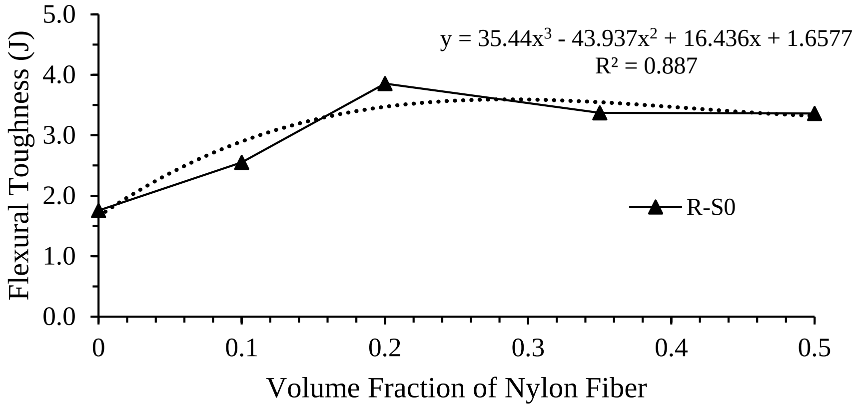


Figure 4.24 Effect of NF on the flexural toughness of RAC

4.8.3 Combined Effect of NF and GGBS in RAC

Both 10% and 20% partial replacement of OPC with GGBS show similar results for the incorporation of nylon fiber in recycled aggregate concrete. At 0.2% V_f of NF in RAC with 20% partial replacement of OPC with GGBS, the sample shows better toughness, whereas for 10% partial replacement the maximum toughness can be observed at 0.35% volume fraction of nylon fiber (Figure 4.25). For 0.35% and 0.5% volume fraction of NF in RAC, the toughness increases at 10% partial replacement of

OPC with GGBS. On the contrary, toughness of the samples decreases for 0.2% volume fraction of NF (Figure 4.26). Furthermore, the toughness of RAC with 0.1% volume fraction of NF, the toughness continues to increases with the addition of GGBS.

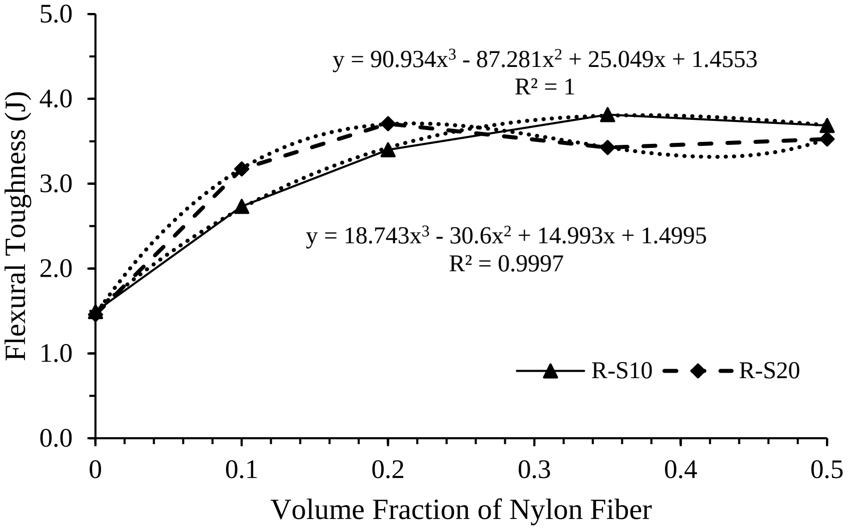


Figure 4.25 Effect of GGBS on the flexural toughness of NF reinforced RAC

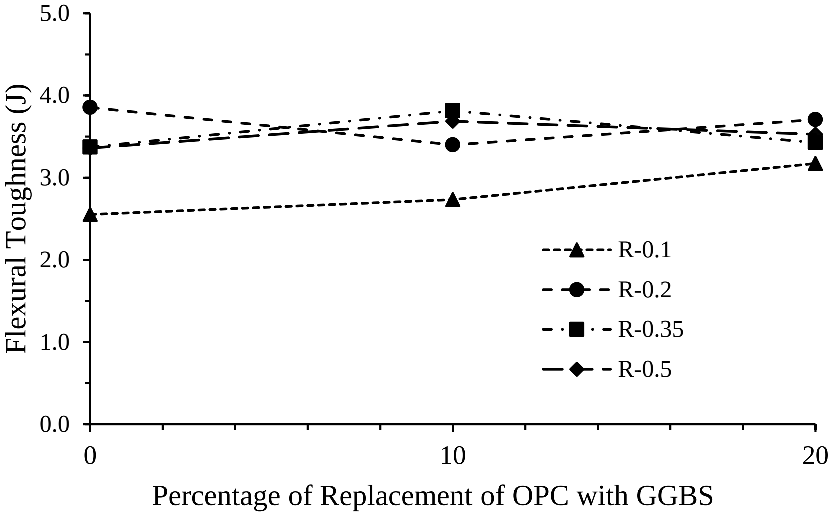


Figure 4.26 Combined effect of GGBS and NF on the flexural toughness of RAC

For all the mixes, the variation of toughness with standard deviation as error bar is shown in Figure 4.27. The addition of fiber increases the toughness or energy absorption capacity. The toughness is maximum within the range of volume fraction of 0.2% to 0.35%. Load-deflection curves are provided in Appendix A.2.5.

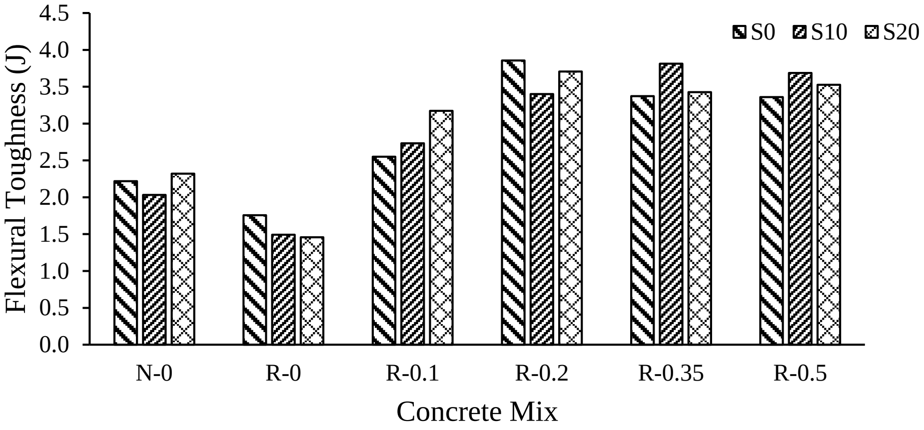


Figure 4.27 Flexural toughness of all the mixes

According to Spadea et al. (2015), the utilization of a higher percentage of nylon fiber in cement-based mortar causes the specimens able to bear a higher load and able to extend the specimens' lifespan. An additional percentage of nylon fiber will increase the plasticity of the mortar thus delaying the process of cracking and enhancing the flexural strength of mortar.

4.9 Elastic Rebound Hammer Test

Elastic rebound hammer test was conducted to compare the compressive strength from rebound number with the actual crushing strength of hardened concrete. The data consists of measurement of rebound number and related crushing strength of cylinder. Rebound hammer measurements were recorded from concrete cylinders at 28 days of curing. Samples gone through the non-destructive test, were later used in compressive strength test. Table 4.7 shows the results of the rebound hammer test performed horizontally on the curved surfaces of concrete cylinders made using recycled aggregates with 0.1% nylon fiber. Other results are given in Appendix A.2.3. Table 4.8 shows the rebound number, strength and mean error for all the mixes.

Table 4.7 Rebound hammer test results of RAC with 0.1% V_f of nylon fiber

Mix	Rebound Values (10 Points)					Average Rebound Number	Calibrated Average Rebound Number	Rebound Strength (MPa)	Mean Error, Δ (MPa)
R-0.1-S0	40	41	42	44	38	41.0	42.4	38	± 6.0
	41	39	38	43	44				

Table 4.8 Rebound hammer strength results for each type of mix

Mix	Average Rebound Number (Horizontal)	Calibrated Average Rebound Number	Compressive Strength from Rebound Hammer Test (MPa)	Mean Error, Δ (MPa)	Actual Compressive Strength (MPa)	Comments
N-0-S0	43.1	44.6	42	± 6.5	46	Within Range
R-0-S0	39.8	41.2	36	± 6.0	45	Not Within Range
R-0.1-S0	41.0	42.4	38	± 6.0	49	Not Within Range
R-0.2-S0	39.6	41.0	36	± 6.0	48	Not Within Range
R-0.35-S0	41.6	43.0	39	± 6.0	46	Not Within Range
R-0.5-S0	43.1	44.6	42	± 6.5	45	Within Range
N-0-S10	42.9	44.4	41	± 6.5	48	Not Within Range
R-0-S10	41.8	43.2	39	± 6.0	46	Not Within Range
R-0.1-S10	43.0	44.5	41	± 6.5	51	Not Within Range
R-0.2-S10	43.0	44.5	41	± 6.5	49	Not Within Range
R-0.35-S10	42.9	44.4	41	± 6.5	48	Not Within Range
R-0.5-S10	42.6	44.1	41	± 6.5	46	Within Range
N-0-S20	41.7	43.1	39	± 6.0	46	Not Within Range
R-0-S20	40.9	42.3	38	± 6.0	44	Within Range
R-0.1-S20	41.9	43.3	40	± 6.0	49	Not Within Range
R-0.2-S20	41.6	43.0	39	± 6.0	46	Not Within Range
R-0.35-S20	41.5	42.9	39	± 6.0	45	Within Range
R-0.5-S20	41.7	43.1	39	± 6.0	44	Within Range

Detailed results are provided in Appendix A.2.3. Rebound number is the least reliable and it just provides a range of strength. Moreover, the test was conducted on the curved surfaces of the concrete cylinder and hence the surface condition may have effect on the test results.

4.10 Relationship of Mechanical Properties with Compressive Strength

Mechanical properties i.e. splitting tensile strength, flexural strength, and modulus of elasticity can be correlated to the compressive strength of the concrete cylinder. Previous studies and ACI suggested specific equations for predicting these mechanical properties from the crushing strength.

4.10.1 Relationship of Splitting Tensile Strength with Compressive Strength

According to ACI 363R-92, splitting tensile strength can be determined from the compressive strength by the following equation:

$$f_{sp}' = 0.59 \sqrt{f_c'} \quad (4.1)$$

Where,

f_{sp}' = Splitting tensile strength (MPa)

f_c' = Actual compressive strength (MPa)

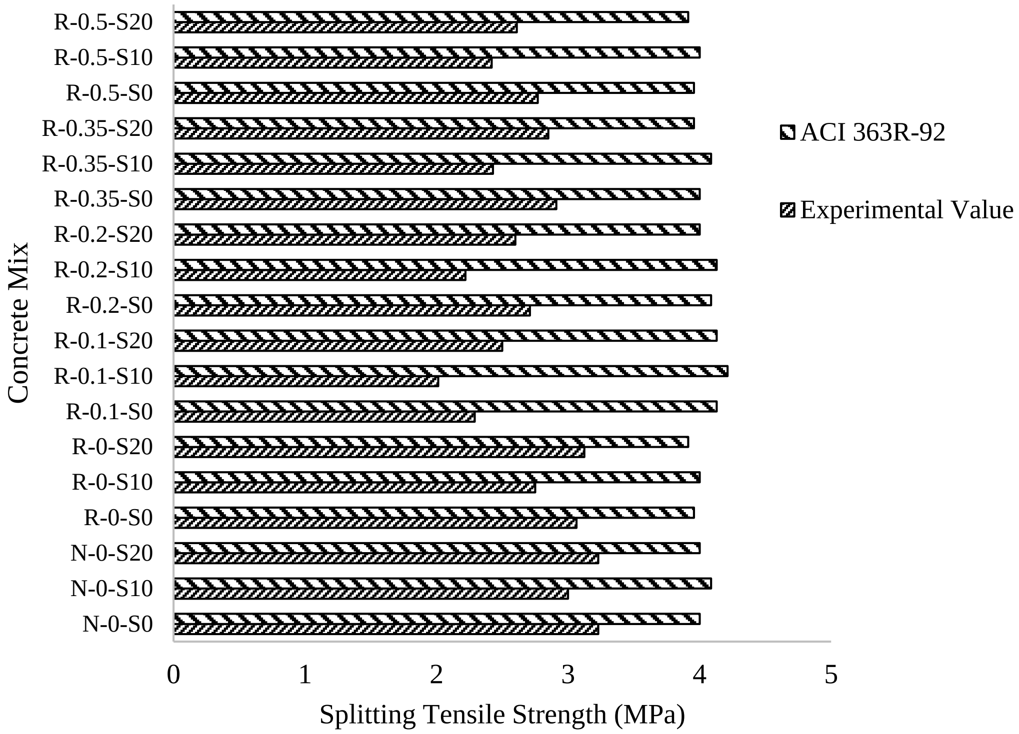


Figure 4.28 Relationship of splitting tensile strength with compressive strength

In this case, the ACI equation over-estimates the experimental value of the splitting tensile strength (Figure 4.28). For RAC, the variation of the strength is significant. Hence, type of aggregate may be the influencing factor for such variation. Equation suggested by ACI is valid for normal-weight concrete.

4.10.2 Relationship of Modulus of Rupture with Compressive Strength

According to ACI 363R-92, modulus of rupture or flexural strength can be determined from the compressive strength by the following equation:

$$f_r^{'} = 0.94\ \sqrt{f_c^{'}} \tag{4.2}$$

Where,

$f_r^{'}$ = Splitting tensile strength (MPa)

$f_c^{'}$ = Actual compressive strength (MPa)

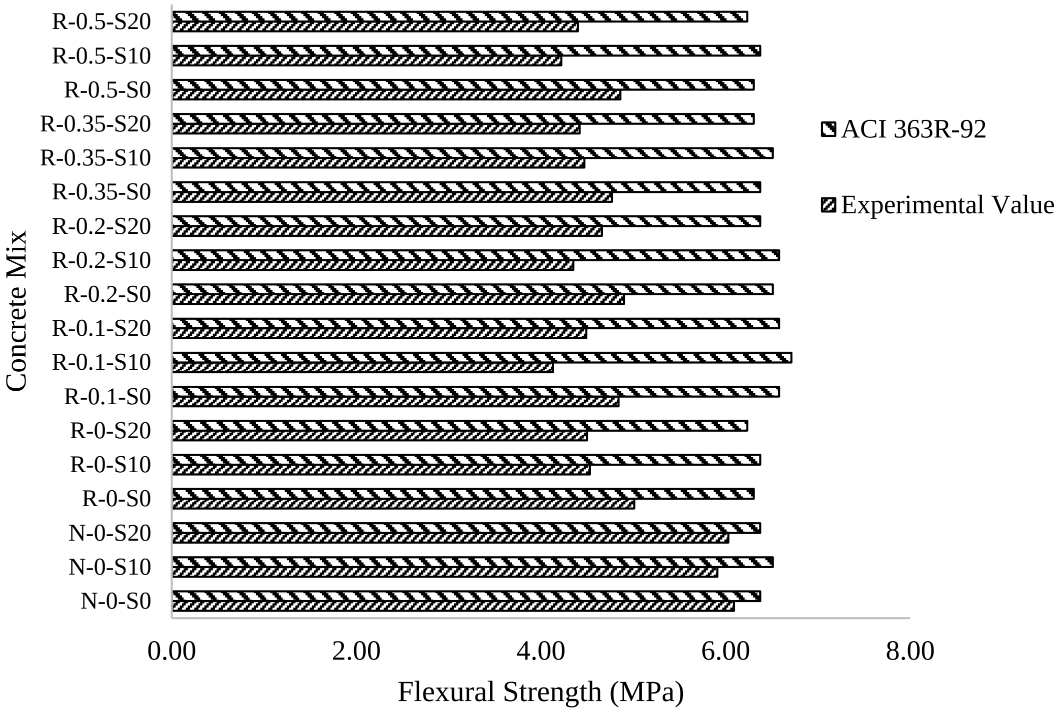


Figure 4.29 Relationship of flexural strength with compressive strength

From Figure 4.29, similar results were observed for NAC considering the ACI equation and experimental value. GGBS has no significant effect on the variation. Overall, the empirical equation of ACI equation overestimate the modulus of rupture of nylon fiber reinforced recycled aggregate concrete. Again, presence of RCA might be responsible for variation of the modulus of rupture from empirical equation of ACI.

Chapter 5

CONCLUSIONS AND SUGGESTIONS

5.1 Introduction

This study deals with the mechanical properties of nylon fiber reinforced recycled aggregate concrete with the partial replacement of Ordinary Portland Cement. Previous studies have shown that nylon fiber has a positive effect on the mechanical properties of concrete i.e. compressive, tensile and flexural strength of the concrete and recycled aggregate concrete has lower strength compared to natural aggregate concrete. Fibrous composite concrete is one of the outstanding solutions to overcome the limitations of recycled aggregate concrete. Moreover, GGBS can also improve the compressive strength and workability of the concrete. In this project the effect of the nylon fiber and Ground Granulated Blast-furnace Slag on RAC had been assessed as a part of the improvement research works regarding fiber reinforced concrete.

5.2 Conclusion

The following conclusion can be drawn from the tested results and analysis of the study:

a) The increase in the volume fraction of the nylon fiber decreases the workability i.e. the slump value of the fresh concrete. Interfacial confinement between cement paste and fiber has significant influence on the workability. In recycled aggregate concrete, 0.5% volume fraction of nylon fiber reduces the workability about 40% compared to RAC without any fiber and GGBS. Moreover, in NAC, slump value increases about 37% with 10% partial replacement of OPC with GGBS, but it starts increasing with further replacement of OPC. On the other hand, partial replacement of OPC with GGBS reduces the slump value about 13% on average in RAC.

b) Addition of nylon fiber of 0.1% volume fraction increases the compressive strength of RAC over the compressive strength of the control mix. However, with more addition of fiber, the strength decreases. 10% partial replacement of OPC with GGBS and 0.1% volume fraction of nylon fiber increases the crushing strength about 10.9% compared to that of control mix. Besides, 10% partial replacement of OPC increases the compressive strength.

c) In RAC, addition of 0.1% volume fraction of nylon fiber and 10% partial replacement of OPC with GGBS, the splitting tensile strength reduces about 34.3% compared to that of NAC. All the doses of nylon fiber in RAC are unable to improve the splitting tensile strength. Though nylon fiber reinforced RAC show lower splitting strength, the split parts do not fall apart with the further increment of the applied load. RAC without fiber and NAC do not show such type of behavior. Furthermore, partial replacement of OPC with GGBS does not improve the splitting tensile strength significantly, though 20% replacement of OPC with GGBS shows better performance comparatively.

d) In NDT, the rebound hammer number obtained from curved surfaces of the concrete cylinder, merely indicates the range of compressive strength of the corresponding mix. The results were similar for all the batches. Hence, the results from rebound hammer test is not practically significant in this study.

e) Addition of nylon fiber in RAC has no significant effect on modulus of elasticity. The partial replacement of OPC with GGBS does not show any noteworthy change in modulus of elasticity. Hence, nylon fiber and GGBS have negligible combined effect on the modulus of elasticity of RAC.

f) Partial replacement of OPC has no certain effect on Poisson’s ratio on recycled aggregate concrete. Due to insignificant effect of nylon fiber and GGBS on the lateral and longitudinal deformation, no remarkable change is observed in the Poisson’s ratio of recycled aggregate concrete. All the mixes possess the Poisson’s ratio within the range of 0.1 to 0.2.

g) In recycled aggregate concrete, with 10% partial replacement of OPC with GGBS and 0.1% volume fraction of nylon fiber the modulus of rupture reduces about 32.2% compared to that of RAC without any fiber and GGBS. Minimal effect of the addition of fiber and GGBS on the flexural strength, can be observed for the addition of 0.2% volume fraction of nylon fiber and 20% replacement of OPC with GGBS, though this combination reduces the flexural strength about 2.2% compared to control mix. In all cases, natural aggregate concrete has higher flexural strength. However, nylon fiber reinforced recycled aggregate concrete shows more ductility over NAC and RAC without any fiber due to fiber’s resistance to crack propagation.

h) From the load-deflection curve of flexural strength test, the toughness was found maximum at 0.2% volume fraction of nylon fiber reinforced recycled aggregate concrete. With the addition of 0.2% nylon fiber and without any partial replacement of OPC with GGBS in RAC, the flexural toughness increases about two times of the toughness of recycled aggregate concrete. Moreover, without fiber the partial replacement of OPC with GGBS showed no remarkable effect on the energy absorption capacity of the recycled aggregate concrete.

5.3 Limitations of the Present Study

In spite of being cautious at every phase of the study, some limitations can be addressed.

a) Mix design was adopted from the previous study of Saha (2019). The amount of binder added in each mix was higher than the amount of fine aggregate. Hence, the mix design is uneconomical and the samples might not evidently show the effect of RCA, NF, and GGBS.

b) Only three different percentages of partial replacement (0%, 10% and 20%) of GGBS were evaluated in this study. Hence, the graph related to the percentage of GGBS might not show the proper relationship of GGBS with the mechanical properties.

c) Recycled aggregate used in this study was collected from the dumping area. Hence, RCA derived from different grades of concrete were used in this study.

d) Relationship of splitting tensile strength and modulus of rupture with the compressive strength of nylon fiber reinforced recycled aggregate concrete were compared with the empirical equations recommended by ACI though the equations are valid for normal weight plain concrete.

5.4 Suggestions

This study provides the following suggestions for the nylon fiber reinforced recycled aggregate concrete and also partial replacement of OPC with GGBS in RAC:

a) Effect of nylon fiber on the durabilities of RAC may be studied. Besides the effect of partial replacement of OPC with GGBS should also be evaluated.

b) Partial replacement of natural stone aggregate with recycled stone/brick chips can also be included in further studies.

c) Higher percentage of partial replacement of OPC with GGBS in nylon fiber reinforced concrete may be evaluated in future studies.

d) Combined effect of nylon fiber, recycled aggregate and GGBS on shrinkage property of concrete may be an interest in further studies.

e) Bond strength of nylon fiber reinforced RAC should be examined.

g) The behavior of nylon fiber reinforced RAC under creep load may be considered.

h) Applicability of nylon fiber reinforced recycled aggregate concrete in structural members with rebar should be checked.

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APPENDIX

A.1 Properties of Fine, Coarse Aggregate and Nylon Fiber

This article covers the grain size distribution curve of aggregate, Los Angles Abrasion value determination, and calculation of fiber density.

A.1.1 Sieve Analysis of Coarse and Fine Aggregate

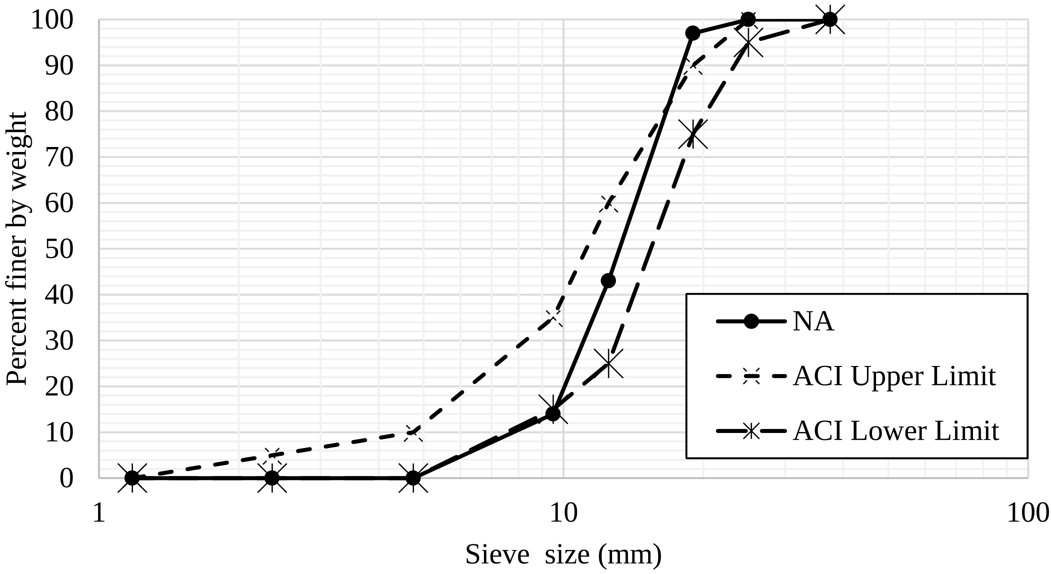

Figure A1.1 Grain size distribution of NA

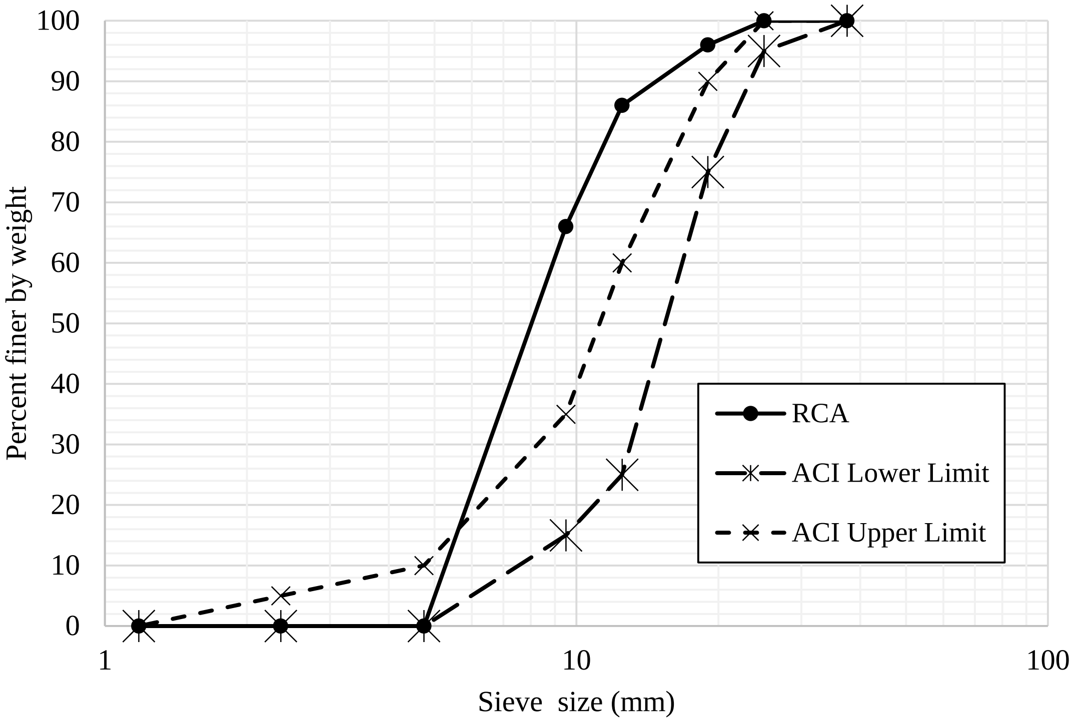

Figure A1.2 Grain size distribution of RCA

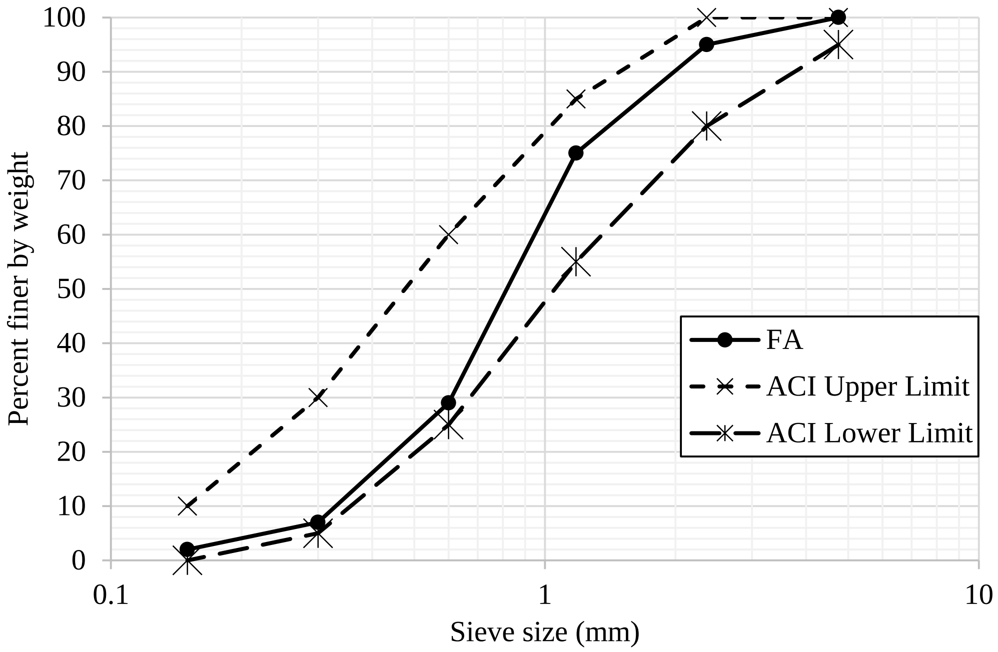

Figure A1.3 Grain size distribution of FA

A.1.2 Los Angeles Abrasion value

L.A.A. value = $\frac{C-Y}{C}$ x 100

Where,

C = mass of original test sample, g

Y = final mass of the test sample, g

Natural Aggregate: L.A.A. value = $\frac{5000-4303}{5000}$ x 100 = 13.9%

Recycled Concrete Aggregate: L.A.A. value = $\frac{5000-3698}{5000}$ x 100 = 26.4%

A.1.3 Fiber Density and Doses Calculation

Table A1.1 Properties of nylon fiber

No. of Sample	60
Total Length(mm)	1197
Avg. diameter(mm)	0.1
Volume(m^3), V	0.0000000094
Mass (kg), M	0.00000684
Density, ρ = M/V	727.56

A.2 Mechanical Properties of the Samples

Sample calculation and tested data are provided in this section.

A.2.1 Compressive Strength of Cylinder at 28 days

Table A2.1 Compressive strength test data

Mix	Sample No.	Ultimate Load (kN)	Strength (MPa)	Avg. Strength (MPa)	Type of Failure
N-0-S0	1	365	45.1	46.2	Combined
	2	375	46.3		Combined
	3	382	47.2		Combined
R-0-S0	1	360	44.4	44.9	Combined
	2	355	44.2		Combined
	3	373	46.1		Combined
R-0.1-S0	1	391	47.9	49.4	Combined
	2	408	51.1		Combined
	3	403	49.2		Combined
R-0.2-S0	1	386	48.3	48.3	Combined
	2	406	50.9		Combined
	3	373	45.8		Combined
R-0.35-S0	1	380	47.1	46.4	Combined
	2	365	45.2		Combined
	3	378	46.8		Combined
R-0.5-S0	1	376	45.8	45.1	Combined
	2	369	45.2		Combined
	3	362	44.2		Combined
N-0-S10	1	386	47.1	47.7	Combined
	2	394	48.3		Combined
	3	389	47.6		Combined
R-0-S10	1	380	47.1	46.3	Combined
	2	383	46.8		Combined
	3	377	44.9		Combined

Contd. Table A2.1

Mix	Sample No.	Ultimate Load (kN)	Strength (MPa)	Avg. Strength (MPa)	Type of Failure
R-0.1-S10	1	411	50.6	50.6	Combined
	2	409	50.9		Combined
	3	407	50.3		Combined
R-0.2-S10	1	395	48.7	48.8	Combined
	2	392	49.2		Combined
	3	390	48.5		Combined
R-0.35-S10	1	382	47.0	47.7	Combined
	2	396	49.3		Combined
	3	382	46.8		Combined
R-0.5-S10	1	377	45.8	45.8	Combined
	2	356	44.9		Combined
	3	387	46.8		Combined
N-0-S20	1	372	46.3	46.3	Combined
	2	383	47.2		Combined
	3	378	45.5		Combined
R-0-S20	1	300	38.2	44.5	Combined
	2	406	49.5		Combined
	3	373	45.8		Combined
R-0.1-S20	1	403	49.6	48.5	Combined
	2	391	47.7		Combined
	3	395	48.2		Combined
R-0.2-S20	1	372	45.7	45.6	Combined
	2	378	46.0		Combined
	3	366	45.2		Combined
R-0.35-S20	1	370	45.0	45.1	Combined
	2	362	46.2		Combined
	3	356	44.1		Combined
R-0.5-S20	1	345	43.2	43.7	Combined
	2	366	44.8		Combined
	3	348	43.1		Combined

A.2.2 Splitting Tensile Strength of Cylinder at 28 days

Table A2.2 Splitting tensile strength test data

Mix	Sample No.	Ultimate Load (kN)	Splitting Tensile Strength (MPa)	Avg. Strength (MPa)
N-0-S0	1	103	3.18	3.23
	2	119	3.70	
	3	91	2.80	
R-0-S0	1	95	2.92	3.06
	2	113	3.50	
	3	91	2.78	
R-0.1-S0	1	76	2.35	2.29
	2	72	2.23	
	3	75	2.30	
R-0.2-S0	1	91	2.77	2.71
	2	86	2.62	
	3	89	2.74	
R-0.35-S0	1	85	2.54	2.91
	2	95	2.91	
	3	107	3.28	
R-0.5-S0	1	101	3.08	2.77
	2	89	2.74	
	3	81	2.49	
N-0-S10	1	105	3.22	3.00
	2	95	2.92	
	3	93	2.85	
R-0-S10	1	97	2.99	2.75
	2	89	2.74	
	3	83	2.51	
R-0.1-S10	1	66	2.04	2.01
	2	60	1.85	
	3	70	2.15	

Contd. Table A2.2

Mix	Sample No.	Ultimate Load (kN)	Splitting Tensile Strength (MPa)	Avg. Strength (MPa)
R-0.2-S10	1	72	2.23	2.22
	2	75	2.28	
	3	70	2.15	
R-0.35-S10	1	81	2.45	2.43
	2	85	2.59	
	3	74	2.25	
R-0.5-S10	1	77	2.35	2.42
	2	89	2.69	
	3	72	2.22	
N-0-S20	1	130	3.98	3.23
	2	95	2.93	
	3	91	2.79	
R-0-S20	1	101	3.09	3.12
	2	111	3.41	
	3	93	2.87	
R-0.1-S20	1	77	2.36	2.50
	2	81	2.47	
	3	86	2.65	
R-0.2-S20	1	79	2.43	2.60
	2	85	2.60	
	3	91	2.77	
R-0.35-S20	1	98	3.01	2.85
	2	91	2.81	
	3	91	2.73	
R-0.5-S20	1	79	2.43	2.61
	2	89	2.72	
	3	87	2.68	

A.2.3 Non-destructive Test Using Elastic Rebound Hammer

Rebound hammer test was performed horizontally on cylindrical concrete samples. Calibration factor and shape factor used for the calibration of rebound number were 0.976 and 1.06 respectively.

Table A2.3 Rebound hammer test data

Mix	**Rebound Values**										**Average Rebound Number**	**Calibrated Average Rebound Number**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
N-0-S0	44	43	41	40	42	45	40	46	47	43	43.1	44.6
R-0-S0	34	41	39	41	41	39	42	38	42	41	39.8	41.2
R-0.1-S0	40	41	42	44	38	41	39	38	43	44	41.0	42.4
R-0.2-S0	38	39	39	39	37	44	37	44	40	39	39.6	41.0
R-0.35-S0	45	39	40	44	44	41	41	39	44	39	41.6	43.0
R-0.5-S0	41	46	43	43	45	45	42	40	46	40	43.1	44.6
N-0-S10	44	45	45	42	41	41	43	40	42	46	42.9	44.4
R-0-S10	44	41	40	41	44	44	40	40	44	40	41.8	43.2
R-0.1-S10	42	44	44	45	41	41	44	45	42	42	43.0	44.5
R-0.2-S10	43	41	46	44	45	39	42	44	43	43	43.0	44.5
R-0.35-S10	44	43	43	43	44	43	41	44	42	42	42.9	44.4
R-0.5-S10	44	44	46	39	39	41	45	46	40	42	42.6	44.1
N-0-S20	42	39	40	44	42	43	41	44	39	43	41.7	43.1
R-0-S20	42	38	41	43	42	41	41	44	38	39	40.9	42.3
R-0.1-S20	40	46	44	39	42	39	39	42	43	45	41.9	43.3
R-0.2-S20	40	41	40	40	42	42	39	45	41	46	41.6	43.4
R-0.35-S20	41	43	42	44	42	42	40	40	38	43	41.5	45.5
R-0.5-S20	42	40	45	40	39	43	44	44	41	39	41.7	46.5

A.2.4 Modulus of elasticity and Poisson's ratio of concrete

Modulus of elasticity and Poisson's ratio of hardened concrete cylinder were determined using equation no. 3.1 and 3.2 respectively.

Table A2.4 Modulus of elasticity and Poisson's ratio of the concrete mixes

Mixes	Modulus of Elasticity (MPa)	Poisson's Ratio
N-0-S0	48263	0.13
R-0-S0	49987	0.10
R-0.1-S0	48608	0.13
R-0.2-S0	46884	0.20
R-0.35-S0	49642	0.18
R-0.5-S0	45850	0.15
N-0-S10	51711	0.12
R-0-S10	51366	0.10
R-0.1-S10	51366	0.16
R-0.2-S10	47918	0.21
R-0.35-S10	45160	0.13
R-0.5-S10	39300	0.15
N-0-S20	48953	0.17
R-0-S20	46884	0.09
R-0.1-S20	47918	0.19
R-0.2-S20	47918	0.16
R-0.35-S20	42058	0.17
R-0.5-S20	50676	0.14

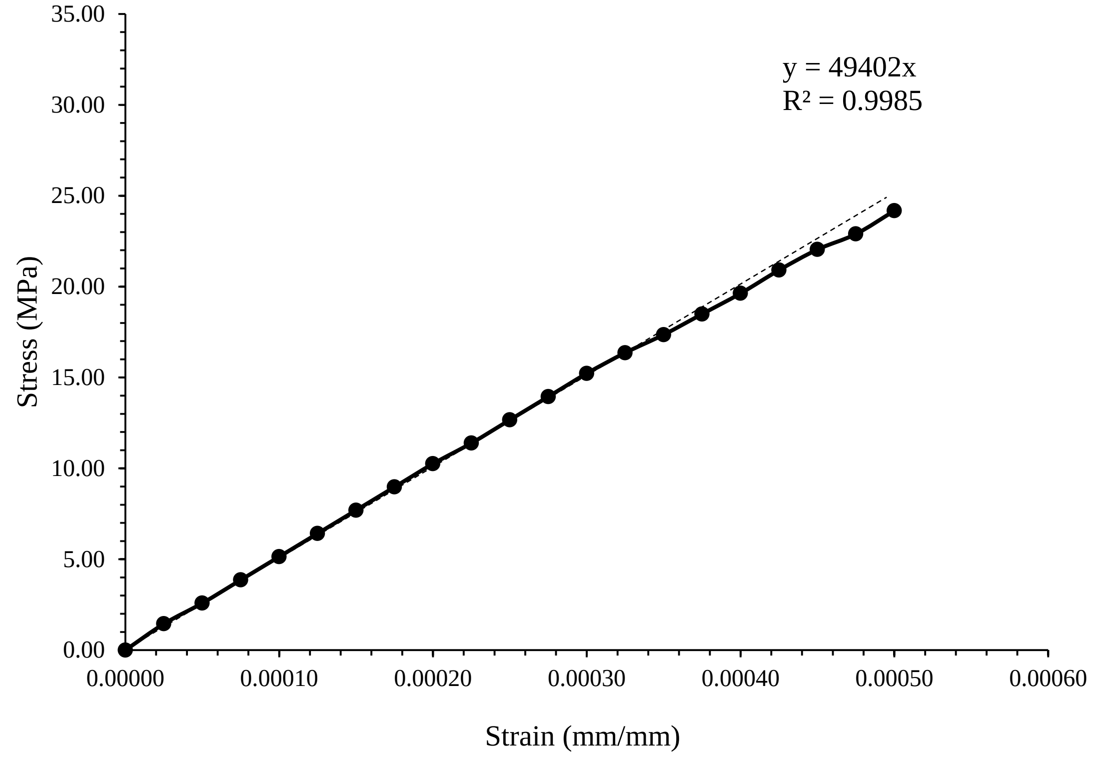

Figure A2.1 Typical stress-strain diagram of concrete cylinder

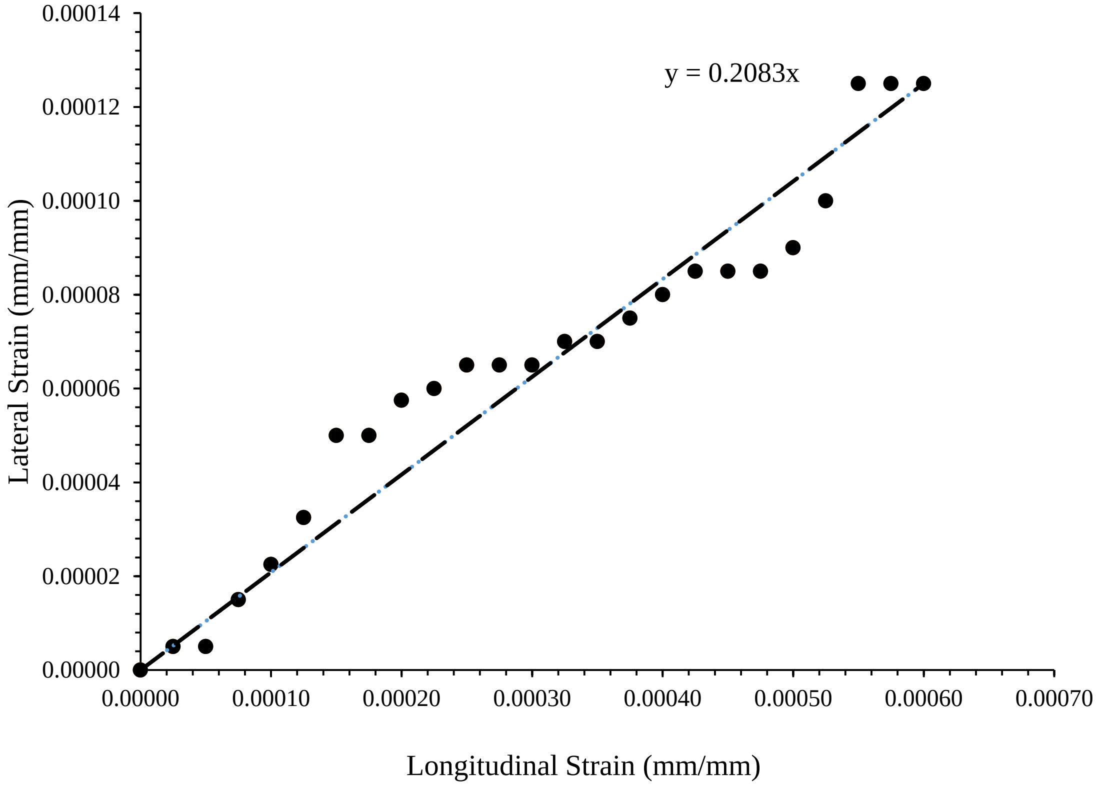

Figure A2.2 Relationship between lateral strain and longitudinal strain

A.2.5 Modulus of rupture and flexural toughness of prisms at 28 days

Modulus of rupture was determined by using third point loading on the concrete prisms and flexural toughness was determined from the recorded midpoint deflection and corresponding load.

Table A2.5 Flexural strength test data

Mix	Sample No.	Maximum Load (kN)	Modulus of Rupture (MPa)	Avg. Modulus of Rupture (MPa)
N-0-S0	1	11.92	6.29	6.09
	2	11.25	5.80	
	3	11.78	6.19	
R-0-S0	1	9.46	4.98	5.01
	2	10.01	5.12	
	3	9.42	4.94	
R-0.1-S0	1	9.24	4.82	4.84
	2	9.35	4.92	
	3	9.24	4.78	
R-0.2-S0	1	9.24	4.90	4.90
	2	8.88	4.67	
	3	10.02	5.14	
R-0.35-S0	1	10.56	5.34	4.77
	2	7.48	3.92	
	3	9.68	5.06	
R-0.5-S0	1	9.49	4.82	4.86
	2	9.12	4.78	
	3	9.43	4.98	
N-0-S10	1	12.44	6.38	5.91
	2	12.01	6.21	
	3	9.76	5.14	
R-0-S10	1	9.01	4.64	4.53
	2	8.57	4.43	
	3	8.86	4.52	

Contd. Table A2.5

Mix	Sample No.	Maximum Load (kN)	Modulus of Rupture (MPa)	Avg. Modulus of Rupture (MPa)
R-0.1-S10	1	7.90	4.05	4.13
	2	8.17	4.22	
	3	7.78	4.11	
R-0.2-S10	1	8.24	4.36	4.35
	2	8.26	4.33	
	3	8.24	4.34	
R-0.35-S10	1	9.02	4.59	4.47
	2	8.46	4.39	
	3	8.68	4.43	
R-0.5-S10	1	8.44	4.37	4.22
	2	7.54	4.02	
	3	8.17	4.25	
NO-0-S20	1	12.20	6.35	6.03
	2	11.56	5.94	
	3	11.36	5.80	
R-0-S20	1	9.14	4.83	4.50
	2	8.02	4.21	
	3	8.48	4.46	
R-0.1-S20	1	9.00	4.71	4.49
	2	7.90	4.11	
	3	8.93	4.64	
R-0.2-S20	1	8.96	4.72	4.66
	2	9.64	5.05	
	3	8.04	4.22	
R-0.35-S20	1	8.69	4.60	4.42
	2	8.08	4.22	
	3	8.62	4.44	
R-0.5-S20	1	8.46	4.38	4.40
	2	8.54	4.36	
	3	8.68	4.46	

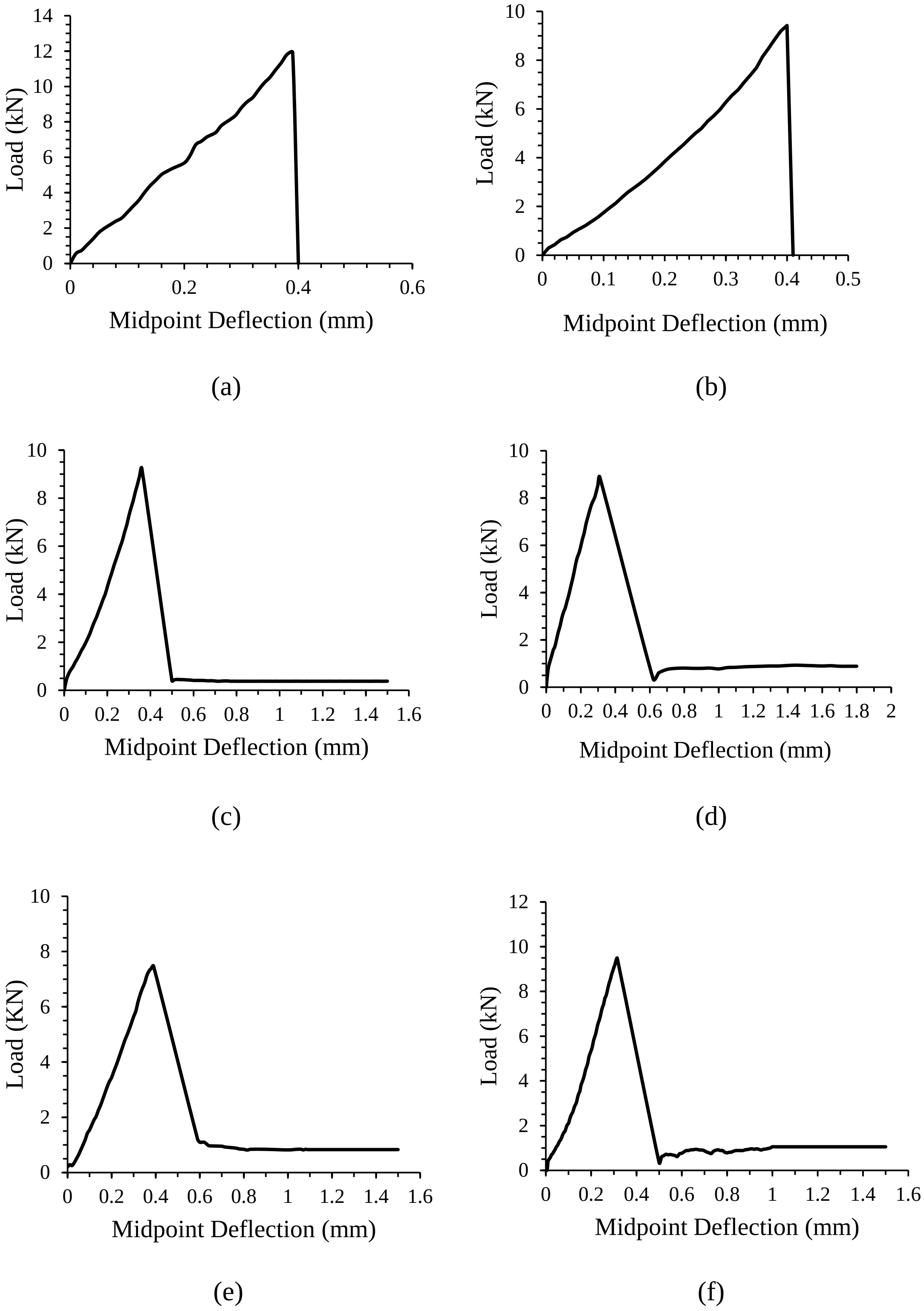

Figure A2.3 Load-deflection curve of the concrete mixes under flexural load (a) N-0-S0 (b) R-0-S0 (c) R-0.1-S0 (d) R-0.2-S0 (e) R-0.35-S0 (f) R-0.5-S0