INFLUENCE OF GALVANISED IRON AND POLYPROPYLENE FIBERS ON THE PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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INFLUENCE OF GALVANISED IRON AND POLYPROPYLENE FIBERS ON THE PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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This thesis titled “INFLUENCE OF GALVANISED IRON AND POLYPROPYLENE FIBERS ON THE PROPERTIES OF RECYCLED AGGREGATE CONCRETE”, submitted by Ehsani Khatun, Roll no: 1012110001, Session:2012-2013, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Structural Engineering) on 14-7-2020.

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PREFACE

Some portions of the work outlined in this thesis have been submitted (see list below) for possible publication. The contributions of her research supervisor consisted of, providing guidance, supervision and helping in the development of the final versions of the publications.

Refereed Conference Publications

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ABSTRACT

Significant amount of concrete waste generates every day from construction and demolition (C&D) works and has become a global concern from environmental perspective. Recycled aggregate produced from these C&D waste can be used as an alternative material for natural aggregate (NA) which has finite resources. Recycled aggregate (RA) has lower density, higher water absorption, lower mechanical properties compared to normal aggregate (NA). Inclusion of fiber along with RA in concrete mixes improves the mechanical properties of concrete. This study investigates the fresh and hardened properties of normal aggregate concrete (NAC) and recycled aggregate concrete (RAC) made with locally available low-cost galvanized iron (GI) fiber, as an alternative to steel fibers, and polypropylene (PP) fibers. The objective of this study is to explore the effect of GI fiber and PP fiber in terms of compressive strength, stress-strain behavior, splitting tensile strength, and flexural strength. The study has been completed in two phases. In the first phase, GI fiber and PP fiber with 0.5%, 1% and combination of GI and PP fiber are used to prepare NAC to find out the optimum fiber type and percentage. From test results it has been observed that concrete with 0.5% GI fiber produced best results in terms of strength and ductility than the concrete with PP fiber, other GI fiber content and combination of GI and PP fibers. In the second part of the study, diameter and length of the GI fiber has been varied while keeping the fiber percentage of 0.5% constant. From local market three different diameters of GI fibers, such as 0.51 mm, 0.70 mm and 1.21 mm, have been used in NAC to evaluate the effect of GI fiber diameter on the properties of NAC. In terms of the performance against workability, compressive and splitting tensile strength, 0.51mm diameter GI fiber has chosen for the next part of the study. Finally, GI fiber of 0.51 mm diameter considering three different aspect ratios, such as 30, 50 and 70, for which the fiber lengths were 15, 26, and 36 mm respectively, have been incorporated in both NAC and RAC. For NAC, GI fiber of length 26 mm and for RAC, GI fiber of length 36 mm showed the highest compressive strength. In general, the test results have showed that RAC has lower strength than NAC at 28 days. However, at 56 days RAC have showed better strength compare to NAC. Inclusion of GI fiber has improved the mechanical properties of both NAC and RAC. On the other hand, incorporation of PP fiber has very little effect on the compressive, tensile and flexural strength of NAC and RAC.PP fiber showed reduced compressive and split tensile strength. But PP fiber performed better at lower fiber content. At 0.5 % PP fiber content,

concrete had low air content. However, against flexural loading concrete with PP fiber showed better ductility. PP fiber performed better with RAC than the NAC.

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LIST OF SYMBOLS, ABBREVIATIONS

f_y	Yield Strength of Rebar
f_u	Ultimate Strength
T	Splitting Tensile Strength
P	The Maximum Load At Failure
L	Length of The Specimen
D	Diameter of The Specimen
fc',f_{Cm}	Compressive Strength
E,E_c,E_{ci}	Young Modulus
σ_b	Flexural Strength
l	Span
b	Width of Failed Section
h	Height of Failed Section
$\overline{\sigma_b}$	Flexural Toughness Factor
T_b	Flexural Toughness
δ_{tb}	Deflection of L/150 of Span , 2 Mm When Span is 30 Cm or 3 mm when Span is 45 cm
$R^D_{T,150}$	Equivalent Flexural Strength Ratio
$T^D{}_{150}$	Toughness
$f_{ctm,sp}$	Splitting Tensile Strength
f_{ctm}	Mean Tensile Strength
f_t, f_{spt}	Tensile Strength
$\psi(t)$	Time Dependent Constant
SF	Steel Fiber
PPE	Polypropylene fiber
FRC	Fiber Reinforced Concrete
NAC	Normal Aggregate Concrete
RAC	Recycled Aggregate Concrete
GI	Galvanized Iron
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute

CHAPTER-1: INTRODUCTION

1.1 Background

Concrete is the most used building material around the world in all type of civil engineering works .According to the Cement Sustainability Initiative (CSI), more than 25 billion tons of concrete is produced worldwide per year which is double as much as the other building material [2]. Most importantly this concrete demand is increasing each day due to rapid urbanization and development. At the same time, large amount of concrete waste generates every day from Construction and Demolition (C&D) of structures which is a global concern in environmental and economic aspects. According to a report from Transparency Market Research, by the year 2025, construction waste amount generated internationally will become 2.2. billion tons per year [3]. In Asia, C&D wastes add about 40% to total generated waste [4]. Currently most of this waste is land filled which is major concern for the environment.

Concrete is most commonly used construction material which is a mixture of cement sand, gravel or crushed stone and water. Sand and gravel or crushed stone which are considered as inert materials which are held together by harden paste of cement and water. Properties of concrete are highly dependent on the characteristics of these constituent components. To ensure the desired strength of concrete, maintaining the properties of cement and aggregate is very important. Concrete has some drawbacks, such as it is weak in tension and less ductile. Reinforcement is used to get rid of these flaws of concrete.

Concrete is comparatively good in compression, but poses much lower tensile strength. Low tensile strength, poor ductility and small resistance to cracking are the main disadvantages of concrete. Concrete has some built-in internal micro cracks in it and these micro-cracks propagate slowly. Thus, reduces its tensile strength, ultimately produce a brittle material. In order to overcome these defects of concrete material, many investigations have been conducted to enhance the properties of concrete, especially the toughness of the concrete.

Concrete has properties unlike any other construction material and it can be recycled and reused. Moreover, the natural resources of natural aggregates are depleting very rapidly caused by continuous demand of infrastructure development. The worldwide market for construction aggregates is projected to be 51.7 billion tons in 2019, representing an annual growth rate of 5.2% [5]. To fulfill the demand of concrete industries, these C&D waste can be recycled and used as a replacement of natural aggregate (NA) which may help not only to protect NA from depletion but will also reduce the environmental hazards. Recycled aggregate concrete (RCA) has inferior physical and mechanical properties than the normal aggregate concrete (NAC), which is the major drawback for the application of RAC. Furthermore, RCA exhibits more brittle behavior and lower fracture energy than the NAC [6].

Fiber Reinforced Concrete (FRC) is gaining great attraction in civil engineering field with large potential. It is a composite mixture of cement mortar, aggregate, and discontinuous, detached and regularly distributed fibers. These uniformly distributed and randomly oriented fibers increase the structural integrity of FRC. Fibers are known to improve the mechanical and durability properties of concrete. Numerous studies have been conducted to study the performance and advantages of FRC. The addition of fibers generally improves the mechanical properties of concrete as fibers have the ability to hinder the propagation of cracks, reduce the growth rate of cracks and lessen the stress gathering at crack tips. Fibers along with silica fume also reduce the water absorption of concrete [7]. FRC performs better than non-FRC at maximum exposure temperatures [8].

Addition of uniformly distributed small and unified spaced fiber to concrete would act as crack arrester and can improve strength and other mechanical properties of concrete [9]. Usually plastic shrinkage and drying shrinkage cracking of concrete can be controlled by using fiber. Fibers have anti-cracking, reinforcing, and toughening effects on concrete [10].

The anti-cracking action provides the ability of blocking and lessens the formation and propagation of shrinkage cracks in the concrete. The improvement of the mechanical properties by decreasing the adverse effect of the defects inside the concrete can be narrated as the reinforcing action. Finally, the toughening action can be described as the ability of fiber to bridge across the cracks inside the concrete, thus improving the toughness of the concrete after cracking.

There are different types of fibers like steel fibers, glass fibers, synthetic fibers and organic fibers. The properties of FRC depend upon number factors such as relative fiber matrix stiffness, volume of fiber, aspect ratio, fiber orientation, workability and compaction of concrete, size of coarse aggregate, mixing and so on. Slabs, architectural panels, precast products, offshore structures, structures in seismic regions, thin and thick repairs, crash barriers, footings, hydraulic structures have been productively constructed by FRC. The addition of steel fiber has considerably influences on the mechanical properties of concrete [11] and significantly enhanced the splitting tensile strength and flexural strength of concrete [7]. Concrete produced from steel fiber (SF) and polypropylene fiber (PPF) shows reduction in workability of fresh concrete [7, 9, 12], however, imparts higher ductility [13].

Recycled aggregate concrete (RAC) refers to the concrete that is composed of recycled aggregate (RA) obtained by crushing waste concrete and replacing natural aggregate partially or fully. Properties of RAC is highly depends on the properties of recycled aggregate (RA). RAC has lower strength and ductility compared to the concrete made using natural aggregate. In general, RAC has compressive strength 10-30 % lower than the natural aggregate concrete (NAC) [14]. Furthermore, it has reduced workability and lesser durability.

Recycled aggregates consist of the original aggregates with attached hydrated cement paste which result in low specific gravity and high porosity in comparison to natural aggregates**.** Due to these shortcomings, RA is applied mostly in low strength concrete; for example, pavement, base and slab, rather than used in structural concrete. Sub-base in road construction, bank protection, noise barriers and embankments, many types of general bulk fills and fill materials for drainage structures are the most applied fields where RCA is used frequently.

Higher porosity and water absorption of RA compared to that of NA are the main causes for inferior mechanical properties of RAC compared to those of NAC. The present study is exploring the options of strengthening the plain RAC with viable aids. Limitations in the mechanical behavior of RAC can be overcome by incorporating fiber with RAC [15].The addition of fiber controls micro cracks due to shrinkage and provide positive effects on cracking and increased splitting tensile strength of RAC.Experimental tests results claim that recycled concrete aggregate with fiber can be utilized in structural concrete [16].When steel fiber is added to RAC, compressive behavior and toughness shows similar behavior to the fiber-reinforced natural aggregate concrete [6]. However, steel fibers are costly and not locally available which made it unpopular in Bangladesh. Galvanized iron (GI) fiber is locally available as straight fiber with relatively lower cost compare to the steel fiber. On that matter, fibers from GI fiber can produce a low usable replacement of steel fiber to produce fiber reinforced concrete.

1.2 Objectives of the Study

The main objective of this study is to understand the behaviour of concrete produced from recycled coarse aggregate and to study the efficacy of addition of galvanized iron fiber (GI fiber) and polypropylene (PP) fiber to normal and recycled aggregate concrete (RAC) in terms of mechanical properties. This main objective will be achieved through the following specific objectives:

- Evaluate the performance of concrete with a combination of GI fiber and PP fiber for both NAC and RAC.
- Study the effect of diameter and length of GI wire fiber on the physical and mechanical properties of both NAC and RAC.

1.3 Scope of the Study

To achieve the objectives, the scope of this research includes:

- To evaluate the performances of normal aggregate concrete (NAC) with various fiber types (galvanized Iron (GI) and polypropylene (PP)) and percentages of fibers.
- To study the effects of GI fiber diameter on physical properties of normal aggregate concrete.
- To assess the effect of GI fiber length on the physical mechanical properties of normal aggregate concrete (NAC) and recycled aggregate concrete (RAC).

1.4 Organization of the Thesis

The study of above objectives is presented in the several chapters of this paper. A diminutive description of each chapter is as follows:

Chapter 1 presents the background of the research, describes the properties of the material used and highlights the objective and scopes of the work.

Chapter 2 presents a comprehensive literature review on RAC, NAC and RAC made with PP fiber and locally available GI wire fiber. This chapter also provides an elaborate overview of work done so far on comparative analysis of NAC and RAC as well as concrete mixed with GI fiber.

Chapter 3 discusses about the physical properties of the materials used for this study, mix design and methodology of the different test programs.

Chapter 4 discusses the experimental results of the test in tabular and graphical forms and discussion and comparison on the results obtained from different experiments.

Chapter 5 provides the summary of test results with limitations, potential contribution, and recommendation for the future study.

CHAPTER-2: LITERATURE REVIEW

2.1 Introduction

Concrete is the most popular construction material among civil engineers around the world for decades. It is chosen for its better performance, extended life and lower maintenance cost during its life time. Concrete is very well known for its higher compressive strength. On the other hand, fiber reinforced concrete (FRC) is a new structural material which is gaining popularity among other construction material due to its improving engineering properties of concrete. Engineers have found FRC to be very useful to overcome some flaws of concrete.

With rapid urbanization every year old and smaller structures are being demolished and newer and modern ones are being constructed. Most of these demolished materials are being landfilled and are not reused for any purpose. For this reason, these lands are remaining unused and become unfertile. Considering the sustainability issue that impacting the construction industry and environment at the same time, scientist and engineers throughout the world are searching for sustainable and reusable construction materials. One such material is recycled aggregate (RA). Concrete with RA, also known as the recycled aggregate concrete (RAC), has lower mechanical and durability properties compared to the natural aggregate concrete. In order to improve its properties, many researchers have considered adding fiber as a suitable solution. Using recycled aggregate will not only reduce the demand on natural aggregate and the cost of landfill, but also take the world one step ahead to sustainability.

This chapter presents a detailed discussion on the existing literature of RAC, specially, on various properties of RAC with fiber, the fresh and hardened properties of NAC and RAC with and without fiber. This chapter also discusses about the available knowledge on the properties of RAC using useful information, and discusses their advantages and disadvantages in an orderly manner.

2.2 Fiber

Fibers are usually used to control plastic shrinkage and drying shrinkage cracking of concrete. They lower the permeability of concrete and impart abrasion resistance. Fibers have gained importance in construction industries as it provides some extra benefits and increase structural integrity of concrete. However, some fibers reduce the strength of concrete. There are different type of fibers used in construction, such as steel fiber, synthetic fiber (Polypropylene fiber, nylon fiber carbon fiber, asbestos fiber), Glass fiber and natural fiber (Grass, Coconut coir, flax, jute, sugarcane, wood ,bamboo).In this study GI fiber in replacement of steel fiber and Polypropylene fiber are the main matters to discuss.

2.2.1 Steel Fiber

Steel fiber (SF) is one of the most commonly used fibers due to its higher addition and lower price, followed by synthetic and other fibers. Use of steel fiber significantly improved in flexural, impact, fatigue strength and ductility of concrete. The core difference between steel fiber and other reinforcement solutions is that instead of providing strength in distinct locations, it became a part of concrete matrix turning concrete into a composite material. Steel fiber forms a reinforcing network throughout the entire concrete structure which makes concrete a ductile material from a brittle material.

Different type of steel fiber of various shape is available in market. According to ASTM A820[17] specification steel fiber can be of following five general category based on the product or process used as a source of the fiber material. Type I-Cold drawn Wire, Type II-Cut sheet, Type III- Melt extracted, Type IV-Mill cut and Type V-Modified cold-drawn wire. Fibers can be straight or deformed. Difference type of steel fibers are shown in Figure 2-1.

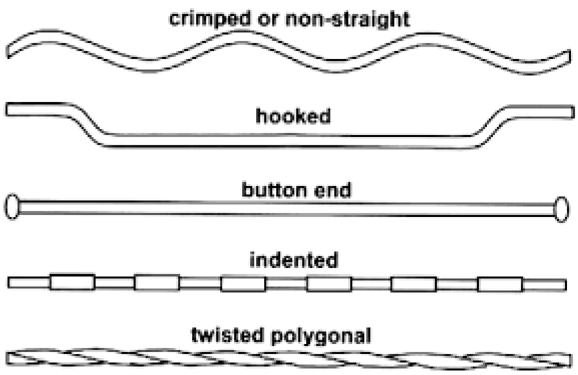


Figure 2-1: Different type of steel fibers [18]

2.2.2 Polypropylene (PP) Fiber

Polypropylene (PP) fiber is a synthetic fiber which is transformed from 85% propylene. The monomer of polypropylene is propylene. Polypropylene fiber is generally superior to other synthetic fiber in elasticity and resiliency. It has good heat insulation properties and is highly resistance to acids, alkalies and organic solvents. It is a light fiber and its density is the lowest of all synthetic fibers. It does not absorb moisture. Furthermore, PP fibers are found to be suitable for imparting strength. It has very high tensile strength but has low modulus of elasticity. The thermal conductivity of PP fiber is lower than that of other fibers. This fiber has been used in concrete to improve its certain properties like flexural tensile strength and flexural strength from early ages.

2.2.3 Galvanized Iron (GI) Fiber

Galvanised iron wire (GI wire) is zinc coated wire of iron where zinc actas a protective layer against corrosion in the form of rusting. It is locally available straight wire without any end hook unlike SF. However, it is cheaper and readily available as compared to SF.

2.3 Fiber Reinforced Concrete

Fiber reinforced concrete (FRC) possesses some advantages such as minimize cracking, improve ductility, and improve impact and abrasion resistance. Increase energy absorption, improve freeze and thaw resistance and enhance the residual strength of the composite. All these advantages that are possessed by fiber are caused by the energy that produced by the reinforced mechanism created by fiber in concrete matrix. After crack started, fiber banish some energy during fiber pull out process. Fiber geometry, fiber inclination, fiber embedment length and concrete properties are the factors that affect the peak pullout force and the energy banished during this pullout process [19].

2.3.1 Steel Fiber Reinforced Concrete

Steel fiber reinforced concrete (SFRC) is made of hydraulic cements containing fine and coarse aggregate and discontinuous discrete steel fibers. Normal concrete is weak in tension and shows brittle behavior. In tension, SFRC fails only after the steel fiber breaks or is pulled out of the cement matrix shows a typical fractured surface of SFRC. It allows high level of stress redistribution, providing a significant deformation capacity of a structure between crack initiation and its failure, which increases the structural safety [19]. However, SFRC properties highly depend on the fiber type. Steel fibers can be hooked, crimped, twisted, flattened and so many. Fibers can be straight or deformed. Figure 2-2 shows different type and size of steel fiber. Steel fiber generally possesses high strength and modulus of elasticity. Steel fibers with surface roughness help to increase mechanical bond with cement matrix. Also, mechanical properties of steel fiber are not influenced by long term loading. The average tensile strength of each fiber shall not be less than 50 000 psi or 345 MPa [17]. According to ACI 544.1R, Steel fiber should have aspect ratio (ratio of length to diameter) from about 20 to 100 and length dimension ranges from 6.4 to 76 mm [20]. Its properties are dependent on aspect ratio of fiber. SFRC is a concrete with increased strain capacity, impact resistance energy absorption, and tensile strength. However, these increments depend on the quantity and type of fibers used. the properties will not increase at the same rate as fibers are added [21].

Steel fibers affect the fresh properties of FRC. The workability of SFRC may decrease by 1 to 4 inch upon fiber addition [20]. High aspect ratio of steel fiber may cause fiber balling, which also depend on gradation of aggregate, fiber volume, shape and method of adding fiber to concrete. Fiber content inversely effects the workability of concrete [22]. Gueriniet. et. al [23] studied and found that steel fiber effects workability negatively than the polypropylene fiber . There are very few studies on the air content of FRC. Steel fiber content slightly increases the air content of SFRC [23]. Uygunoglu [22] found that The unit weight of SFRC decreases with the increase of fiber content and length as high fiber content and long fiber hamper the fiber distribution and increase air content in concrete mix.

In SFRC, SF improve ductility under all modes of loading but the effectiveness of enhancing compression, tension, shear, flexure behavior may vary. Fiber content is an important factor in strength gaining of concrete. In a research article Zheng et.al [24] found that compressive strength, split tensile strength and flexural strength of SFRC increased with the fiber content, while fiber content is less than 1% the strength increase rate is faster. But Balendran et al. [25] reported that owing to 1% fiber content by volume, the density and compressive strength of SFRC were not much affected by steel fiber.

However, Cylinder splitting tensile strength and modulus of rupture were increased. Furthermore, SFRC provides substantially greater flexural strength than tensile or compression strength due to the ductile behavior of SFRC.

Based on the outstanding cracking resistance of SFRC in structure construction, many attempts have been made to study the fracture behavior of SFRC. A basic parameter for measuring the fracture behavior of cementitious materials is the fracture energy. A reasonable addition of steel fiber improved the fracture toughness of SFRC, while the fracture energy of SFRC developed with curing age [26]. A study had been conducted on Stress-strain curves for SFRC under compression and the results indicate that Fiber addition increases the strain corresponding to the peak stress [27].

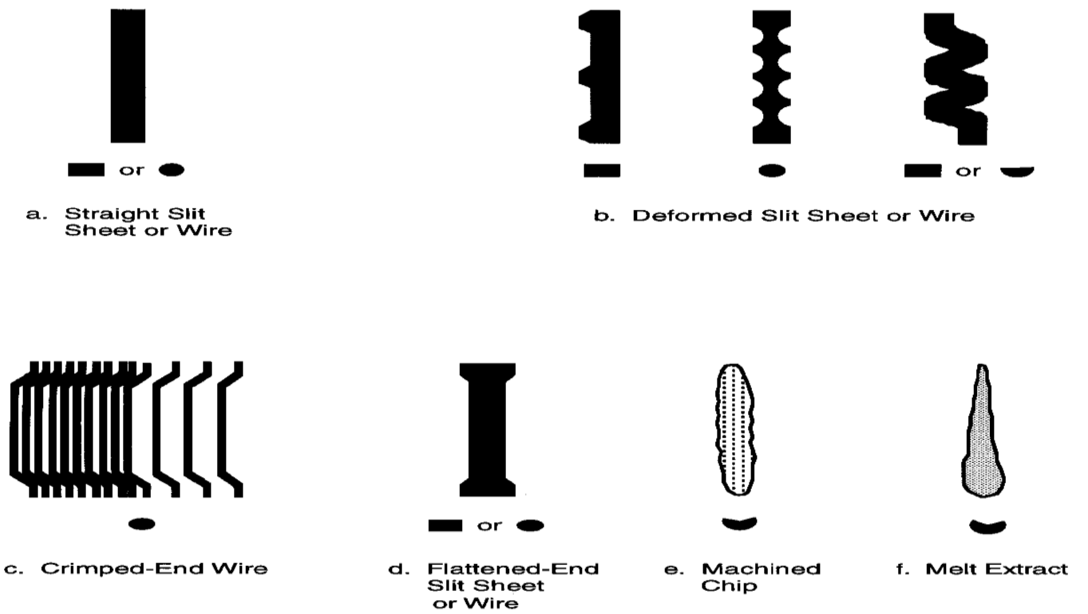


Figure 2-2: Different Type & Shapes of Steel Fibers [20]

The strain range and the capability of elastic deformation SFRC is found to be augmented in the pre-failure zone. However, the slope of the descending part of the stress- strain curved extends with increasing fiber content and increasing aspect ratio [27]. Figure 2-3 supports the statement.

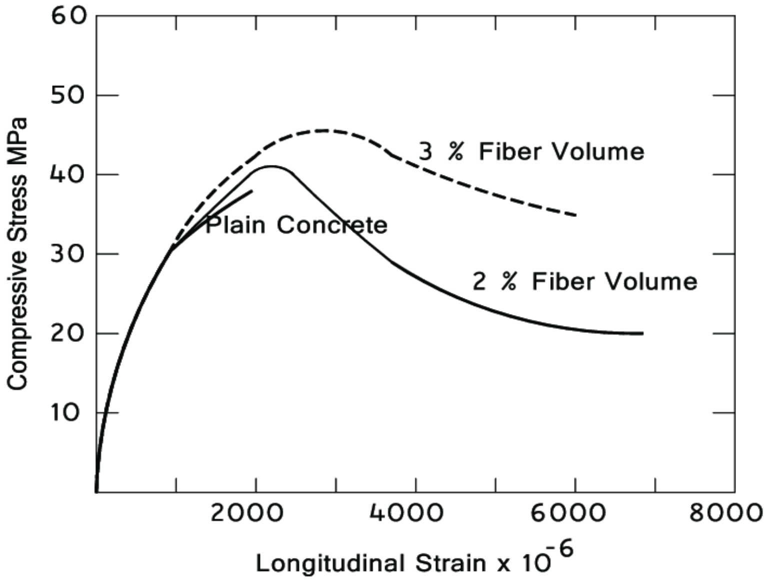
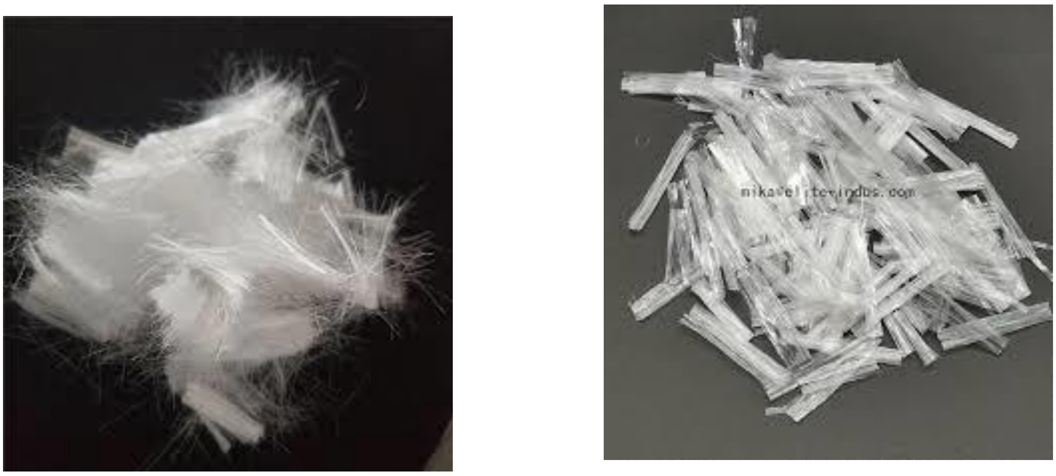


Figure 2-3 : Stress strain curve in compression of SFRC [28]

Toughness is the measure of the area under the stress-strain curve of concrete. The toughness concrete is considerably increased by adding of crimped steel fibers to concrete. Considering drying shrinkage measurements, the presence of a large amount of metallic fibers is capable of not only to drop the initial expansion, but also to reduce the final shrinkage by 35 % [29]. The flexural behavior of fibrous beams was superior to that of beams without fiber because of the crack bridging action of fibers.

2.3.2 PP Fiber Reinforced Concrete

Among the polymer fibers, polypropylene (PP) has achieved great attention among researchers because of its low cost compared to other synthetic fiber. It has low moisture absorption, chemical resistance to acids and alkalis, high abrasion resistance, formidable toughness and enhanced shrinkage cracking resistance in concrete. Polypropylene fibers are produced by pulling wire procedure with circular cross section or by releasing the plastic film by rectangular cross section. PP fiber can be seen either as fibrillated bundles, mono filament or micro filaments as shown in Figure 2-4. Plastic films are expanded to form fibrillated PP fiber, which are later separated into strips and then slit.



(a) (b)

Figure 2-4: PP fiber (a) monofilament fiber (b) Fibrillated fiber[1]

Fibrillated strands are separated during mechanical mixing into mini strands. In this study Mono filament PP fiber is used. Monofilament PP fiber dispersed in concrete during mixing.

PP fiber reduces the workability of fleshly mixed concrete as PP fiber has large surface area [30] and also reduces the rate of bleeding and segregation compared to normal concrete as fiber put all the element of concrete together and deem the chance of settlement of aggregate [31]. But Ramakrishnan et al.[32] reported that PP fiber enhances the bleeding and segregation of concrete with high volume of PP content. Workability was affected negatively by PP fiber. They also noted that concrete with high PP fiber content had higher air content.

PP fibers are mainly used to improve toughness and ductility rather to improve strength of concrete. Some studies found PP fiber reduces the Compressive strength of concrete [32, 33]. Alhozaimy et al. [34] studied the effect of PP fiber on the compressive and flexural strength, toughness and impact resistance of concrete on the basis of volume fraction of PP fiber content. They found that PP fiber does not affect the compressive strength and flexural strength but improve toughness, first crack and impact resistance of concrete. Effectiveness PP fiber reduce the crack area, maximum crack width and the number of cracks. Flexural strength increment is a function of volume fraction and aspect ratio of fiber. 0.1% volume content of pp fiber reduces the extent of cracking by a factor of 5-10. The extent of crack reduction is proportional to the fiber content in the concrete [31].

PP fibers reduce the plastic shrinkage crack area due to their flexibility and ability to keep in its form. Sohaib et al.[35] studied the use PP fiber in concrete to achieve maximum strength. It was concluded that the significant improvement was observed in ultimate compressive strength after 7 and 28 days. The optimum percentage of PP fiber was obtained to be 1.5 percent of cement by volume. So, the addition of small amount of PP fiber improved the mechanical properties of concrete. PP fiber has potential to increase toughness in both single and hybrid form. For PP hybrid fiber reinforced concrete absorbed more destructive energy with augmented fiber content. Hybrid fiber performed better than the single fiber [36]. Mazaheripour et al. [37] studied effect of polypropylene fibers on the properties of fresh and hardened lightweight self-compacting concrete and found that the adding PP fiber to Light weight self-compacting concrete affects the slump value and reduces it up to 40 %. They also found that PP fiber did not influence compressive strength but increased the tension and flexural strength. Another study demonstrated that PP fiber caused delay the starting of degradation process by reducing permeability, reducing the amount of shrinkage and expansion of concrete that can significantly affect the life span of structures. Microscopic image was also taken to inspect the fiber effects on the cracking and strength of concrete that showed the fibers are located in the width of formed crack and creating the connecting bridge [38].

2.3.3 GI Fiber Reinforced Concrete

Galvanized Iron (GI) fiber is produced by cutting large straight GI wire in preferable size. Galvanization is a process of coating steel sheet or steel or iron to form a protective layer against corrosion. GI fiber is not a widely used fiber in concrete industry. Its application is still is under research. Concrete reinforced with Galvanized Iron fiber is known as GI fiber reinforced concrete (GFRC). GI wire usually found in straight and round shape and also it varies in diameter.

Figure 2-5: GI Wire

There are not many literatures available on GI fiber reinforced concrete. Galvanized iron (GI) wire fiber is a locally available low-cost fiber which can be alternative option for relatively expensive steel fiber and considered to behave like steel fiber [39]. Conventional steel fibers are not available in local markets in Bangladesh; therefore, GI fibers are reported the effectiveness of GI wire fibers to enhance the overall performance of concrete. Following the specification of steel fiber, tests were conducted for 0.50 mm, 0.70 mm and 1.00 mm diameter of GI wire. Considering the highest tensile strength of 1870 MPa, 0.70 mm GI wire was selected for successive experiments [40]. Another case study was conducted and the experimental results showed that GI wire fiber can be used as suitable substitute for steel fiber in FRC considering fiber specifications and requirements. GFRC significantly improve certain mechanical properties such as compressive strength, flexural behavior, toughness etc compared to normal concrete. Even Load-deflection behavior and ductility of GFRC was also found to be similar to SFRC [41]. Micro concrete was also produced with GI fiber to evaluate its properties. Adding GI fiber also reduced slump as steel fiber. However, 28 days compressive and split tensile strength were increased with fiber content. This study also revealed that GI fiber reduces the initial absorption rate but in long term increases secondary absorption rate [39]. Savita et al [42] also used GI wires used as a fiber with aspect ratio 50 and found that at 0.2 % fiber content compressive, split tensile and flexural strength was maximum compared to control concrete.

2.4 Fiber Reinforced Recycled Aggregate Concrete

Concrete with aggregate from recycled materials, which eventually able to save natural aggregate, is considered to have lower mechanical properties than the normal concrete. Fresh and the hardened properties of concrete made with recycled concrete aggregate are affected by these characteristics of the aggregate. Concrete with recycled aggregate obeys very restrictive material properties and its applications are also restricted. It is expected that concrete mixes produced with recycled aggregates present lower mechanical performance than the mixes produced with natural aggregates. On the other hand, the idea of adding fibers to that concrete mix with recycled aggregate may change the material properties of such concrete, improve its behavior and bring about new type of applications. The fiber reinforced concrete made with recycled concrete aggregate are found to apply in a large scale of structures, starting from underground structures to selected elements of civil engineering complexes. Several researches have been conducted on the combination of different fiber with RAC to evaluate different behavior of RAC [6, 43-53] and inclusion of fiber has positive effects on RAC properties.

2.4.1 Steel Fiber Reinforced Recycled Aggregate Concrete

Steel Fiber Reinforced Recycled Aggregate Concrete (SFRRAC) is the concrete made with Recycled Aggregate (RA) contain steel fiber. RCA has lower properties than normal aggregate. Recycled Aggregate (RA) has adhered mortar attached to it. This attached mortar has been considered the viral reason for RA to be weaker than the NA[54]. The mechanical properties of Recycled Aggregate Concrete (RAC) are highly affected by the properties of RA. To minimize the shortcoming steel fiber can be added and the addition of SF significantly reduced the adverse effects caused by the inclusions of RCA in the mixes.

RA reduces the workability of concrete due to its high water absorption and rough surface texture [55]. Another study [56] found RAC has acceptable workability and air content. On the other hand, the addition of SF decreases the water absorption compared to plain concrete counterparts with RCA, 1, 2 and 3% of steel fiber content caused reductions in water absorption by 6, 16 and 22%, respectively. Inclusion of SF attributed to densify the concrete [57].

As it is known RAC has decreased compressive strength than the conventional concrete whereas addition of steel fibers in the RAC slightly increased the compressive strength of the concrete by 10% at 1% of steel fibers content. Split tensile strength also found to be increased than conventional concrete. However RAC with steel fiber had better load deflection behavior [58]. A study [53] has been conducted on flexural and shear behavior of RAC beam. Steel fibers increases the mechanical properties of concrete by (2.25%, 19%, 17.5% and 8.75%) for compressive strength, tensile strength, flexural strength and elastic modulus respectively than the non-fibrous concrete. Bhikshma and Manipal [44] investigated the mechanical properties of recycled aggregate concrete containing steel fibers of two different aspect ratios 40 and 60. Fiber content was 0.0, 0.5, 1.0 and 1.5%. From experimental results it was found that compressive, split tensile, flexural strength and modulus of elasticity were better for RAC with fiber and proportional to the fiber content

As the steel fibers are the better fibers, so they can resist the crack failure a lot more than the other fibers. Steel fiber also increased ultimate moment, deflection of RAC beam the first crack loads and ultimate loads come faster in RAC than NAC. But Steel fiber in concrete delayed the first crack and ultimate load and made concrete more ductile than concrete without fiber [53]. Flexural strength of RAC is higher with steel fiber than RAC without fiber. Carneiro et al. (2014) [6] studied Compressive stress–strain behavior of steel fiber reinforced-recycled aggregate concrete and concluded that the mechanical properties of concrete with steel fiber and recycled aggregate increased and Steel fiber controlled its fracture process in a better manner. The stress–strain curve of the RAC revealed that the fiber addition controls the post-crack regime and toughness was increased which has similar pattern to that of fiber-reinforced natural aggregate concrete.

Chan et al (2019) [45] evaluate the feasibility of using FRRAC in pavements design, in which the fiber volume and CO_2 emissions were evaluated for different slab thicknesses and from the experiment results it can be feasible to use FRRAC to produce more sustainable rigid pavements. Steel fibers also helps to improve the ductility and the cracking behavior of recycled aggregate concrete (RAC) significantly after exposure to high temperatures that allows RAC to come one step forward towards the application of RAC in building construction [46]. The use of RA is limited to non-structural applications such as tunnel lining and slab on ground. Senaratne concluded how the addition of SF can improve the strength of RAC to use in structural applications[59].

2.4.2 PP Fiber Reinforced Recycled Aggregate Concrete

Use of polypropylene fiber in the field of RAC is gaining popularity nowadays. Inclusion of short discrete PP fiber at different proportions can improve the mechanical strength of RAC. As attached mortar of the RA is porous, the workability of RAC is much lower than NAC. But with the increase in fiber content in concrete, the workability decreases. This is may be due to the frictional resistance between ingredients of concrete and PP fiber [52].

From a study[49] it was found that with PP at the 0.6% fibers content, compressive strength was maximum for RAC specimens . The results also showed that the water absorption and porosity characteristic of RAC are significantly reduced with the introduction of PP fiber. If PP fiber content is greater than 0.5%, there was a decrease in the flexural strength. Inclusion of PP fiber in further quantity increases the void content in concrete matrix. These voids are responsible for reduction in flexural strength values [52].Another study also supports the optimum PP fiber content should be 0.5 % [60]. From another study[43] it was found that PP fiber does not affect the compressive strength significantly. At the same time both flexural tensile strength and splitting tensile strength increase with PP fiber addition and recommended fiber content as 1 %. From practical test results, from the perspective of static reliability, PP fiber reinforced RAC can be used to construct some load-bearing constructions for buildings [50].Hanumesh, Harish and Ramana[47] concluded that the compressive strength, split tensile and shear strengths of RAC increase with the increment of PP fiber content and with 1% of PP fiber volume, the strengths increment were 15.68%, 34.84% and 38.32% respectively compared to reference mixes. The increment in strength may be due to presence of PP fibers in the interfacial transition zone. The PP fiber rough surface produces good bond in the matrix of the mix. During application of load, fibers may transfer the stress in the matrix and also PP fibers make better bond with the concrete, so that it may not debond easily and also it takes more energy to failure.

2.4.3 GI Fiber Reinforced Recycled Aggregate Concrete

Concrete reinforced with Galvanized Iron (GI) fiber with recycled aggregate is known as GI fiber reinforced recycled aggregate concrete. There is a lack of information regarding the mechanical behavior of GI fiber reinforced recycled aggregate concrete. According to Author's knowledge only one literature is available for this. Islam (2014)[61]pursued his MSc thesis on Behaviour of GI fiber reinforced concrete made with natural and recycled brick aggregates. He used manually made hooked end G.I wires of length50 mm and aspect ratio of 55.6 are used as fiber reinforcement in a volume fraction of 0.50% and 1.00%, respectively for the both Normal and Recycled brick aggregate concrete. The experimental results showed that around 10% to 15% and 40% to 60% increase in 28 days compressive strength and tensile strength of GI fiber reinforced concrete, respectively compared to control specimen (0% G.I. fiber replacement). On the other hand, concrete strain at failure of G.I. fiber reinforced concrete had increased almost 2 times compared to the control specimen. It was also observed that effect of fiber reinforced concrete made with 1% fiber is more than 0.5% fiber for the both cases of aggregates in the terms of maximum strain of concrete. He worked on recycled brick aggregate. But this thesis work is intended to work on recycled stone aggregate with GI wire.

2.5 Conclusions

Based on the literature review following findings can be summarized: Fiber is a small piece of reinforcing material that can improve the static and dynamic properties of concrete. Steel fiber (SF) with higher elastic modulus imparts strength and stiffness to the concrete but the effectiveness of enhancing compression, tension, shear, flexure behavior may vary. It also improves ductility under all modes of loading. Polypropylene (PP) fiber with lower elastic modulus helps to absorb large amount of energy thus impart greater degree of toughness and resistance against impact. However, both SF and PP are costly and not produced locally rendering them unpopular among construction industries in Bangladesh.The type of aggregates used to produce the concrete has significant effect in the mechanical properties of the concrete.The addition of fiber controls micro cracks due to shrinkage and provide positive effects on cracking and increased splitting tensile strength of RAC. Fiber content and aspect ratio of fiber are important factors for fiber reinforced concrete (FRC). The fiber content does not significantly influence the compressive strength, but higher fiber content tends to increase the modulus of elasticity and flexural strength for FRC and FRRAC. High fiber content or fibers which are too long tend to "ball" in the mix and create workability problems.

CHAPTER 3: MATERIAL AND METHODOLOGY

3.1 General

Researchers always try to introduce new materials to improve concrete quality. Inclusion of fiber is one of them. Fiber reinforced concrete (FRC) is not a new concept in construction industries. In the 1950s, the concept of composite materials came into being and fiber reinforced concrete was one of the topics of interest. By the 1960s, steel, glass and synthetic (such as polypropylene) fibers were used in concrete.

Choosing proper materials for concrete composition is the preliminary job to get required concrete. This chapter gives a detailed description of the materials used in this research. Physical and mechanical properties various materials were calculated and reported. Based on the material properties, concrete mix design was performed. Furthermore, the specimen preparation, curing, testing procedures, test setups are also discussed in this chapter. Therefore, this chapter focuses on the material selection and the methodology of the whole study.

3.2 Materials for Concrete

3.2.1 Cement

Cement is the binding material in concrete and an important component of concrete. There are several kinds of cement. This study is all about the evaluation of general mechanical properties of FRC. Therefore, for this study, ASTM Type I Ordinary Portland Cement (OPC) has been chosen as the binding material following the specification of ASTM C150 [62]. Cement was collected from the local manufacturer. Physical and mechanical properties of cement was performed in the laboratory and the results are illustrated in Table 3-1.

3.2.2 Aggregate

Aggregates are inert granular materials such as sand, gravel, or crushed stone that along with water and Portland cement are an essential ingredient in concrete. Aggregates comprise as much as 60% to 80% of a typical concrete mix, so they must be properly selected to have a durable concrete. For a good concrete mix, aggregates need to be clean, hard, strong particles free of absorbed chemicals or coatings of clay and other fine materials that could cause the deterioration of concrete. In general, there are two types of aggregate, such as coarse and fine.

Table 3-1: Material Properties of OPC.

Properties	Specific Gravity	Normal Consistency	Initial Setting Time	Final Setting Time	Fineness	Soundness
Standard	ASTM C 188-14) [63]	ASTM C 187-11) [64]	ASTM C 191-13) [65]	ASTM C 191-13) [65]	ASTM C430-08) [66]	(ASTM C-151) [67]
Values	3.12	29%	115 mins	275 mins	330 m^2/kg	2.5mm

3.2.3 Properties of Coarse Aggregate

Concrete strength properties are dependent on coarse aggregate properties, especially at higher strength. In this study two type of coarse aggregate were used. Crushed stone as natural aggregate and recycled coarse aggregate. Properties of these both type of aggregate are described below. Coarse aggregates were tested extensively before incorporating in the concrete. Tests include specific gravity and absorption capacity, unit weight, sieve analysis have been conducted at the laboratory according to ASTM C127[68], ASTM C29 [69] and ASTM C 136 [70], respectively. Fresh and hardened properties of concrete can be affected by the gradation of aggregate. Improper gradation can affect the air content, slump, and result in excessive voids in the hardened concrete.

3.2.3.1 Crushed Stone

For this present study, crushed stone chips were collected from Pakur, India as shown in Figure 3-1. Sieve analysis of coarse aggregate is plotted in

Figure 3-2 along with ASTM upper and lower limits. Maximum size of coarse aggregate was 19.5 mm and minimum size was 2.36 mm. From the figure it can be seen that the coarse aggregate gradation is closer to the ASMT lower limit. Major properties of crushed stone chips, recycled aggregate and sand are shown in Table 3-2.

Figure 3-1: Crushed stone chips

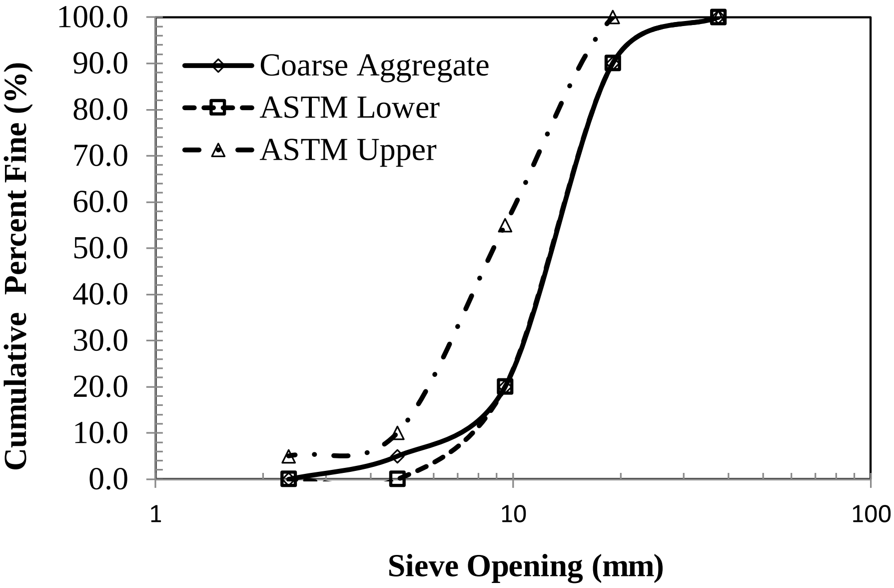


Figure 3-2: Gradation of coarse aggregate.

Table 3-2 : Properties of Aggregate

Variables	**Unit**	**Crushed Stone**	**Recycled Aggregate**	**Sand**
Loose Unit Weight	Kg/m³	1492	1317	1656
Rodded Unit Weight	Kg/m³	1550	1429	1757
Oven Dry bulk Sp. Gravity		2.84	2.59	2.58
SSD bulk Sp. Gravity		2.86	2.76	2.61
Apparent Sp. Gravity		2.90	3.11	2.66
Absorption	%	0.70	6.38	1.2
Fineness Modulus		6.85	6.58	2.71

3.2.3.2 Recycled Coarse Aggregate

In this study, recycled coarse aggregates were also used as an alternative to natural crushed stone aggregate. To produce recycled aggregates, cylindrical samples from lab have been collected which are already tested in different time under Centre For Advisory and Testing Services (CATS-MIST). The cylindrical samples were from different sources and also the casting age were varied between 1 -2 years. Most of these tested samples are dumped and landfilled. In this study Construction and Demolition (C&D) were of primary concern for recycled aggregate. But the amount of recycled aggregate required for the whole test program could not be collected from demolition site. Due to this limitations lab waste cylindrical samples were collected to produce recycled aggregate

These cylindrical samples were collected and crushed by using a jaw crusher. Aggregates were coated with mortar and fine dust. Therefore, crushed aggregates were first washed, cleaned and then sieved using a mechanical sieve shaker. Aggregate particles passing through 2.36 mm opening sieve was discarded. Figure 3-3 shows recycled concrete aggregate.

Recycled coarse aggregates are tested extensively before incorporating in the concrete. Tests, such as specific gravity and absorption capacity, unit weight, sieve analysis, have been conducted at the laboratory according to ASTM C127 [68], ASTM C29 [69] and ASTM C 136 [70], respectively. Fresh and hardened properties of concrete can be affected by the gradation of aggregate. Improper gradation can affect the air content, slump, and result in excessive voids in the hardened concrete. Gradation of aggregate also has significant effect on mechanical properties of concrete. Therefore, to eliminate the gradation effect on coarse aggregate gradation same gradation was used for both crushed stone and recycled aggregate. Sieve analysis of coarse aggregate is plotted in

Figure 3-2 along with ASTM upper and lower limits. Physical properties of recycled coarse aggregate are shown Table 3-2. Recycled aggregate has lower unit weight and specific gravity but higher water absorption than crushed stone. As recycled aggregate has some mortar attached to it which makes it more porous.

Figure 3-3: Recycled Concrete Aggregate

3.2.4 Properties of Fine Aggregate

The purpose of the fine aggregate is to fill the voids in the coarse aggregate to prevent honeycomb in the concrete matrix. Fine aggregate used in this study has been collected from Sylhet district of Bangladesh. Basic properties of the aggregate were tested before using it in the experimental process. Tests include specific gravity and absorption capacity, unit weight, sieve analysis and these tests have been conducted at the laboratory according to ASTM C127 [68], ASTM C29 [69] and ASTM C 136 [70], respectively. Aggregate gradation of fine aggregate is plotted in Figure 3-5 along with ASTM upper and lower limits. Major properties of sand are shown in Table 3-2.

3.2.5 Fibers

Two types of fibers, GI fiber and PP fiber were adopted in this study to assess the effectiveness of fibers to improve the short and long-term mechanical properties of natural aggregate concrete (NAC) and recycled aggregate concrete (RAC).

3.2.5.1 GI Fiber

According to the limited previous study, GI fiber has the potential to be used as fiber in concrete. GI wire which is mainly a low-cost mild steel wire with a thin coating of zinc, available in local market in different diameters. From a recent study it has been uncovered that GI wire has the potential to be used as a replacement of commercially available steel fibers which are costly [40].GI wire of different diameters were collected from local market and tested for tensile strength, elongation and Young’s modulus following ASTM A 679 [71]. The material properties of GI fibers of different diameter used in the experiment are shown in Table 3-3.

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Figure 3-4: GI fiber of 0.51 mm diameter

Figure 3-6 shows the stress strain curve for GI wire of different diameter.GI fiber of diameter 0.51mm has a greater difference between its yield strength and ultimate strength than other samples of diameter 0.7mm and 1.21mm. Also, the elongation percentage at break point of GI fibers of diameter 0.51mm makes it more ductile

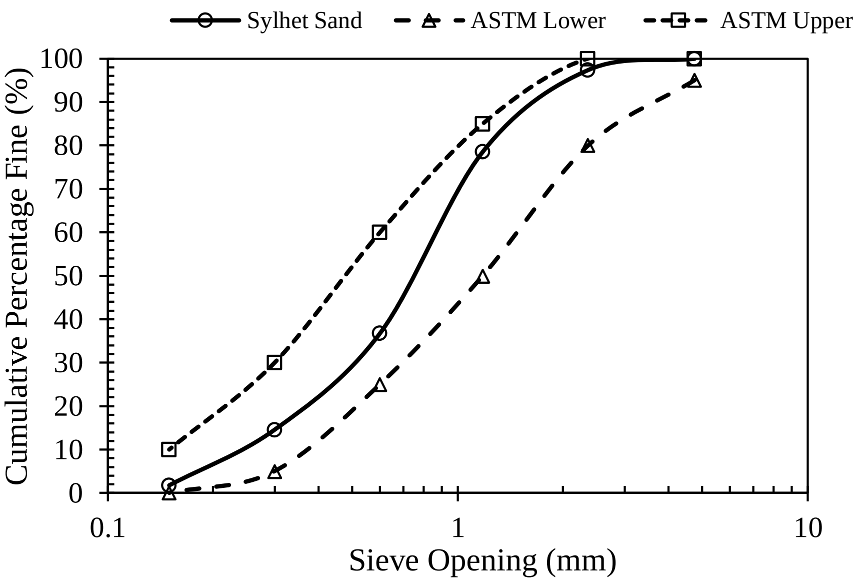


Figure 3-5: Gradation curve of sand.

Table 3-3 : Properties of GI wire of different diameter

Diameter (mm)	f_y (MPa)	f_u(MPa)	Elongation (%)	Average			
				f_y(MPa)	f_u(MPa)	Elongation (%)	Young Modulus (GPa)
0.51	210	320	12.6	223	365	18.0	17.5
	190	350	22.7				
	270	425	18.6				
0.7	211	284	6.3	210	308	15.7	15.8
	203	324	19.8				
	216	316	21.1				
1.21	326	374	14.0	279	372	16.4	17.8
	292	372	17.5				
	218	370	17.6				

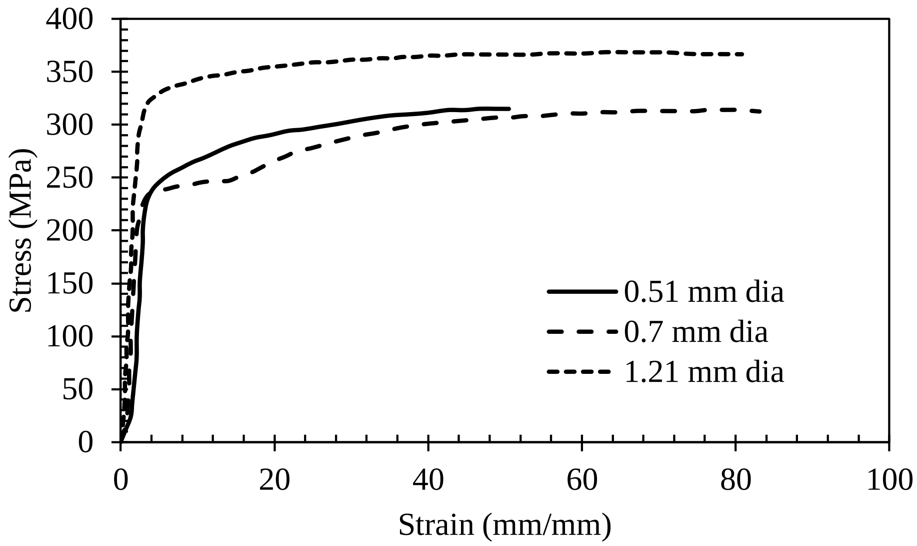


Figure 3-6: Stress-strain curve of different diameter GI wire fiber.

3.2.5.2 PP Fiber

Polypropylene (PP) fiber is one of the most commonly used fibers in concrete. It is relatively cheaper than the steel fiber (SF), has also gained very popularity in the field of FRC. The PP fiber used in this study was obtained from a Japanese supplier. Basic properties of PP fiber provided by supplier are shown in Table 3-4. Figure 3-7 shows the PP fiber used in this study.

Figure 3-7: Polypropylene fiber

Table 3-4: Properties of PP fiber

Basic properties	Specific Gravity (gm/cm^3)	Fiber Diameter (μm)	Fiber Length (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)
Values	0.91	25-30	12	480	7.0

3.2.6 Admixture

In order to improve the workability of concrete at lower water-cement ratio, a high-performance super plasticizer FosrocAuramixV200 was used as admixture. Fosroc Auramix V200 is designed to meet the contradictory requirements of contemporary concrete where high fluidity, retention for longer periods of time in backdrop of varying concreting materials properties and lack of binder content. Fosroc Auramix V200 keeps concrete mixes fluid, uniformed and placing friendly in these demanding requirements. It reduces sensitivity to variations in moisture content in aggregates and eliminates segregation and bleeding in mixes. It has no effect on fluidity of mixes either in initial stage of the mix or in retention period and no adverse effect on early or later age strength. It also exhibits better surface finish.

3.3 Methodology

3.3.1 Mix Design

Proportioning of constituent materials of concrete properly is called "Mix Design" which is very important to achieve desired properties of concrete. In this study concrete mix has been selected following ACI 544. 3R [72] which is the guideline of mix design for SFRC. The experimental work of this study has been conducted in two steps-

- Step 1 (Case 1): To determine performances of GI and PP fibers at various percentages NAC.
- Step 2 (Case 2): To determine the effects of different diameter and length of GI fiber on the properties of NAC and RAC and to compare their performance.

For case-1, six series of concrete mixtures were prepared in the laboratory including one reference mixture without any fiber. A constant water cement (w/c) ratio of 0.40 for all mixes was used. Two different percentages (0.50% and 1.0% by volume) fiber were used for both of the GI fiber and PP fiber and one mixture was made by combining both fibers with 0.5 % fiber content each. Diameters for GI fiber was 0.70 mm with aspect ratio 54.43 and diameters for PP fiber was 0.03 mm with aspect ratio 400. Concrete mix proportion was designed based on aggregate with SSD condition. The mix proportion for 1 cum of concrete representing all mix proportions are shown in Table 3-5.

Case-2 has performed in two stages. In the first stage, diameter of the GI fiber was varied; whereas, for the second stage length of the GI fiber was varied. For diameter variation four series of concrete mixtures were prepared in the laboratory including one reference mixture without any fiber. A constant water cement (w/c) ratio of 0.40 for all mixes was used. Fiber content was 0.5 % by volume of concrete. To evaluate the effects of GI fiber diameter three different diameters, such as 0.51, 0.70 and 1.21 mm diameter were collected from the local market for application. Aspect ratio (A/R) of fiber was kept constant at 50 for all three GI fiber diameters. Therefore, the lengths of fiber were 26, 35 and 61 mm, respectively. An admixture was used in the concrete mix in order to improve the workability of the mix and dosage of admixture was constant for all mix, which was 1 kg admixture per 100 kg of cement. Concrete mix proportion was designed based on aggregate with SSD condition.

For the second stage, length of GI fiber was varied. Due to the limitations of the study, only diameter, i.e. 0.51 mm, was used for this stage. Length of the GI fiber was selected based on the A/R. According to ACI 544.1R, steel fiber should have an A/R ranging from 20 to 100. Therefore, neglecting the extreme aspect rations, three aspect ratios were chosen for the current study. Length of the GI fiber selected were 15mm (A/R 30), 25mm (A/R 50) and 36mm (A/R 70) for further analysis of compressive, tensile, and flexural strength of concrete. For this stage, recycled aggregate was also used in the concrete. Three series of concrete mixtures for NAC and five combinations of RAC mixture (one control without any fiber content, three with three different fiber lengths and one with PP fiber content) were prepared in the laboratory. A constant water cement (w/c) ratio of 0.40 for all mixes was used. Fiber content was 0.5 % by volume of concrete.

3.3.2 Sample Preparation

Concrete mixes were mixed in a mixture machine. First cement and aggregate were poured into the machine. After mixing these elements, fibers were mixed with the mixture. After that water was added. Freshly mixed concrete is used for the slump test and air content test. For each concrete batch, 24 cylinders (100 mm diameter and 200 mm height) were prepared for compression and split tensile strength test and 3 beams (500 mm x 100 mm x100 mm) were casted for flexural strength test as shown in Figure 3-8. All concrete specimens were placed in a humid room for 24 hours and then demolded and placed in a curing tank with constant temperature of 23±2ºC for curing. The cylinders/beams were taken out from the curing chamber and dried before testing on the specified dates. Different stages of sample preparation have been shown in Appendix A.

(a) (b)

Figure 3-8: (a) Sample preparation (b) Curing of samples

3.4 Test Procedure

This section describes the experimental test programs adopted in this study to determine the hardened mechanical properties of concrete mixtures. Compression tests and splitting tensile tests were conducted on cylindrical specimens to determine the compressive strength and tensile strength, respectively of the concrete mixtures. The flexural test was conducted on beam specimens to determine the flexural strength of the concrete mixtures.

3.4.1 Compressive Strength Test

The compressive strength of concrete cylinder was determined by using compression testing machine following ASTM C-39 [73]. **Error! Reference source not found.** shows the typical setup of the compressive strength test of concrete cylinder. A loading rate of 0.25 MPa/s were used during the test. The loading rate was maintained constant until the ultimate failure of the specimen was reached. For each combination three samples were tested and later on the average was reported as the compressive strength of the cylinder. To obtain precise stress-strain characteristics under compressive loading, a compressometer with two linear strain conversion transducers (LSCT) were attached to the specimen. Both longitudinal and transverse strain values of the concrete cylinders under compressive loading were logged until the specimen fails.

(a) (b)

Figure 3-9: Compressive strength test set-up

Table 3-5: Proportion of aggregates for concrete mixtures per cubic meter

Designation	w/c ratio	Water (kg)	Cement (kg)	Sand (kg)	Coarse Aggregate (kg)	Admixture (kg)	GI fiber (kg)	PP fiber (kg)
Case 1								
NG_0P_0	0.4	148	370	565	1225	-	0	0
$NG_{0.5}P_0$	0.4	148	370	565	1225	-	39	0
$NG_{1.0}P_0$	0.4	148	370	565	1225	-	77	0
$NG_0P_{0.5}$	0.4	148	370	565	1225	-	0	5
$NG_0P_{1.0}$	0.4	148	370	565	1225	-	0	9
$NG_{0.5}P_{0.5}$	0.4	148	370	565	1225	-	39	5
Case 2								
NG_0P_0 (Control)	0.4	148	370	589	1296	3.7	0	-
$NG_{0.5}$ $D_{0.51}L_{26}$	0.4	148	370	589	1296	3.7	39	-
$NG_{0.5}$ $D_{0.70}$ L_{35}	0.4	148	370	589	1296	3.7	39	-
$NG_{0.5}$ $D_{1.21}$ L_{61}	0.4	148	370	589	1296	3.7	39	-
$NG_{0.5}D_{0.51}L_{15}$	0.4	148	370	589	1296	3.7	39	
$NG_{0.5}D_{0.51}L_{26}$	0.4	148	370	589	1296	3.7	39	
$NG_{0.5}D_{0.51}L_{36}$	0.4	148	370	589	1296	3.7	39	
$NG_0P_{.5}$	0.4	148	370	589	1296	3.7	-	5
RG_0 P_0(Control)	0.4	148	370	589	1251	3.7	-	-
$RG_{0.5}D_{0.51}L_{15}$	0.4	148	370	589	1251	3.7	39	-
$RG_{0.5}D_{0.51}L_{26}$	0.4	148	370	589	1251	3.7	39	-
$RG_{0.5}D_{0.51}L_{36}$	0.4	148	370	589	1251	3.7	39	-
$RG_0P_{0.5}$	0.4	148	370	589	1251	3.7	-	5

Where,

NG_XP_Y:N = Normal aggregate concrete; G_x= GI fiber X%; P_Y= PP fiber Y%

$NG_XD_YL_Z$:N = Normal aggregate concrete; G_X = GI fiber X%; D_Y = GI fiber diameter, Y mm, L_Z = GI fiber Length, Z mm

RG_XP_Y:R = Recycled aggregate concrete; G_x= GI fiber X%; P_Y= PP fiber Y%

$RG_XD_YL_Z$: R = Recycled aggregate concrete; G_X = GI fiber X%; D_Y = GI fiber diameter, Y mm, L_Z = GI fiber Length, Z mm

The control mixture in this study is designated as NG_0P_0, having no GI or PP fiber with water cement ratio of 0.40. Other mixtures are designated likewise based on the percentage GI or PP fiber. For instance, mixture $NG_{0.5}P_{0.5}$ represents the mixture with 0.5% GI fiber 0.5% of PP Fiber and mixture $NG_{0.5}$ $D_{0.51}L_{26}$ represents the mixture with 0.5% GI fiber of diameter 0.51 mm and length 26 mm.

3.4.2 Split Tensile Strength Test

For the splitting tensile test, ASTM C496/C496M [74], standard test method for splitting tensile strength of cylindrical concrete specimen was followed. The loading rate was maintained 0.8 MPa/min. For each combination three samples were tested and their average was reported as the splitting tensile strength of the concrete cylinder. Figure 3-10 shows the typical setup for tensile strength test of concrete cylinder.

The maximum load at failure was recorded and the splitting tensile strength (MPa) was calculated as follows

$$\boldsymbol{T = 2P/\pi DL}$$

Where, P = the maximum load at failure (N), L = Length of the specimen (mm), D = Diameter of the specimen (mm)

Figure 3-10 : Tensile strength test of concrete cylinder

3.4.3 Flexural Strength Test

Flexural strength of the concrete prisms is tested according to ASTM C78[75].The concrete beam specimens were tested using an Universal Testing Machine (UTM) with a capacity of 1000kN. The size of the concrete prism is 100 mm × 100 mm × 500 mm. The beams were subjected to third point loading with the support span of 300mm. The bottom of the beam was placed on the semicircular upper end so that the support can be act as the simply supported beam. The flexural test is performed at a displacement-controlled rate of0.2mm/min. The test set up is shown in the Figure 3-11. The loading is continued until the beam fails. The load and the corresponding deflection were calculated automatically using a data acquisition system.

Figure 3-11: Test set up for quasi-static flexural test

3.4.4 Flexural Parameters

Toughness, flexural toughness factor and equivalent flexural toughness ratio has been calculated according to JSCE-SF4 Method [76]. According to JSCE-SF4 Method -

1. Flexural Strength

$$\sigma_b = \frac{Pl}{bh^2} \qquad \textbf{3-1}$$

Where,

σ_b = flexural Strength (N/mm^2)

P = maximum load (N)

l = span (mm)

b = width of failed section (mm)

h = height of failed section (mm)

2. Flexural toughness shall be determined to three significant digits from the area below the load-deflection curve until measured deflection becomes l/150 of the span

3. Flexural Toughness Factor

$$\overline{\sigma_b} = \frac{T_b}{\delta_{tb}} \cdot \frac{l}{bh^2} \quad \textbf{3-2}$$

Where,

$\overline{\sigma_b}$ = flexural toughness factor (N/mm^2)

T_b = flexural toughness (J)

δ_{tb} = deflection of l/150 of span , 2 mm when span is 30 cm or 3 mm when span is 45 cm

4. Equivalent. Flexural Strength Ratio

$$R^D_{T150} = \left(\frac{150.T^D{}_{150}}{\sigma_b.b.h^2}\right) * 100 \quad \textbf{3-3}$$

Where,

$R^D{}_{T,150}$= Equivalent flexural strength ratio

$T^D{}_{150}$ = Toughness

3.4.5 Relationship Between Strengths and Young's Modulus

There are various guidelines and equations for relationship of compressive strength with the tensile strength and Young's modulus. In this section, design guidelines from the ACI 318-14 [77], fib2010 [78] and available equation given by researchers are used to predict the splitting tensile strength and Young modulus of the concrete specimens from the compressive strength results. Table 3-6 shows different equations for relationship of compressive with tensile strength and Young's modulus.

Table 3-6 : Equation showing relation of Compressive with Tensile Strength and Young Modulus

Splitting tensile strength	ACI 318-14[77]	$f_{ctm,sp} = 0.556\sqrt{f'_C}$; where $f_{ctm,sp}$ is mean splitting tensile strength in MPa and f'_C is the compressive strength of concrete in MPa
	fib2010 [78]	$f_{ctm} = 0.3(f_{Cm})^{\frac{2}{3}}$; where f_{ctm} is mean tensile strength in MPa and f_{cm} is mean compressive strength in MPa
	Mohammed et al.[79]	$f_t = 0.50\sqrt{f'_C}$; where f_t is tensile strength in MPa
	Xu and Shi [80]	$f_{spt}=0.21(f_{cs})^{0.83}$; where f_{spt} is tensile strength in MPa and f_{cs} is the compressive strength of concrete in MPa
Young Modulus	ACI 318-14[77]	$E_c = 4700\sqrt{f'_C}$; where E_c is Young modulus in MPa and f'_C is the compressive strength of concrete in MPa
	fib2010 [78]	$E_{ci} = E_{co}.\ \alpha_E \left(\frac{f_{Cm}}{f_{Cmo}}\right)^{\frac{1}{3}}$; where E_{ci} is Young modulus in MPa and E_{co} =2.15 x 10^4 MPa, and f_{cmo} = 10 MPa, α_E is aggregate type dependent scaling factor, which equals 1.0 for quartzite aggregates, f_{Cm} is compressive strength in MPa
	Mohammed et al.[79]	$E_c = 3595\ \psi(t)\sqrt{f'_C}$; where E_c Young's modulus of concrete in MPa, and f'_C is compressive strength of concrete in MPa and $\psi(t)$ is a time dependent constant=1; 0.98, and 0.94 at 28, 14, and 7 days, respectively.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

Fresh and hardened properties of natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) with GI and PP fibers were evaluated through slump test, air content test, compression test, splitting tensile test and flexural test. A total of 432 cylinders and 54 small size prism beams were prepared for two different steps as described in the subsequent sections. The compressive strength (f_{c}'), tensile strength, flexural strength, stress-strain curve, modulus of elasticity (E) were quantified for different concrete mixes. Detailed results of the test programs are discussed and analyzed in this chapter.

4.2 Effect of Fiber Type and Percentage on Concrete Properties

4.2.1 Workability

Slump tests were carried out to determine the workability and consistency of fresh concrete according to ASTM C143[81]. In order to find the suitable percentage of fiber content no admixture was used in this case. Slump test results are tabulated inTable **4-1**.Slump values are very low and some mixes have zero slump. Reasons behind this low slump are low water cement ratio and fiber content. It is evident that fiber content reduces workability of fresh concrete as array of fiber make concrete stiffer. Fibers hindered the flowability of fresh concrete and this caused the decrease in workability of concrete [9, 39]. Adding fiber causes slump loss as fiber absorb more cement paste to wrap around its surface area [36]. Figure 4-1 shows the FRC with zero slumps.

Table 4-1: Slump Values of concrete mixes

Designation	NG_0P_0	$NG_{0.5}P_0$	$NG_{1.0}P_0$	$NG_0P_{0.5}$	$NG_0P_{1.0}$	$NG_{0.5}P_{0.5}$
Slump Value (mm)	30	10	0	5	0	0

Figure 4-1: Slump test of concrete mixes

4.2.2 Compressive Strength

Compressive strength of fiber reinforced concrete (FRC) with GI and PP fiber with different fiber content is shown in Figure 4-2 and Table 4-2. The strength improved to different extents in response to the fiber content. Only for concrete mix containing GI fiber 0.5% showed an increment in 28 days compressive strength. The slightly higher compressive strength in GI wire can be attributed to the reduction in micro cracks under compression load [82]. According to literature, the addition of fibers hardly affects the compressive strength of concrete. All other mixes containing GI or PP fiber or both showed decreased strength. As observed from Figure 4-2, for concrete with GI fiber content 1% and PP fiber content 0.5%, 1% and combination of both fibers, compressive strength decreases by18%, 27%, 51%, and 34%,respectively.Non-uniform compaction and increased porosity of the FRC mixtures resulting in a reduction of the compressive strength. From the results it can be said that concrete with 0.5 % GI fiber content performed better than other fiber content as well as PP fiber. But from other study, it is evident that an enhancement in compressive strength compared to control concrete occurs for the steel fiber concrete and all hybrid fiber concretes [83].

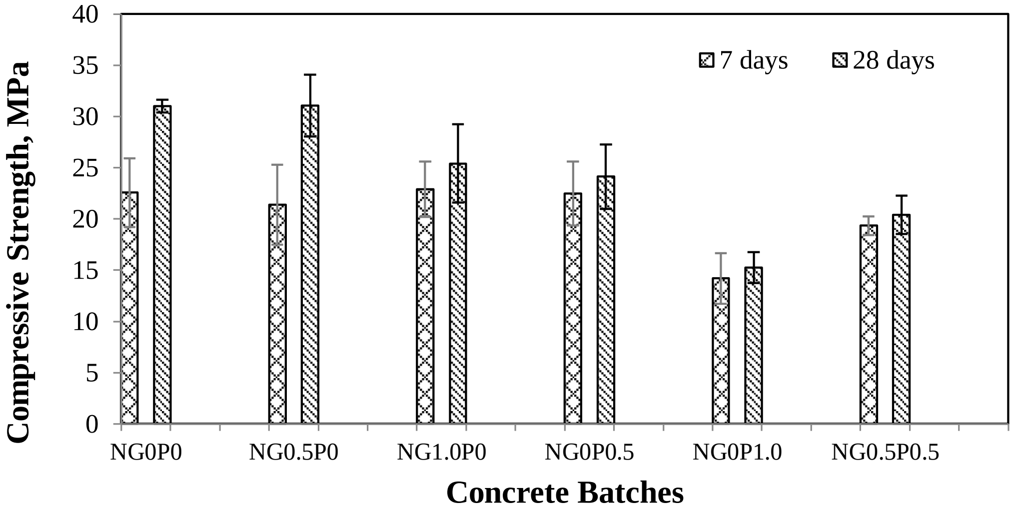


Figure 4-2: Compressive strength of concrete at 7 and 28 days

Table 4-2: Change in compressive strength

Designation	Compressive Strength, MPa (7 days)	Compressive Strength, MPa (28 days)	Strength Decrease (in 28 days)	Strength increase (in 28 days)
NG_0P_0	22.6	31.0	Control sample	Control sample
$NG_{0.5}P_0$	21.4	31.1	-	0.32%
$NG_{1.0}P_0$	22.9	25.4	18.00%	-
$NG_0P_{0.5}$	22.5	24.1	27.10%	-
$NG_0P_{1.0}$	14.2	15.2	50.97%	-
$NG_{0.5}P_{0.5}$	15.8	20.4	34.19%	-

4.2.3 Stress-Strain Behavior

Figure 4-3 shows the stress vs strain curve for the six combinations for 28 days. Concrete reinforced with GI fiber content of 0.5 % shows major improvement in stress and also in the descending or softening branch of the stress-strain curve compared to plain concrete. On the other hand, concretes reinforced with GI and PP fiber in other percentages have shown a less extended softening branch. It is worthwhile to note that FRC with 0.5% of GI fiber content had maximum stress 31.1MPa, where corresponding failure strain was

0.003424 and the next highest value was tabulated for the control mix. All values are tabulated in Table 4-3. From the experimental results, it indicates that the GI contributes significantly to the strength of concrete, and consequently, the strain ductility of the concrete also increases considerably. Modulus of elasticity has been calculated from the slope of stress strain curve. From Table 4-3 it can be seen that concrete containing 1.0 % GI wire has highest Elastic modulus 28.2 GPa with a low fracture strain. But, with 0.5 % GI fiber content fracture strain was maximum with Elastic modulus of 27.8 GPa. Hence, from the discussion above it can be said that GI wire has better ductility than PP fiber and performed better at 0.5 % fiber volume.

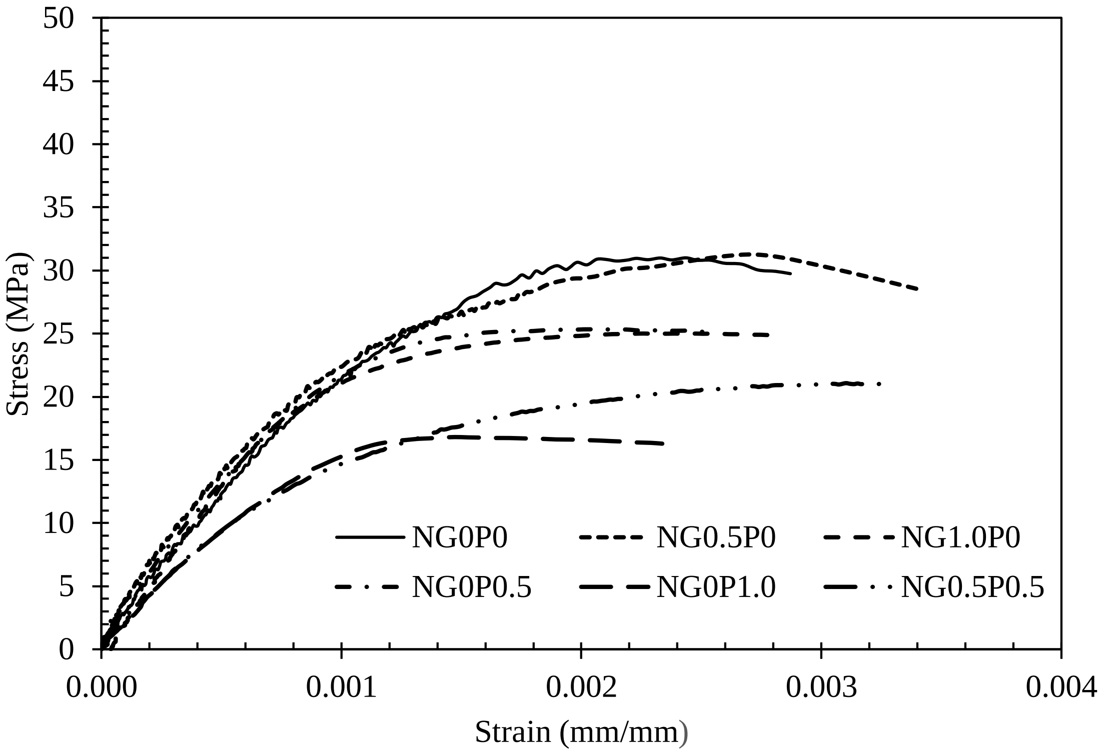


Figure 4-3: Stress- strain plot under compression at 28 days.

Table 4-3: Parameters from Stress strain Curve

Concrete Batch	NG_0P_0	$NG_{0.5}P_0$	$NG_{1.0}P_0$	$NG_0P_{0.5}$	$NG_0P_{1.0}$	$NG_{0.5}P_{0.5}$
Maximum Stress in concrete, σ_c (MPa)	31.0	31.1	25.0	24.1	16.8	21.0
Fracture Strain, ε_c (x 10^{-6})	2872	3424	2796	2534	2371	3250
Elastic modulus, E_c(GPa)	24.2	27.8	28.2	27.1	19.9	18.7

4.2.4 Split Tensile Strength

Split tensile strength of GI and PP fiber reinforced concrete and normal concrete was determined at 7 and 28 days. The test provides an indication of tensile capacity of concrete. Figure 4-4 shows the split tensile strength test results at 7 and 28 days. The splitting tensile strength of the FRC mixtures was generally higher than the corresponding unreinforced concrete except for concrete with 1% PP and combined 0.5% GI & 0.5% PP fiber concrete. Based on the test results; it is evident that GI fiber reinforced concrete has shown better tensile strength than the both concrete without fiber and concrete containing PP fiber. Furthermore, 0.5% PP reinforced concrete performed better than 1% PP reinforced concrete.

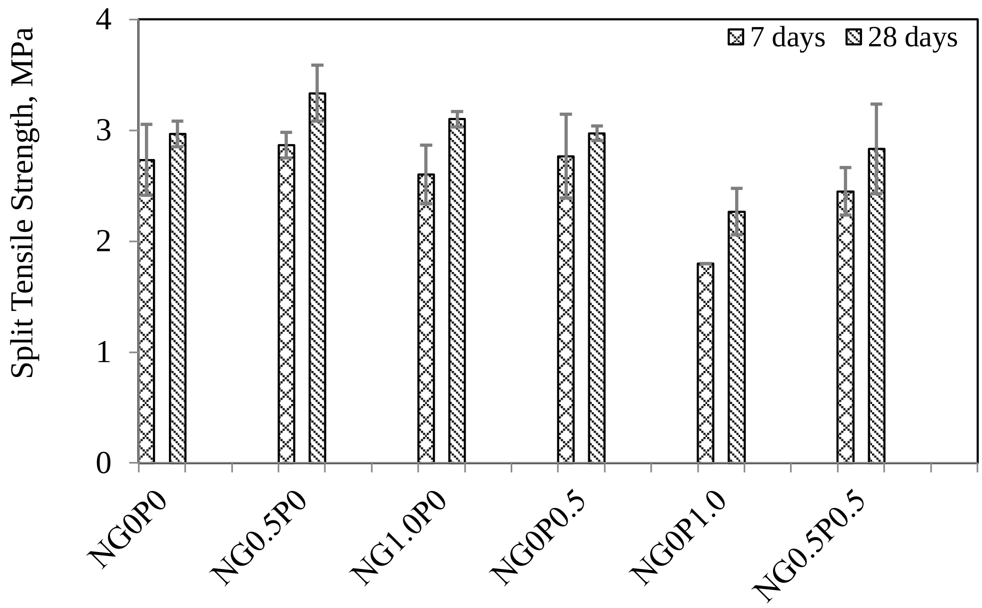


Figure 4-4: Split Tensile Strength at 7 and 28 days

From Table 4-4 it can be seen that for 0.5% GI wire the highest increment of tensile strength comparing with control sample is 12.4% in 28 days. For 0.5% PP fiber, it does not have any effect on the tensile strength. For 1% PP fiber content, the tensile strength of concrete decrease to 23.6%. In case of combination of GI and PP fiber the split tensile strength decreased to 4.49 % comparing with the control sample in 28 days. Only GI wire is showing strength incremental trend. Other study [41] also supports the increase of tensile strength for different dosages of GI wire fiber with respect to the control specimen. On the other hand, higher PP fiber content has negative effects on the strength. Jassim and Anwar [84] also found that PP fiber tends to decrease the tensile strength. But

Hsie et al. [36] found that coarser and stronger monofilament PP fiber can arrest the propagating microcracks and substantially improve the split tensile strength.

Table 4-4: Change in split tensile strength

Designation	Split Tensile Strength, MPa (7 days)	Split Tensile Strength, MPa (28 days)	Strength Decrease (in 28 days)	Strength increase (in 28 days)
NG_0P_0	2.73	2.97	Control sample	Control sample
$NG_{0.5}P_0$	2.87	3.33	-	12.36%
$NG_{1.0}P_0$	2.60	3.10	-	4.49%
$NG_0P_{0.5}$	2.77	2.97	-	-
$NG_0P_{1.0}$	1.80	2.27	23.60%	-
$NG_{0.5}P_{0.5}$	2.45	2.83	4.49%	-

4.2.5 Flexural Strength

Third-point loading test was performed on beams to evaluate flexural strength of FRC. From Figure 4-5, increment in flexural stress has been found for concrete with GI fiber at 28 days. Maximum flexural strength of 5.4 MPa was found for concrete with 0.5% and 1 % GI fiber content. An improvement of flexural strength is noticed at any GI fiber content. On the other hand, Table 4-5shows that concrete with 0.5% and 1.0% PP fiber showed lower strength than the control specimen and the reduction are 1.6 % and 16.42 % respectively. Combination of GI and PP fiber also showed improved strength.

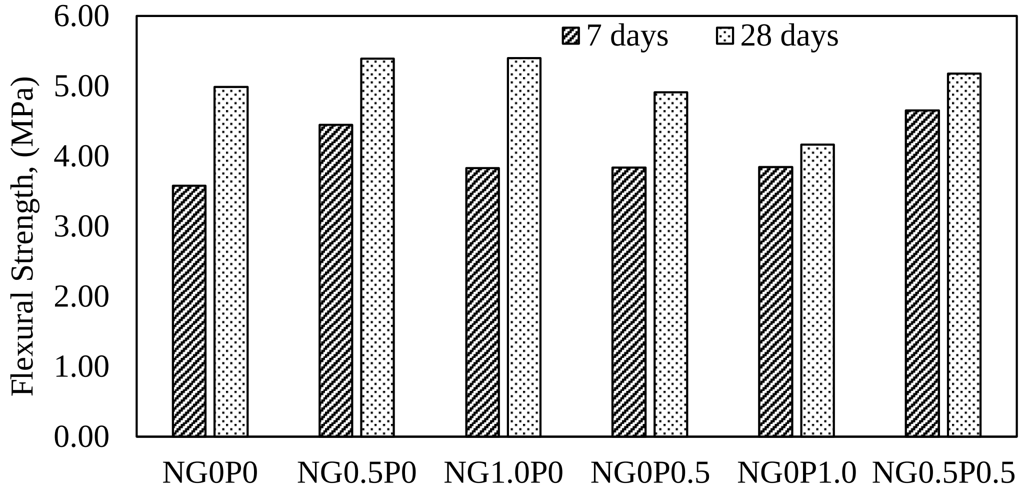


Figure 4-5: Flexural Strength at 7 and 28 day

Table 4-5: Change in Flexural Strength

Designation	Flexural Strength, MPa (7 days)	Flexural Strength, MPa (28 days)	Strength Decrease (in 28 days)	Strength increase (in 28 days)
NG_0P_0	3.58	4.99	Control sample	Control sample
$NG_{0.5}P_0$	4.45	5.39	-	8.02%
$NG_{1.0}P_0$	3.84	5.40	-	8.22%
$NG_0P_{0.5}$	3.83	4.91	1.60%	-
$NG_0P_{1.0}$	3.85	4.17	16.43%	-
$NG_{0.5}P_{0.5}$	4.65	5.18	-	3.81%

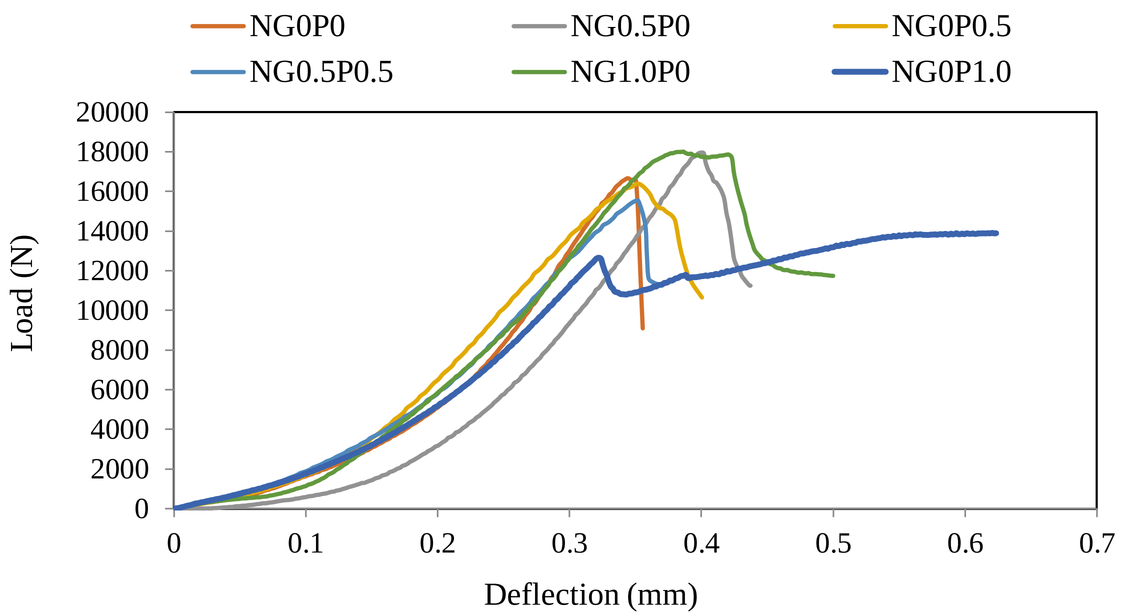


Figure 4-6: Load deflection curve at 28 days

From Figure 4-6 control sample has straight elastic region but the plastic region is not too long. It gives the idea that after the formation of cracks it carries a very little load. But with the inclusion of fiber the appearance of plastic region is delayed. It also shows the ability of taking load after failure like the reinforced concrete. Concrete containing GI fiber shows maximum strength. But concrete containing both GI and PP fiber shows better toughness than other mix.

Toughness, flexural toughness factor and equivalent flexural toughness ratio has been tabulated in Table 4-6.

Table 4-6: Summary of flexural test on test beams

Properties	**Flexural Strength, fp (MPa)**	**Flexural Toughness Factor (FTF) (KPa) (JSCE G-552)**	**Toughness, TD150**	**Eqv. Flexural Strength Ratio, RDT,150 (%)**
NG_0P_0	4.99	0.29	1947.35	6
$NG_{0.5}P_0$	5.39	0.33	2180.71	6
$NG_{1.0}P_0$	5.40	0.50	3313.01	9
$NG_0P_{0.5}$	4.91	0.36	2393.53	7
$NG_0P_{1.0}$	4.17	0.22	1477.42	5
$NG_{0.5}P_{0.5}$	5.18	0.33	2170.49	6

Among all concrete mix GI fiber reinforced concrete showed better results. Fibers fail in pull out mechanism. GI fiber would absorb more energy than PP fiber during failure.GI fiber at 1% fiber content has maximum toughness and also equivalent flexural strength ratio. Equivalent flexural strength ratio indirectly shows the ratio of the flexural loads that can be carried by the fibers once the section is cracked and compared to the peak load. Concrete with any GI fiber content shows better toughness than PP fiber.

4.2.6 Relationship sand Code Comparison

According to Table 3-6 using different equations tensile strength and young modulus have been calculated in terms of compressive strength. Figure 4-7shows Comparison of Split tensile strength with different codes and Figure 4-8shows the similar comparison for young modulus. It can be seen that the values from ACI 318-14 [77] are in good agreement with the experimental results. For control specimen ACI 318-14 [77], fib2010 [78] and Xu and Shi [80] give a ratio closer than 1eventhough it slightly overestimates the value. But for almost other cases it seems all equation have underestimated split tensile strength. Proposed equation by Xu and Shi [80] was for steel fiber reinforced concrete which over predict the values than the other existing equations. Meanwhile, equation from ACI 318-14 [77] underestimates all the Young's modulus except the control mixture and $NG_{0.5}P_{0.5}$ combination. On the other hand according to fib2010 [78] all the Young's moduli are significantly overestimated.

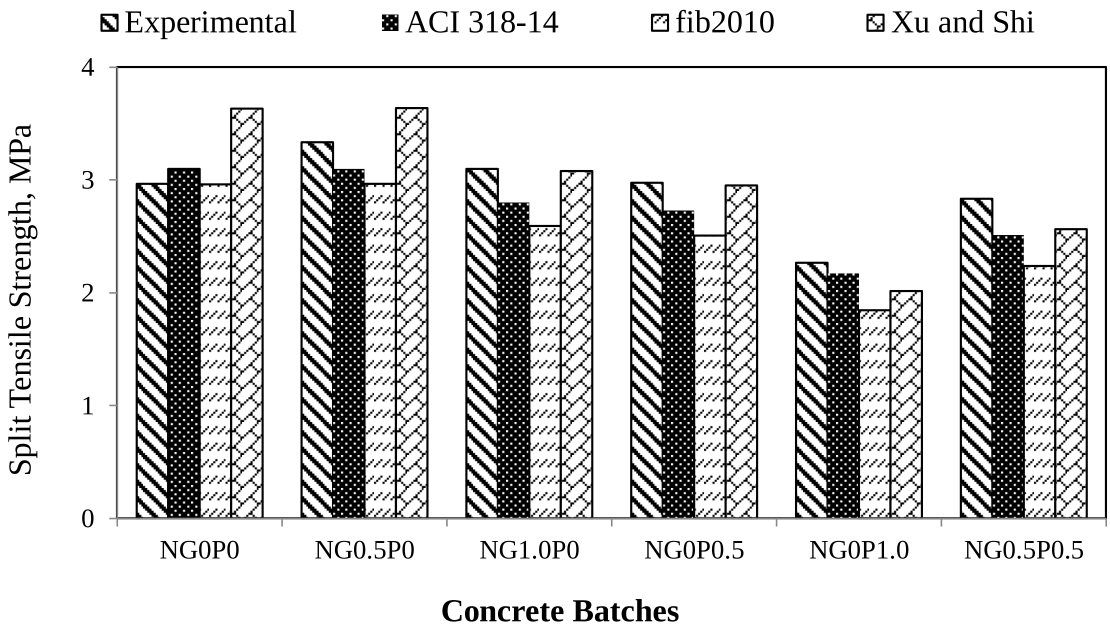


Figure 4-7 : Comparison of split tensile strength with different codes

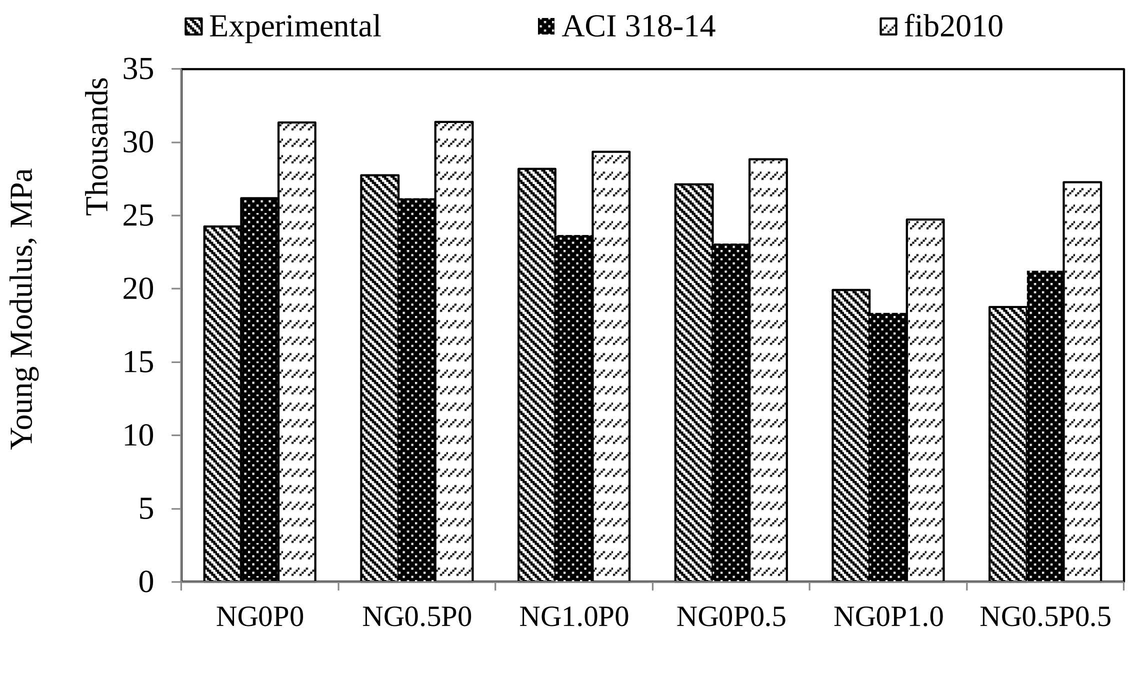


Figure 4-8 : Comparison of young modulus with different codes

4.3 Effects of Different Diameter of GI Fiber on the Properties of NAC

4.3.1 Workability

Slump tests were carried out to determine the workability and consistency of fresh concrete according to ASTM C143 [81]. To increase workability admixture was used this time. Slump test results are tabulated in

Table 4-7. From table it can be seen that slump value decreases with the GI fiber diameter increases. At same aspect ratio larger diameter provided longer fiber. Longer fiber produces increasing difficulty to the coarse particles movement, restricting the mobility of the mixture. This can lead to a loss of workability.

Table 4-7: Slump Values of concrete mixes

Designation	NG_0P_0 (Control)	$NG_{0.5}D_{0.51}L_{26}$	$NG_{0.5}D_{0.70}L_{35}$	$NG_{0.5}D_{1.21}L_{61}$
Slump Value (mm)	120	75	30	5

4.3.2 Compressive Strength

Figure 4-9 depicts the results of compressive strength of concrete containing GI wire with varying diameter. Compressive strength of GI fiber reinforced concrete varies with the fiber diameter. From the figure compressive strength all concrete mixes containing GI wire increases with respect to the control specimen. It may be due to the fact that GI fibers can cross microcracks developing in the coarse aggregate–mortar interface and thus arrest them, increasing the strength of concrete. It shows in case of sample with GI fiber of diameter 0.51mm, the compressive strength significantly increases from the sample without GI fiber content which is 50.3 MPa.

Table 4-8 shows increment of compressive strength at 7, 14 and 28 days due to variation of GI wire diameter. GI fiber has positive effect on concrete compressive strength compare to concrete without fiber. At 28 days for diameter 0.51, 0.70 and 1.21 mm the increments were 45.68%, 27.63% and 22.09% respectively. Maximum increment was recorded for 0.51 mm diameter GI wire.

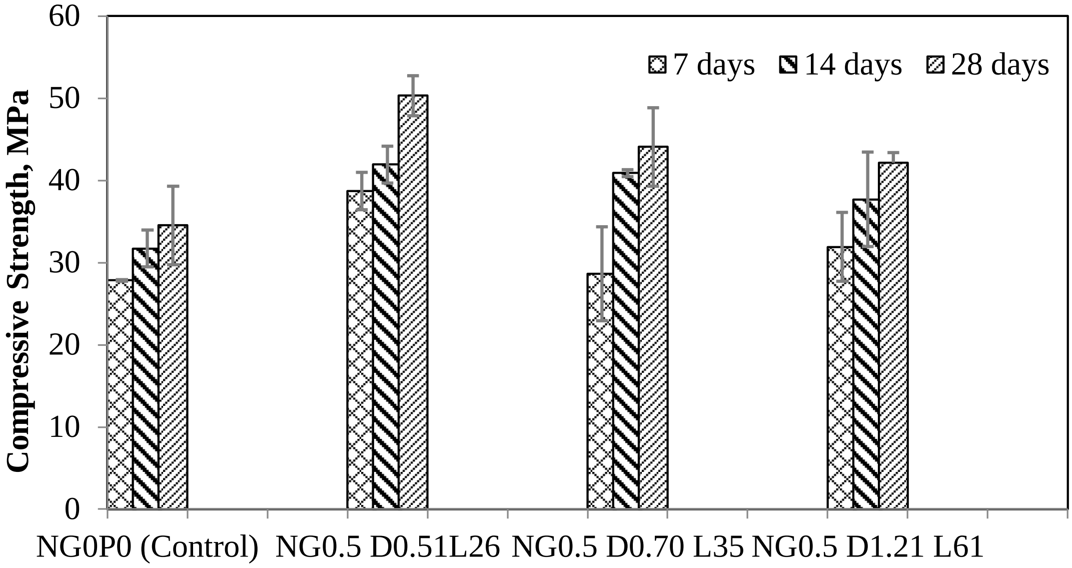


Figure 4-9: Compressive strength of concrete containing GI wire with varying diameter

Table 4-8 : Change in Compressive Strength

Designation	Compressive Strength, MPa (7 days)	Compressive Strength, MPa (14 days)	Compressive Strength, MPa (28 days)	Strength increase (in 28 days)
NG_0P_0 (Control)	27.9	31.7	34.5	Control sample
$NG_{0.5}\ D_{0.51}L_{26}$	38.7	41.9	50.3	45.68%
$NG_{0.5}\ D_{0.70}\ L_{35}$	28.7	40.9	44.1	27.63%
$NG_{0.5}\ D_{1.21}\ L_{61}$	31.9	37.7	42.2	22.09%

4.3.3 Stress-Strain Behavior

Figure 4-10 shows the stress-strain curve of four combinations for different diameter of 0.5% GI fiber content after 28 days curing at w/c ratio of 0.4. Control mix shows low stress and failure strain than the FRC. Concrete made with fiber showed an improvement in stress than control mixture. Concrete reinforced with GI Wire having diameter 0.51 mm shows major improvement in stress and also shows improvement in the descending or softening branch of the stress strain curve compared to plain concrete. The concrete with 0.51mm GI fiber of length 26 mm shows a gradual slope in the curve which indicates its greater ductility. In case of the samples with greater diameter the stress-strain curve gets steeper.

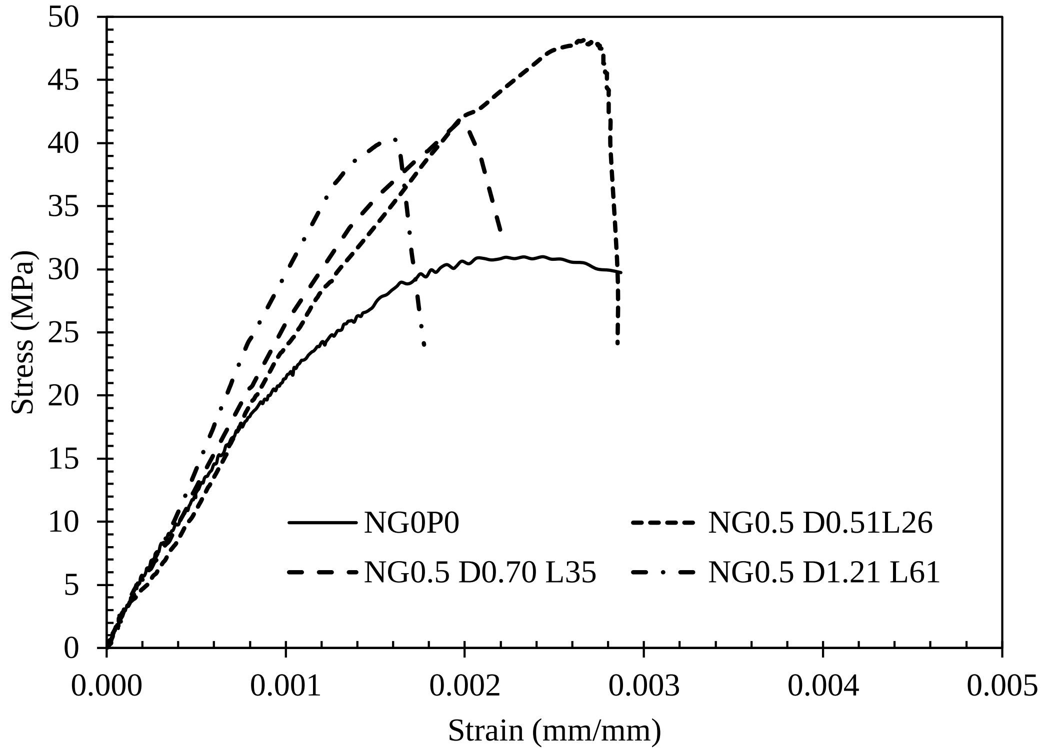


Figure 4-10: Stress-Strain plot for concrete containing GI wire of different diameter

Table 4-9 displays the parameters from stress strain curve. It can be seen that concrete containing GI wire diameter 0.51 mm has maximum stress 49.09 MPa and 0.70 mm diameter has maximum stress 39.5 MPa, where strain was 0.00269 and 0.00187 respectively. So, from the experimental results, it indicates that the 0.51 mm diameter GI wire contributes significantly to the strength of concrete, and consequently, the strain ductility of the concrete also increases considerably. Moreover, Elastic modulus of GI FRC increases with the increment of fiber diameter.

Table 4-9: Parameters from Stress strain Curve

Concrete Batch	NG_0P_0 (Control)	$NG_{0.5}\,D_{0.51}L_{26}$	$NG_{0.5}\,D_{0.70}\,L_{35}$	$NG_{0.5}\,D_{1.21}\,L_{61}$
Maximum Stress in concrete, σ_c (MPa)	31.01	49.07	39.5	38.4
Fracture Strain, ε_c (x 10^{-6})	2871	2852	2198	1772
Elastic modulus, E_c(GPa)	24.24	24.56	25.83	29.77

4.3.4 Split Tensile Strength

Figure 4-11 presents the effects of GI fiber length on splitting tensile strength of GI fiber Reinforced Concrete (GFRC). It can be seen that GI fiber added into the plain concrete greatly improves the splitting tensile strength. GFRC having 0.51 mm diameter fiber has maximum strength of 3.70 MPa. The maximum improvements are 21.98% and 20.88% for GFRC containing fiber diameter 0.51 mm and 1.21 mm respectively compared to the control mixture. This is mainly attributed to the frictional bond between fibers and concrete matrix. Table 4-10 represents the relative change in split tensile strength with fiber diameter increment.

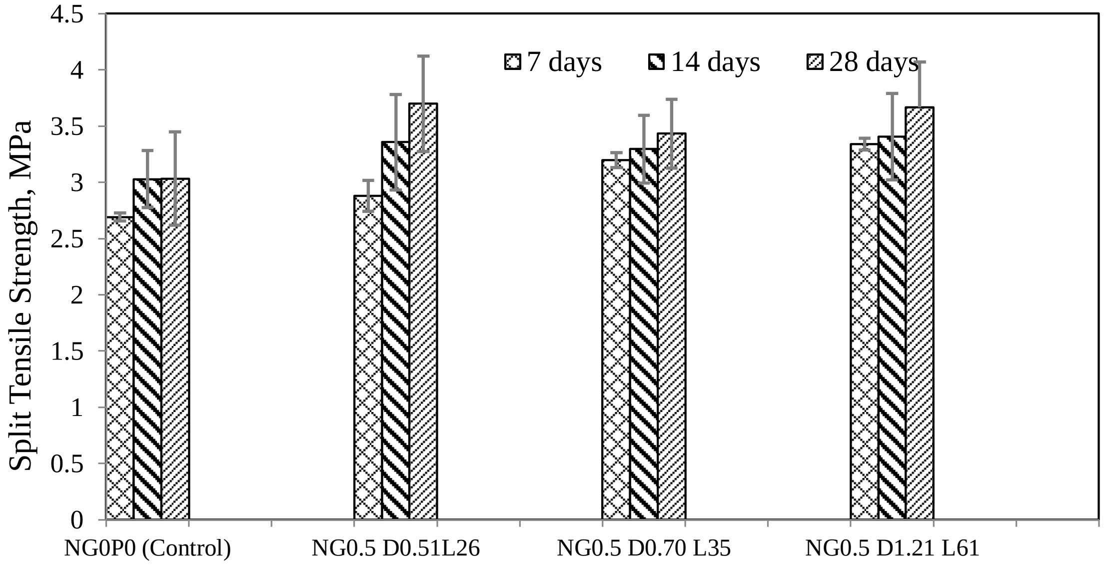


Figure 4-11: Split tensile strength of concrete containing GI wire with varying diameter at 7, 14 and 28 days

Table 4-10 : Change in Split Tensile Strength

Designation	Split Tensile Strength, MPa (7 days)	Split Tensile Strength, MPa (14 days)	Split Tensile Strength, MPa (28 days)	Strength increase (in 28 days)
NG_0P_0 (Control)	2.69	3.03	3.03	Control sample
$NG_{0.5}$ $D_{0.51}L_{26}$	2.88	3.36	3.70	21.98%
$NG_{0.5}$ $D_{0.70}$ L_{35}	3.19	3.30	3.43	13.19%
$NG_{0.5}$ $D_{1.21}$ L_{61}	3.34	3.41	3.67	20.88%

Figure 4-12 shows the failure of natural aggregate concrete without GI fiber content with w/c ratio of 0.4 at the age of 28 days after tensile test. The sample failed without giving significant warning. The failure occurred just after the cracking began with the progressive loading. **Error! Reference source not found.** shows the failure of natural aggregate concrete with 0.5% GI fiber (diameter 0.51mm) content with w/c ratio of 0.4 at the age of 28 days after tensile test. In this case, the sample continues to bear load with the help of GI fibers resisting tensile stress even after concrete fracture at ultimate load. **Error! Reference source not found.**shows that GI fibers bridging across the crack under tensile load.

Figure 4-12: Columnar failure of NAC without GI fiber

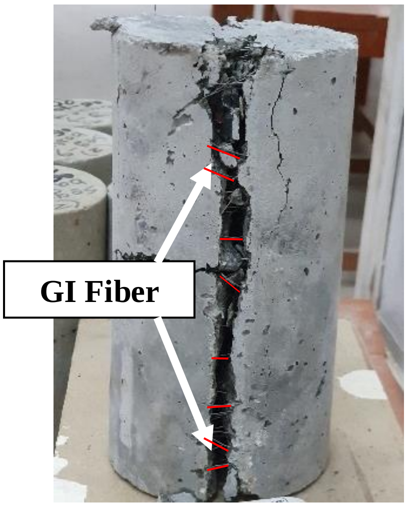


Figure 4-13: Columnar failure of NAC with 0.51mmdiameter GI fiber

4.3.5 Flexural Strength

Third-point loading test was performed on beams to evaluate flexural strength of FRC. Under bending loads, tensile stresses occur in microstructure of concrete and fibers withstand this tensile stress, thus, bending strength of concrete increased. From Figure 4-15it can be seen that flexural strength of concrete with GI fiber increase with the increment of fiber diameter at 28 days. Maximum flexural strength 7.08MPa was found for Concrete with GI fiber diameter 1.21 mm. But Banthia and Sappakittipakorn found that as the diameter of the steel fiber increased, the dispersion of the fiber in the concrete decreased, and the flexural toughness of the macrocrack decreased[85].

(a)

(b)

(c)

Figure 4-14: Failure of Flexure Beam with GI fiber of diameter(a) 0.51 mm (b) 0.70 mm (c) 1.21mm

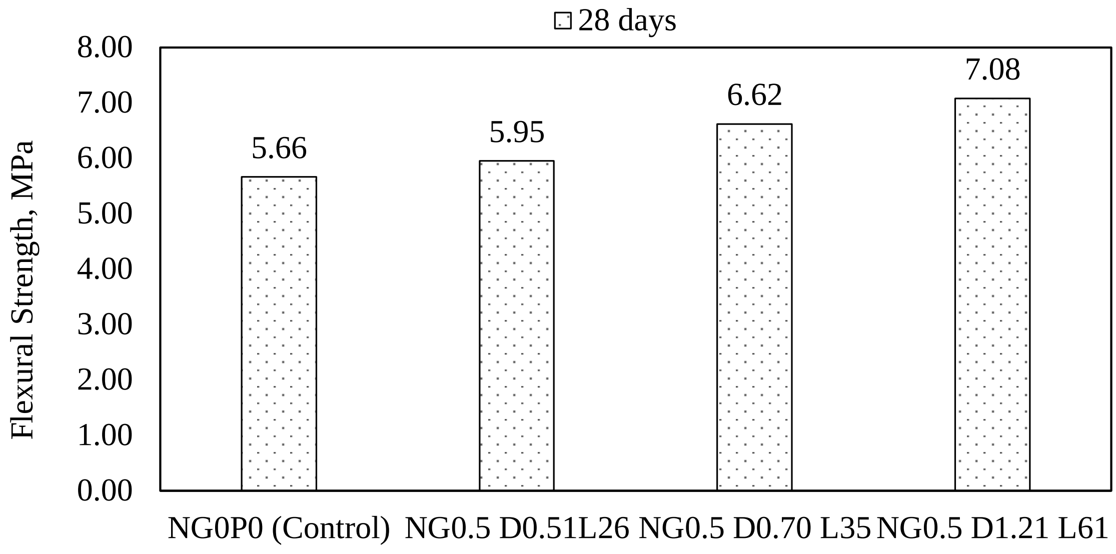


Figure 4-15: Flexural Strength at 28 days

Figure 4-16 displays the load-deflection curve for concrete containing GI wire of different diameter. It is clearly evident that for a given deflection of 0.8 mm, the sample with GI fiber of diameter 0.51mm required maximum load and the sample with GI fiber of diameter 1.21mm required minimum load, which indicates that the concrete beam with 0.51mm diameter GI fiber exhibited maximum yield strength.

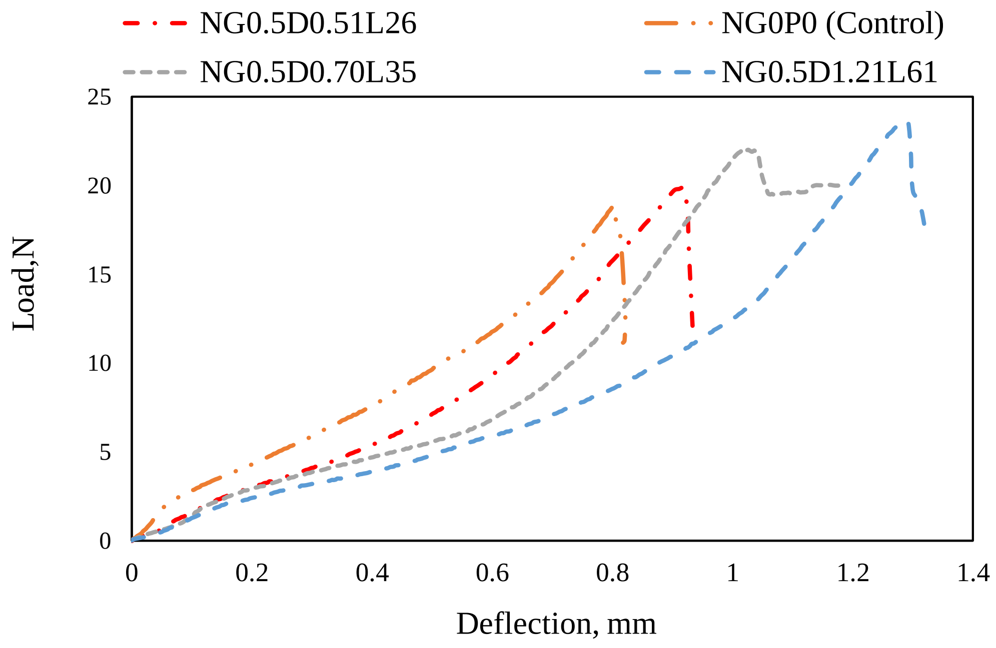


Figure 4-16: Load-Deflection curve at 28 days

However, 1.21 mm diameter fiber led to a larger area under the curve and slightly smoother failure pattern than the other concrete mixes containing 0.51mm, 0.70mm diameter fiber. Table 4-11 shows parameters from flexural test on test beams.

Table 4-11: Summary of flexural test on test beams

Properties	**Flexural Strength, fp (MPa)**	**Flexural Toughness Factor (FTF) (KPa) (JSCE G-552)**	**Toughness, T^D_{150}**	**Eqv. Flexural Strength Ratio, $R^D_{T,150}$(%)**
NG_0P_0 (Control)	5.66	0.67	6724.25	18
$NG_{0.5}D_{0.51}L_{26}$	5.95	0.73	7295.35	18
$NG_{0.5}D_{0.70}L_{35}$	6.62	0.85	8482.24	19
$NG_{0.5}D_{1.21}L_{61}$	7.08	1.07	10735.19	23

Performance of GI fiber is proportional to the fiber diameter in case of flexural strength and also for toughness. It is noticed that toughness of GFRC is increase with the GI fiber diameter increment. 1.21 mm diameter provides highest toughness. It may be due tolarger fiber hold larger crack for longer time.

4.3.6 Relationships and Code Comparison

According to Table 3-6 using different equations tensile strength and young modulus have been calculated in terms of compressive strength. Figure 4-17 shows Comparison of Split tensile strength with different codes and Figure 4-18 shows the similar comparison for young modulus.

From Figure 4-17 it can be seen that the values from ACI 318-14predicts similar results comparable with the experimental results. For control specimen, $NG_{0.5}D_{0.51}L_{26}$ and $NG_{0.5}D_{0.70}L_{35}$, ACI 318-14 [77], fib2010 [78] and Xu and Shi [80] give a ratio of theoretical to experimental value are greater than 1. So, the experimental values are underestimated by the theoretical value. Meanwhile, equation from ACI 318-14 [77] and overestimates all the Young modulus. On the other hand, according to fib2010 all the young moduli are significantly overestimated.

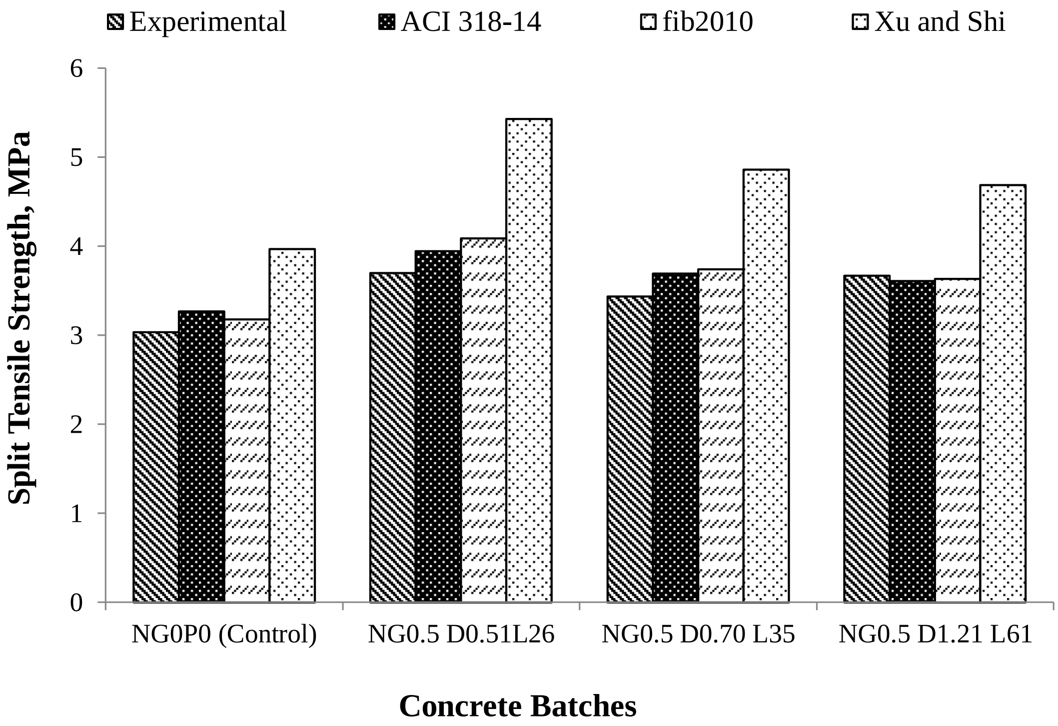


Figure 4-17 : Comparison of Split tensile strength with different codes

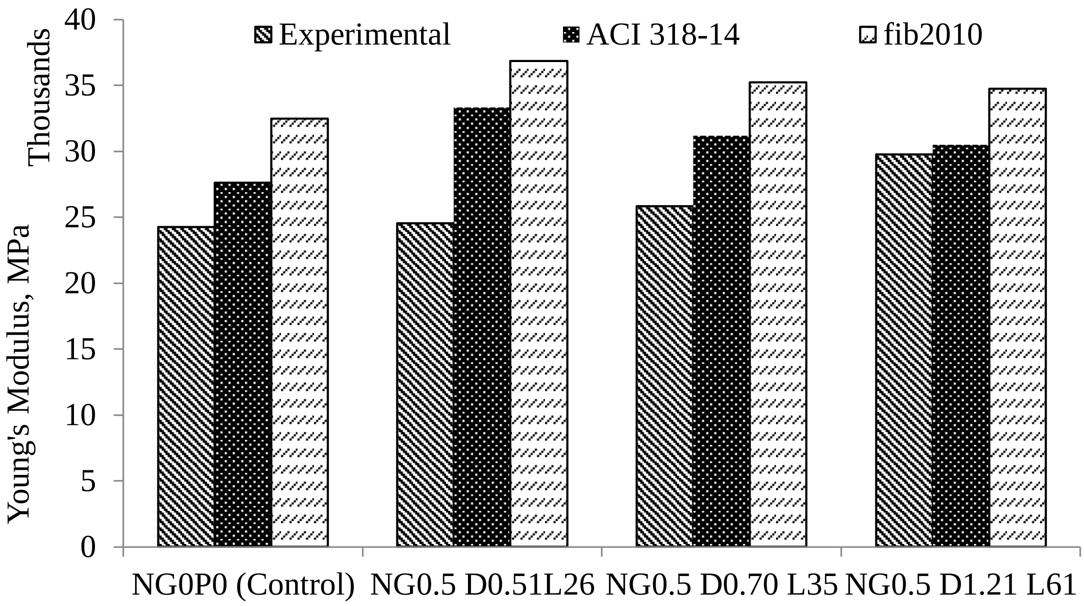


Figure 4-18 : Comparison of young modulus with different codes

4.4 Effect of Fiber Length on the Properties of NAC and RAC

4.4.1 Workability and Air content

Table 4-12 shows the slump value and air content of the concrete mixture. NAC with no fiber shows the highest slump and lowest air content as the W/C ratio is low. The slump of RAC with and without fiber is lower than that of the NAC. The reason for this is RAC has high absorption quality that RA need more water during concrete mixture[86]. Air content shows increased value with fiber content. Longer fiber content concrete has higher air content for both NAC and RAC. As longer fibers do not disperse well in the concrete mix and left some extra voids.

(a) (b)

Figure 4-19 : (a) Slump Test (b) Air void test

4.4.2 Compressive Strength

The results of compressive strength of concrete made with natural and recycled aggregate with and without fiber were presented in Figure 4-20. Compressive tests were done at 7, 28 and 56 days. At 7 and 28 days, NAC showed higher strength than RAC without any fiber. However, at 56 days RAC concrete showed higher compressive strength than the NAC. This can be attributed to the better internal curing due to the higher amount of absorbed water in recycled aggregate (RA) in RAC. This trend is also observed for concrete with fibers.

Table 4-12: Slump value and air content

Designation	Slump (mm)	Air Content (%)
NG_0P_0 (Control)	150	1.2
$NG_{0.5}D_{0.51}L_{15}$	135	3.2
$NG_{0.5}D_{0.51}L_{26}$	120	3.3
$NG_{0.5}D_{0.51}L_{36}$	90	3.4
$NG_0P_{.5}$	75	2.5
$RG_0 P_0$(Control)	114	3.2
$RG_{0.5}D_{0.51}L_{15}$	95	3.3
$RG_{0.5}D_{0.51}L_{26}$	70	3.4
$RG_{0.5}D_{0.51}L_{36}$	62	4.2
$RG_0P_{0.5}$	10	2.7

From Figure 4-20 it can be seen that at same fiber content the inclusion of GI fiber increases the compressive strength of both NAC and RAC than PP fiber. However, inclusion of PP fiber reduces the compressive strength of NAC at 7, 28 and 56 days. On the other hand, RAC with PP fiber showed higher strength at 7 and 28 days compare to the RAC without PP fiber. However, at 56 days compressive strength of RAC with PP has higher value than the control specimen.

When GI fiber length is 15 mm NAC shows higher compressive strength than the RAC at 28 days. But for other two lengths RAC showed better compressive strength than NAC. At 56 days the compressive strength of RAC with GI fiber reveals that RAC can achieve long term strength than NAC. It may be due to the attached mortar of recycled aggregate that contain extra water cause long term hydration process and gain strength with time. For NAC GI fiber with length 26 mm showed compressive strength higher than the other. Reduced dispersion of longer steel fiber may cause the lower compressive strength [87].But for RAC36 mm length GI wire showed maximum compressive strength of 48.9 MPa at 56 days.

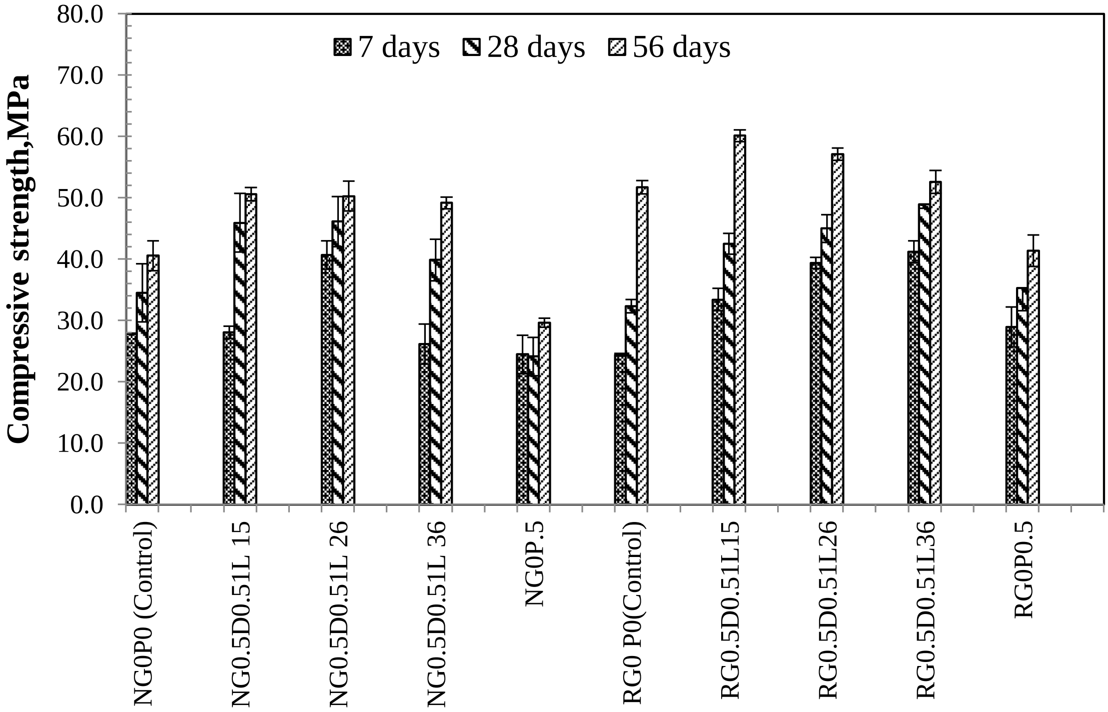


Figure 4-20: Compressive strength of concrete mixes at 7, 28 and 56 days.

Figure 4-22 (a) and (b) shows the stress strain plot of NAC and RAC respectively with and with fiber of varying length. Clearly fibers are improving the stress containing capacity of concrete. At strain value 0.0015, NAC containing GI fiber of length 36 mm showed maximum stress. Concrete containing Fibers shows better ductility than the RAC without fiber. On the other hand, PP fiber did not bear maximum stress but has less steep descending curve made it more ductile than other concrete mix as shown in the figure for both RAC and NAC. RAC containing GI fiber length 36 mm showed maximum stress than the other GI fiber length.

(a)

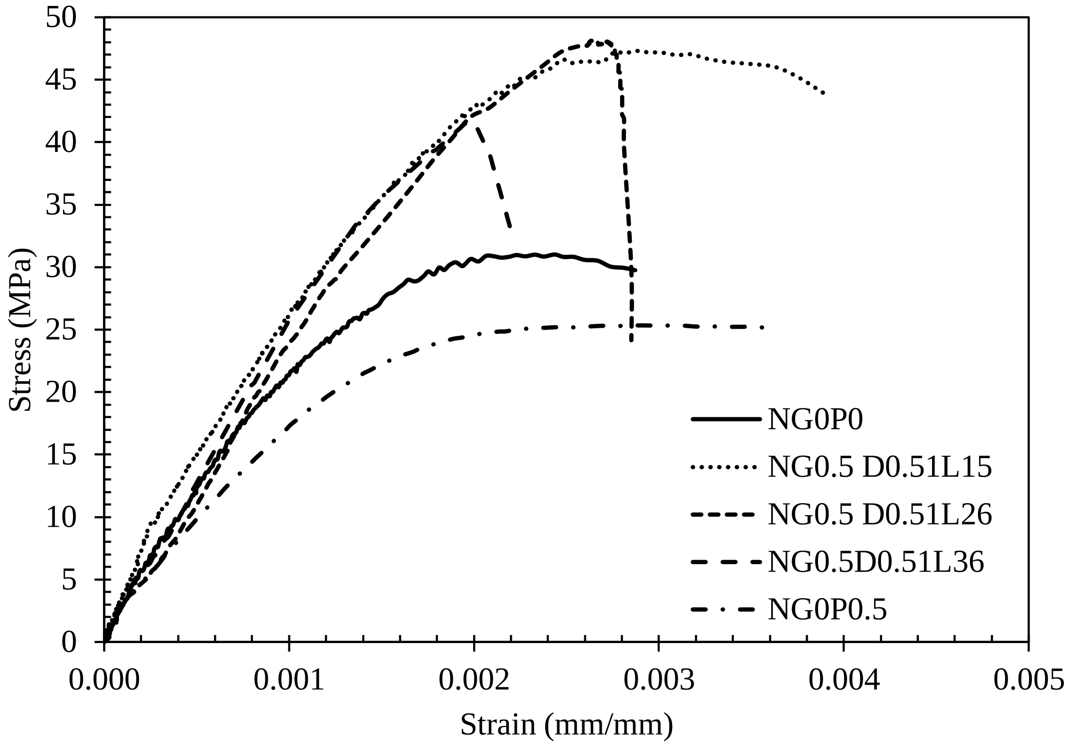
(b)

(c)

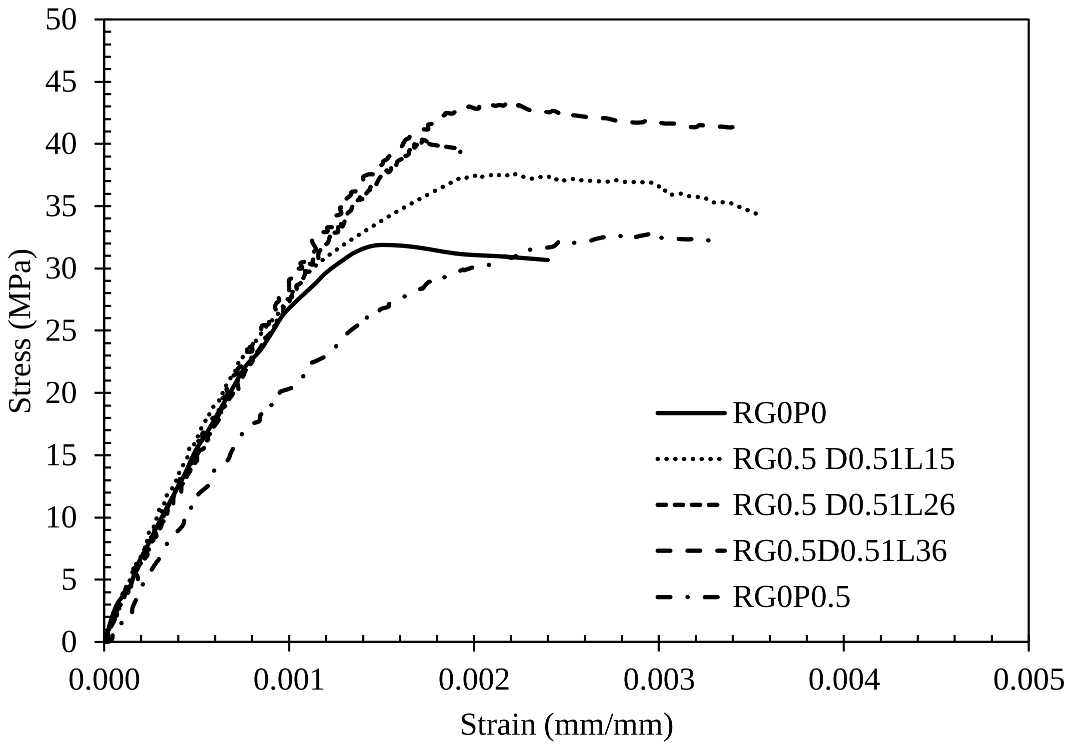
(d)

(e)

Figure 4-21: Failure pattern of RAC cylinder under compression(a)RAC without fiber (b) RAC with GI fiber L=15 mm(c) RAC without fiber (b) RAC with GI fiber L=26 mm (d) RAC without fiber (b) RAC with GI fiber L=36 mm (e) RAC without fiber (b) RAC with PP fiber



(a)



(b)

Figure 4-22 : Stress-Strain Plot of (a) NAC and (b) RAC

4.4.3 Split Tensile Strength

Split tensile strength test results of all 10 concrete mixes are shown in Figure 4-23. RAC without fiber shows higher split tensile strength than NAC without fiber which is 3.43 MPa. NAC with GI fiber imparts better strength than RAC but the strengths are higher also for RAC with fiber. That means adding fiber to RAC may offer similar strength like NAC. For NAC, 36mm length GI fiber provides highest strength of 4.23 MPa and for RAC, 15 mm length GI fiber provides highest strength of 3.80MPa respectively RAC with fiber length 26 mm and 36 mm have the same strength of 3.57 mm. Moreover, RAC with PP fiber shows augmented strength than the NAC with PP fiber.

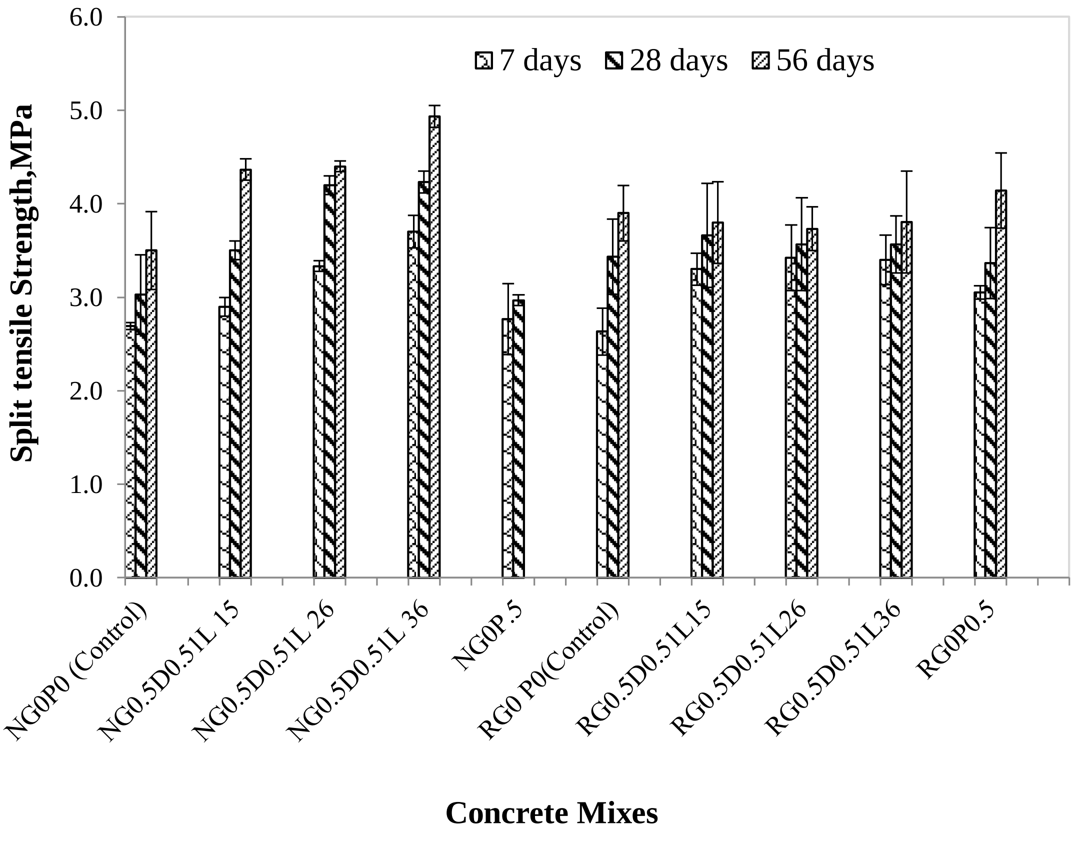


Figure 4-23: Split Tensile Strength of concrete mixes

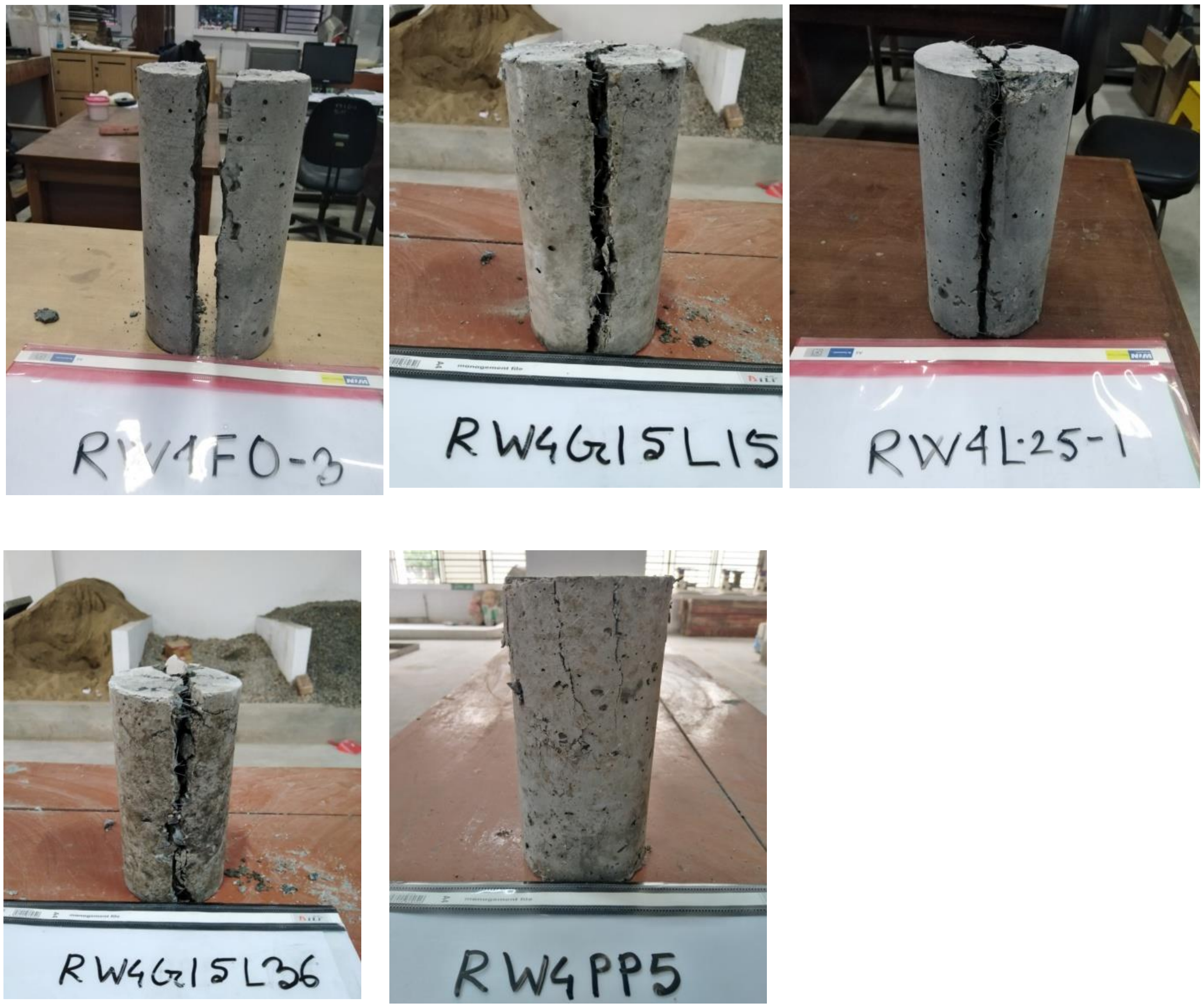


Figure 4-24: Split failure pattern of RAC without fiber and with diffretent length of fiber

4.4.4 Flexural Strength

Figure 4-25 shows the values of flexural strength of all concrete mixes. From literature, Fiber inclusion had incremental effects on concrete [7, 43, 88]. For NAC, 36 mm GI fiber provides maximum flexural strength of 8.2 MPa. But 15 mm GI fiber and PP fiber reduced the flexural strength than NAC without fiber. On the other hand, in case of RAC flexural strength increased with fiber length at same fiber content. GI fiber of length 36 mm provides maximum flexural strength of 6.52 MPa. Flexural strength RAC with fiber increased by 5.9%, 7.88 % and 14.19 % for GI fiber length 15 mm, 26 mm and 36 mm respectively. RAC without fiber has the greater value that of NAC with GI fiber of 15 mm. Recycled aggregate has rough surface that make good bond with cement paste and fiber [89]. But for both NAC and RAC, 36mm GI fiber showed augmented flexural strength. PP fiber does not show any significant results.

Load-displacement curves are plotted in Figure 4-26. From figure it can be seen that RAC with GI fiber length 26 mm,36 mm and with PP fiber has better ductility than the other concrete mixture. RAC performed better than NAC here.

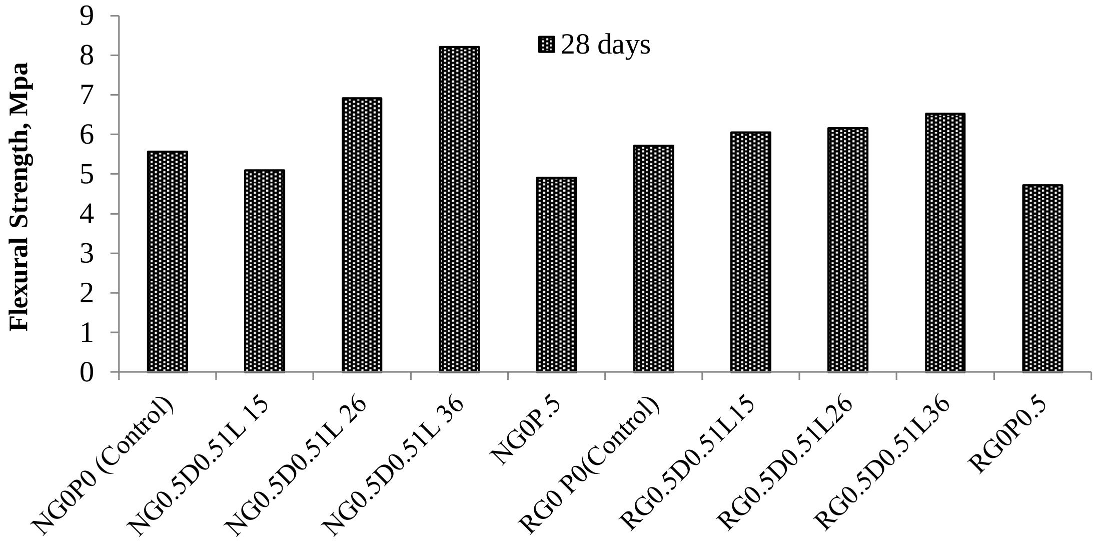


Figure 4-25: Flexural Strength of Concrete mixes

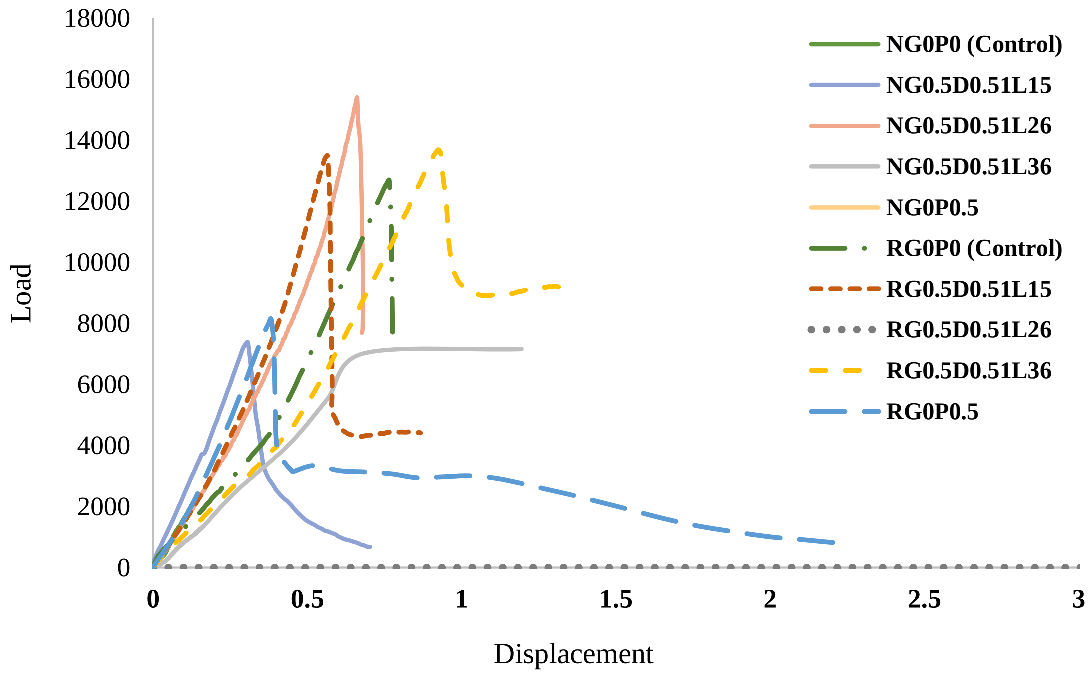
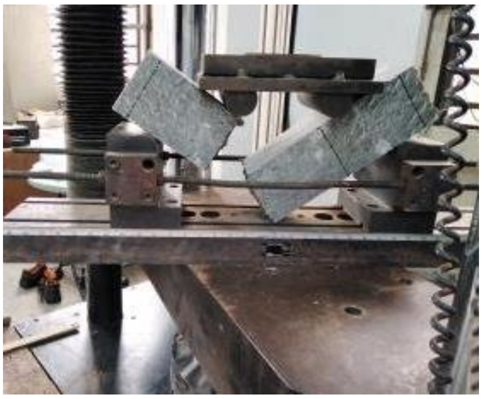


Figure 4-26: Load- Displacement Curve for all concrete mixes


(a)


(b)


(c)


(d)

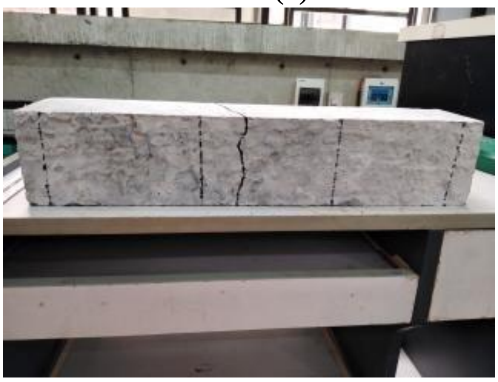

(e)

Figure 4-27: Failure pattern of beam (a)RAC without fiber (b) RAC with GI fiber L=15 mm(c)RAC with GI fiber L=26 mm (d)RAC with GI fiber L=36 mm (e)RAC with PP fiber

4.4.5 Relationships and Code Comparison

According to Table 3-6 using different equations tensile strength and young modulus have been calculated in terms of compressive strength to predict these strengths. Figure 4-28 shows comparison of split tensile strength with different codes and Figure 4-29 shows the similar comparison for Young’s modulus.

Table 4-13: Summary of flexural test on test beams

Properties	Flexural Strength, fp (MPa)	Flexural Toughness Factor (FTF) (KPa) (JSCE G-552)	Toughness, T^{D}_{150}	Eqv. Flexural Strength Ratio, $R^{D}_{T,150}$(%)
NG_0P_0 (Control)	5.56	1.09	7295.35	19.68
$NG_{0.5}D_{0.51}L_{15}$	5.09	0.94	6277.38	18.50
$NG_{0.5}D_{0.51}L_{26}$	6.91	1.01	6724.25	14.60
$NG_{0.5}D_{0.51}L_{36}$	8.2	1.16	7713.85	14.11
$NG_0P_{.5}$	5.18	0.33	2170.49	6.29
RG_0P_0(Control)	5.71	0.63	4202.72	11.04
$RG_{0.5}D_{0.51}L_{15}$	6.05	0.69	4574.27	11.34
$RG_{0.5}D_{0.51}L_{26}$	6.16	0.71	4739.57	11.54
$RG_{0.5}D_{0.51}L_{36}$	6.52	0.96	6429.94	14.79
$RG_0P_{0.5}$	4.73	0.40	2696.34	8.55

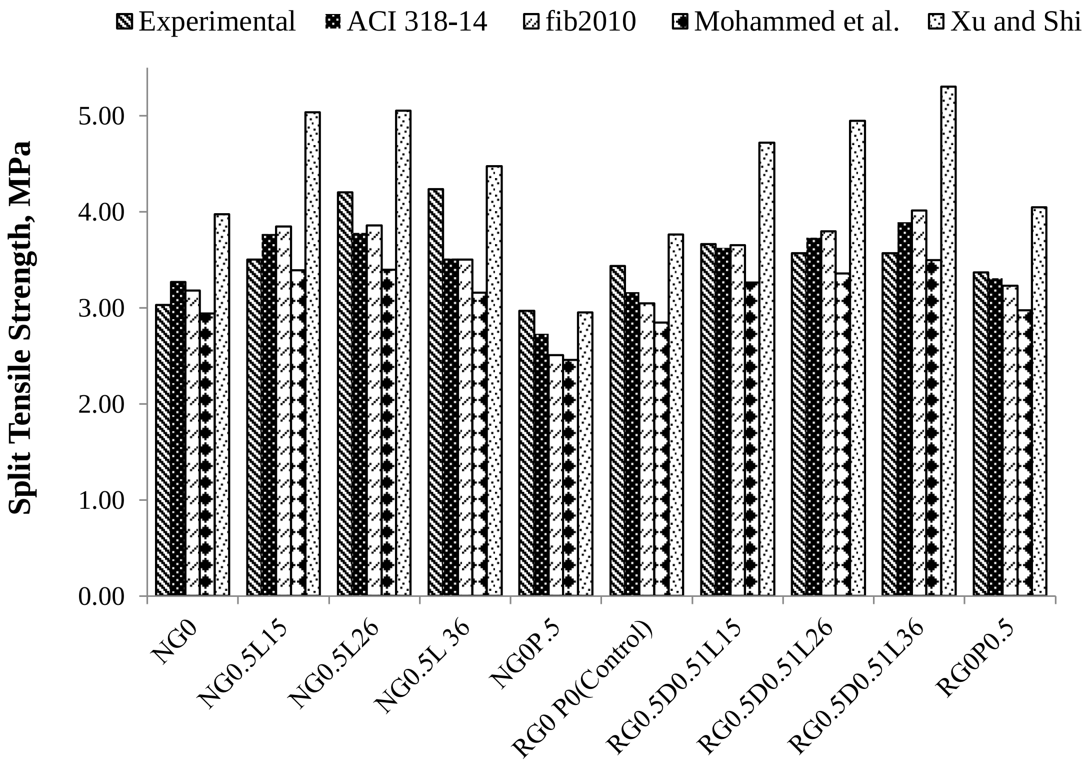


Figure 4-28:Comparison of Split tensile strength with different codes

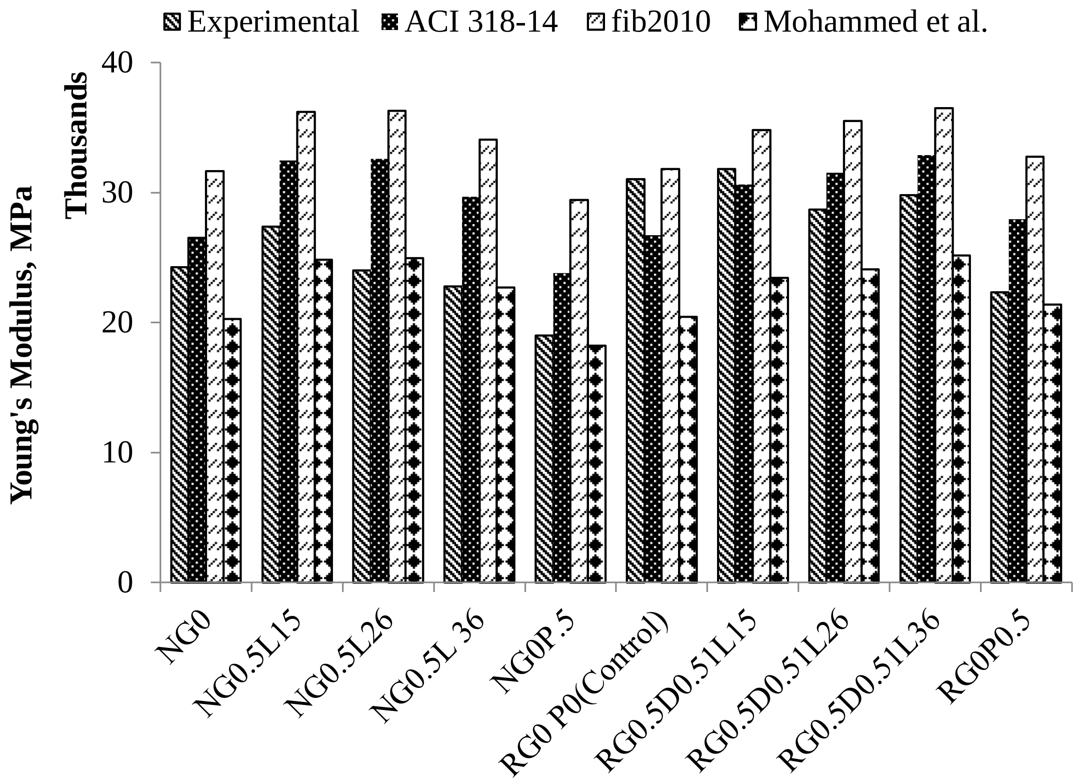


Figure 4-29: Comparison of young modulus with different codes

From Figure 4-28 it can be seen that the values from the equation for SFRC, given by Xu and Shi predicts highest results comparatively than the experimental results. For most of the cases, a ratio of theoretical to experimental value is greater than 1. So, the experimental values are underestimated by the theoretical value for split tensile strength. In case of Young's modulus, experimental values are underestimated by ACI 318-14 [77] except for control RAC and RAC with 15 mm length GI wire and fib 2010 [78] underestimate all values. But equation proposed by mohammed et. al [79] have underestimated split tensile strength and young modulus in some cases.

4.5 Conclusion

This study was conducted in two stages. In the first stage, fiber percentages were varied to find out the most suitable fiber percentage for the second stage of the study. Both fresh and hardened properties were evaluated. As no admixture was used in this step, workability was found to be very low as fiber added to the concrete. Concrete containing 0.5 % GI fiber had maximum improvement in compressive strength although fiber hardly affects the compressive strength of concrete and also showed maximum stress and strain at 28 days. Concrete with GI wire showed better ductility than concrete with PP fiber. However, concrete with 0.5 % GI fiber showed the most improvement in the split tensile strength of concrete. Meanwhile concrete containing GI fiber had maximum flexural strength than other concrete mix. Increased GI fiber content also improved the toughness of concrete. Considering all the test results, between GI and PP fiber, GI fiber has been chosen for further study. Furthermore, among the two fiber percentages (0.5% and 1%) 0.5% was selected for further study as high fiber content cause workability problem.

In the second stage of the study, effects of diameter and length of GI fiber on fresh and hardened properties of concrete was studied. Workability of concrete containing different diameter of fiber at same aspect ratio decreased with the increment of fiber diameter. Compressive strength and split tensile strength significantly increased when 0.51 mm diameter was added to concrete and it also showed better ductility. On the other hand, 1.21 mm diameter fiber demonstrated increased flexural strength compare to concrete with 0.51and 0.70mm diameters GI fiber. However, for concrete with 1.21 mm diameter fiber produced concrete that were less workable, compare to concrete with 0.51 mm diameter GI fiber.

For the next stage of the study, varied length of 0.51 mm diameter GI fiber was adopted in both NAC and RAC. In case of workability, NAC had higher slump value than the RAC; whereas, in case of air content both NAC and RAC had almost similar values. However, air content increases with fiber content in concrete. RAC with fiber possessed comparable compressive strength with NAC. RAC with 26 mm and 36 mm showed better compressive strength than NAC. Furthermore, RAC showed long term strength gain, especially at 56 days. In case of split tensile strength, for NAC, 36 mm length GI wire and for RAC, 15 mm length GI wire provided highest strength. Flexural strength of RAC increased with the increment of GI fiber length. RAC performed better than NAC in case load-displacement and PP fiber was better for ductility. For both NAC and RAC, GI fiber acted better than PP fiber.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 General

In this study, an attempt has been made to find out how locally available GI wire act as a fiber in comparison to PP fiber; and also, the influence of GI fiber on the fresh and harden properties of normal aggregate concrete (NAC) and recycled aggregate concrete (RAC). A comparison of NAC and RAC with fibers was also performed to evaluate the differences in properties of concrete. The effect of fiber type, fiber length and fiber diameter were performed on compressive strength, modulus of elasticity, split tensile strength, flexural strength and ductility of NAC and RAC. Therefore, in the present study, GI fiber length and diameter were varied depending on the availability of GI wire locally. In the first part of the study, performance evaluation of fiber type was conducted between PP and GI fiber with various percentages. In the second part of the study, 0.5% GI fiber was used in concrete with three different GI fiber diameter, such as 0.51 mm, 0.71 mm and 1.21 mm diameter, and cylindrical and beam samples were prepared for strength evaluation. Finally, 0.51 mm diameter GI fiber with three different length 15 mm, 26 mm and 36 mm was incorporated in both NAC and RAC.

5.2 Conclusions

i. For the first part of the study concrete mixes were made without admixture and slump value were found to be zero in most concrete with fibers. Therefore, in the second part of the study, a super plasticizer was used to improve the workability of concrete. Based on the study result, it can be concluded that fibers reduce the workability of concrete. Reduction in workability was proportional to increase in fiber diameter and length; and it decreased from 37.5 to 95.8% for fiber diameter and 10 to 50% for fiber length. Furthermore, RAC concrete had relatively lower workability than the NAC for both concrete with and without fibers. For NAC maximum slump was recorded 150 mm which was10% higher than the RAC. Reduction in workability was higher in PP fiber reinforced concrete compared to the GI fiber reinforced concrete for same fiber inclusion.

ii. Air content in fresh concrete was measured for NAC and RAC. As observed from the results, RAC showed higher air content ranges from 2.7 to 4.2 % where NAC showed air content ranges from 1.2 to 3.4 %. NAC had maximum air content of 3.4; whereas RAC had maximum air content of 4.2. Concrete with GI fiber showed higher air content than concrete with PP fiber. Furthermore, air content increased with increasing GI fiber lengths.

iii. At 28 days, compressive strength of concrete containing 0.5% GI fiber was highest and the value was 31.1MPa. On the other hand, at 1% GI fiber content, the strength was25.4MPa which was even less than the strength of concrete without fiber. Furthermore, 0.5% GI fiber content showed considerable enhancement in stress distribution and had a maximum elastic modulus of 27.8 GPa. Similar to compressive strength, an increment in split tensile strength was found for concrete with 0.5% GI fiber (3.33 MPa) which was 12% higher than the controlled specimen. However, 0.5% PP fiber content did not affect the split tensile strength of concrete but 1% PP fiber had decreased the split tensile strength. Based on the results, it can be concluded that, GI fiber up to 0.5% can improve strength properties of concrete; whereas, high percentage of GI and PP fiber has adverse effect on both compressive and tensile strengths.

iv. Concrete with 0.5% and 1% GI fiber content had improved flexural strength. But PP fiber had caused a reduction in flexural strength of concrete. From the load-deflection curve, it was observed that inclusion of fiber delayed the plastic region. Furthermore, concrete containing GI fiber had better post-crack resistance and ductility.

v. During evaluation of GI fiber diameter effects (among 0.51 mm, 0.70 mm and 1.21 mm diameter of GI fiber) in terms of compressive strength and split tensile strength concrete containing 0.51 mm diameter GI fiber showed maximum strength than the others. At the same aspect ratio concrete containing lower diameter fiber acted better in stress development and showed better ductile behavior than other diameter fiber. Elastic modulus of concrete containing GI fiber was proportional to the increment of fiber diameter and maximum elastic modulus was recorded 29.8 for GI fiber diameter 1.21 mm.

vi. In terms of flexural strength, a contrasting result was observed. Concrete made of 1.21 mm diameter GI fiber showed 20% and 36% higher flexural strength and toughness respectively than the control specimen.

vii. As recycled aggregate (RA) has considerably inferior properties than the NA which reflects the strength of RAC. At 28 days compressive strength of RAC is lower than the NAC. But with fiber inclusion the RAC showed better compressive strength. From 56 days compressive strength results, it can be seen that the RAC resulted higher strength than the NAC. So, it can be said that RAC has long term strength gaining capacity. In long curing period RAC with PP fiber also shows higher results than control specimen. The split tensile strength of NAC with fiber is higher than the RAC with fiber. But fiber improved the split tensile strength of RAC with fiber. However, the strengths of RAC with fibers are compatible with NAC, Considering GI fiber length ,26 mm and 36 mm length GI fiber imparts better results for both RAC than in NAC.

viii. GI Fiber improved the flexural performance of RAC and NAC. GI fiber of 36 mm length performed better than the other length fiber. But PP fiber gave better ductility to concrete. Flexural strength of RAC increased with the GI fiber length. But NAC did not show any pattern like RAC.

ix. From the test results it can be say that GI fiber performs better than PP fiber and it improve the mechanical properties (compressive, tensile and flexural strength) of both NAC and RAC. Among other GI fiber length, 36 mm GI fiber showed better performance to improve strength. On the other hand, RAC exhibits better results in terms of load-displacement. RAC with 36 mm GI wire also showed better ductile behavior.

x. Recycled concrete can be also used in the production of concrete for pavements, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundation. As inclusion of fiber in RAC ids improving its quality so it can be used for structural and non-structural element. It will help to promote sustainable development in the protection of natural and reduces the disposal of demolition waste from old concrete

5.3 Recommendations

i. In this study, strength gain was measured at maximum 56 days. However, long term strength gain can be observed for RAC with fiber.

ii. For this study, recycled aggregate was collected from 1-2 years old concrete. Recycled aggregate from demolished building concrete of different life time can be collected and used for the future study.

iii. RAC and GI fiber can be used for large structural element, such as full-scale beam and column to evaluate their performance.

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Appendices

Appendix A: Figures of Different Stage of Experiment

Figure A.1: Concrete Mixing

Figure A.2: Sample Preparation

Figure A.3: Curing of Samples

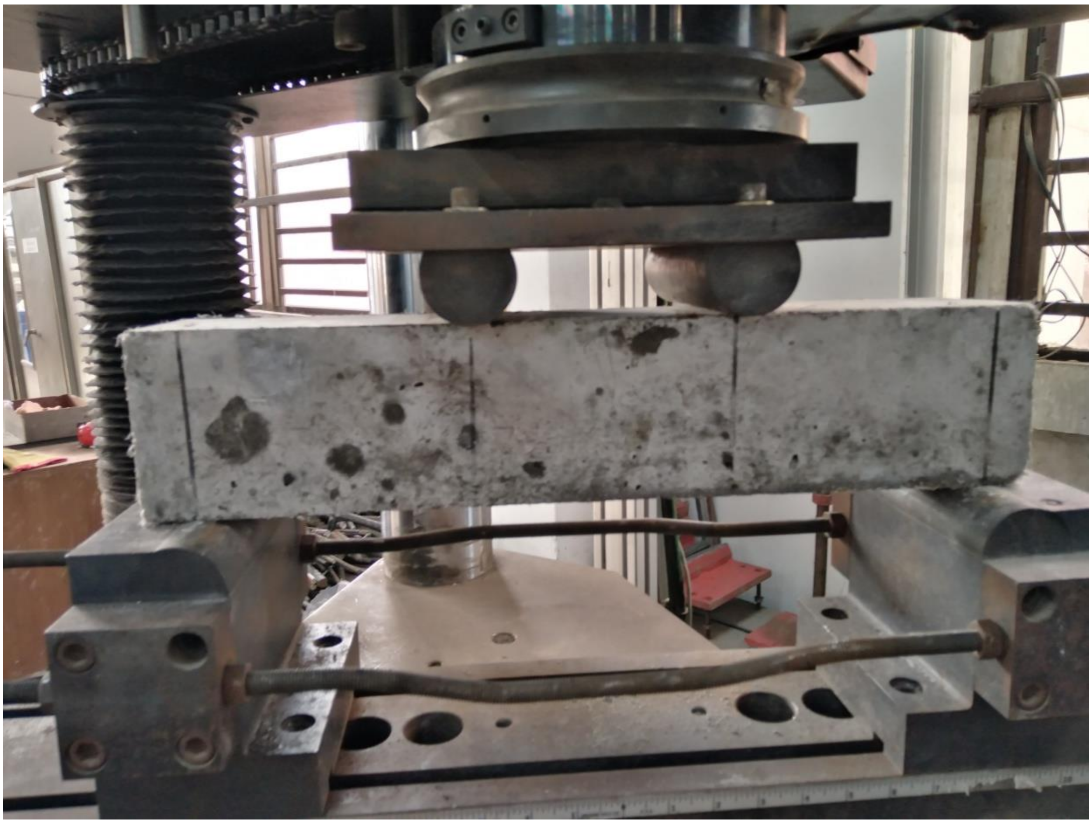

Figure A.4: Sample testing