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Improvement in Properties of Concrete using Hybrid Fiber and Ground Granulated Blast Furnace Slag

by

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I want to dedicate this achievement my parents, teachers and friends who always encourage and support me in every crucial time

CERTIFICATE OF APPROVAL

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Abstract

Concrete is widely used in construction throughout the world because it is available easily, low cost, and can withstand harsh climates. While concrete has many advantages, it also has some disadvantages as well. The cracking of concrete is a very common phenomenon. Cracking has a worse effect on the performance of concrete. Additions of fibers minimize cracking by converting the brittle nature of plain concrete to the tough nature of FRC. Cement, aggregates, and water are the major components of concrete and the cost of concrete depends mostly upon these components. A major component of concrete is the cement that is responsible for the emission of carbon dioxide and other greenhouse gases. These gases are responsible for global warming. Therefore, to minimize this problem alternative to cement is most required. GGBS is the waste creation of iron production factories that can be used to replace cement in concrete. Concrete having glass and banana fiber along with GGBS can minimize the above problems.

This research investigates the mechanical properties, dynamic properties, and water absorption properties of hybrid fiber reinforced concrete along with admixture. Fibers used in the concrete are glass and banana fibers and the admixture is GGBS. The mix design for plain concrete (PC) is 1:2:3:0.6 (cement: fine aggregate: coarse aggregates: water) while the mix design for HFRC is the same as that of PC but the water-cement ratio is kept at 0.7. Length of banana and glass fibers are kept 5cm and fiber contents by 5% mass of cement are used. A total of 42 specimens are cast in the casting yard and placed in water for 28 days. Specimens are tested for dynamic, mechanical, and water absorption properties. SEM imaging is utilized for the analysis of fiber concrete bond conditions. Similarly, a TGA test on HFRC is performed for checking the effect of temperature on the HFRC.

Compressive strength of A1, A2, A3, A4, A5 and A6 mixes are 8.5% , 25%, 15%, 17%, 16% and 16% less than that of PC. Tensile strength of A1, A2, A3, A4, A5 and A6 mixes are 3%, 53%, 36%, 25%; 18%, and 43% less than that of PC. Flexural strength of A1 is 0.01% more than that of PC. Flexural strength of A2, A3, A4, A5, and A6 mixes are 36%, 19%, 7.9% 26%, and 20% less than that of

A0 respectively. Compressive toughness index (CTI) for A0, A1, A2, A3, A4, A5, and A6 mixes are 2.28, 2.25, 4.1, 2.55, 2.61, 2.71 and 3.05, respectively. The compressive toughness index of A1 mix is 1% less than that of PC while CTI of A2, A3, A4, A5, and A6 mixes are 79%, 11%, 14%, 18%, and 33% more than that of PC. While split-tensile toughness index and flexural toughness index of HFRC mixes are more as compared to that of PC. The results show that HFRC mixes have more value of water absorption, damping ratio, dynamic modulus of elasticity, and dynamic modulus of rigidity as compared to that of PC. Uniformly dispersed glass and banana fibers throughout the concrete matrix are seen through SEM images. TGA analysis shows that at higher temperatures there is no mass loss in HFRC specimens are observed. The relationship between water absorption of PC and HFRC is developed by discussing CS, STS, and FS and an empirical equation is formed. The experimental and empirical relation between water absorption is discussed; empirical results and experimental results are in good agreement with each other. It is concluded that the incorporation of glass and banana fibers along with the GGBS in concrete improves the properties of the concrete. Therefore, it is recommended to use glass fiber and banana fiber along with GGBS in concrete for commercial use.

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Abbreviations

A0 or PC	Plain Concrete
A1	8% GGBS
A2	Banana= 4.5%; Glass= 0.5%; 8% GGBS
A3	Banana= 3.5%; Glass= 1.5%; 8% GGBS
A4	Banana= 2.5%; Glass= 2.5%; 8% GGBS
A5	Banana= 1.5%; Glass= 3.5%; 8% GGBS
A6	Banana= 0.5%; Glass= 4.5%; 8% GGBS
BF	Banana Fiber
BFRC	Banaa Fiber Reinforce Concrete
CTI	Compressive Toughness Index
$\mathbf{E}_T$	Total Energy Absorption
$\mathbf{E}_\alpha$	Energy Absorption till Maximum Load
$\mathbf{E}_\beta$	Cracked Energy Absorption till Ultimate Failure
Exp	Experimental
FTI	Flexural Toughness Index
G	Glass Fiber
GGBS	Ground Granulated Blast Furnace Slag
GPa	Giga Pascal
GF	Glass Fiber
GFRC	Glass Fiber Reinforce Concrete
HFRC	Hybrid Fibers Reinforced Concrete
kN	Kilo-Newton
mm	Millimeter
MPa	Mega Pascal

RF_l	Resonance Frequency Longitudinal
RF_r	Resonance Frequency Rotational
RF_t	Resonance Frequency Transverse
SEM	Scanning Electron Microscopy
STI	Split-tensile Toughness Index
TGA	Thermogravimetry Analysis
WA	Water Absorption
W/C	Water Cement Ratio
XRD	X-rays Diffraction

Symbols

δ	Strength
Δ	Deformation/Deflection
ε	Strain
ξ	Damping Ratio
$\mathbf{E}_{dyn}$	Dynamic Modulus of Elasticity
$\mathbf{G}_{dyn}$	Dynamic Modulus of Rigidity
$\mathbf{P}_{max}$	Maximum Load

Chapter 1

Introduction

1.1 Background

The use of one fiber enhanced the properties of concrete but the hybridization of fibers in concrete gave more smart working properties to the concrete. As the performance of one fiber accelerated the properties of another fiber and dynamic properties of concrete were enhanced by using two types of fibers [1]. Properties of high-strength concrete by using hybrid fibers were investigated. Palm and steel fibers were used for the preparation of hybrid fiber concrete. When these fibers were used, flexural toughness and rigidity got improved [2]. Concrete is an important construction material and used all over the world. Concrete has a lot of advantages but in the same manner, there are a lot of flaws in concrete as well. One of the most alarming conditions that appear in the concrete is the generation of cracks during its different ages. Cracking occurs due to several reasons. During the pre-hardening stage of concrete, plastic cracks occur and when concrete is fully hardened, there appear shrinkage cracks. With time these cracks increase in size and the microstructure of concrete is exposed to rain and other harmful ingredients like silicate, calcium, and bromide. Different types of structural failure are due to cracking. Usually, concrete made from admixture and hybrid fibers was light weight having lower density and higher flexural strength [3, 4, and 5].

The incorporation of steel, polypropylene, and carbon fibers in concrete increased the compressive and split tensile behavior of concrete thus decreased the brittleness of the concrete [6]. Properties of high-strength lightweight aggregate by using mono and hybrid fiber were studied. Stress-strain curve, compressive behavior, flexural behavior, split tensile behavior and water absorption properties of concrete were discussed. Concrete having hybrid fibers had superior properties as compared to concrete having mono fibers [7]. Properties of lightweight aggregate concrete in the presence of admixture were studied. Mono and hybrid fiber were used in concrete, improvement in splitting tensile behavior and flexural strength was observed when compared to the PC [8]. Glass and steel fiber along with the GGBS and metakaolin in concrete enhanced the thermal properties of concrete. A higher dose of super-plasticizer was added to the concrete to make it more workable. With various percentages of fiber, 20% metakaolin, and 10% GGBS compressive strength of concrete was increased [9]. Usage of concrete is increasing day by day due to the innovation in construction. High-strength concrete is used for construction purposes. Due to rapid urbanization, there is a lot of demand for high-strength concrete to lessen the size of structural members and to save natural resources [10]. From the past researches, it was shown that the incorporation of steel fiber along with natural fiber lessens the slump values of the concrete while flexural and split tensile strength of the concrete was increased [11 and 12]. When polypropylene fiber was added in concrete mix ductility and impact energy absorption of concrete was increased [13 and 14]. The presence of glass fiber in concrete controlled the abrupt crack formation and hence ductility of concrete was increased [10]. By increment of glass fiber from 0% to 1.2% the compressive strength increased from 58.735 MPa to 65.2 MPa. Tensile strength increased from 3.25 MPa to 4.5 MPa, while flexural strength increased from 5.215 MPa to 7.21 MPa [15]. Impact resistance behavior of steel-sisal and steel-polypropylene fiber in concrete was examined, steel-polypropylene fiber performs well under compressive loading as compared to steel-sisal fiber [16]. The use of other admixtures such as silica fume and rice husk improved the cracking behavior of concrete and hence increased the split-tensile properties of the concrete [17 and 18].

The behavior of high-strength concrete by using hybrid fibers was inspected. Hybrid fibers were used in different ratios along with metakaolin and micro silica. Material properties of hybrid fiber and ductility properties of the concrete improved up to 25% than that of PC [19]. The behavior of high-performance self-compacting concrete beams having no course aggregates by incorporating polypropylene fibers was studied. The compressive strength of high-performance self-compacting concrete beams was increased [20]. Flexural and durability characteristics of high-strength concrete by using hybrid fibers and admixtures were examined. Silica fume and GGBS were used as mineral admixtures and single hooked, double hooked steel fibers and polyvinyl alcohol (PVA) fibers with different concentrations were added to the concrete mix. Compressive test, split tensile test and electrical resistivity tests were performed on the concrete specimens. The results indicated that the addition of silica fume enhanced the toughness properties of concrete and more durable concrete was obtained by the addition of silica fume and GGBS [18]. The addition of steel fibers enhanced the mechanical parameters of concrete, post cracking flexural resistance, and durability of concrete [17]. The effect of steel and polypropylene fiber on the mechanical properties of concrete was studied. The compressive and flexural behavior of the concrete was enhanced when 2.5% of steel fibers were added to concrete matrix [21].

Properties of quaternary blended high routine concrete by adding banana and steel fibers were calculated. Silica fume and GGBS were added 5% to 10% in the replacement of cement. Results showed that mechanical properties were enhanced while the workability was decreased [22]. Concrete manufacture from cement is responsible for the emission of greenhouse gases, therefore cement is replaced with fly ash, GGBS, and metakaolin. GGBS affects the strength of the concrete more as compared to other admixtures [23]. Properties of hybrid fibers reinforced concrete by using metakaolin were studied. Mechanical properties of hybrid fibers reinforced concrete including steel fibers, polypropylene fibers, and sisal fibers were compared with PC. Results showed that the cracking was reduced up to 1.5% by using steel and polypropylene fibers [24 and 25].

From the literature review, it is clear that the use of hybrid fibers along with admixtures gives attractive engineering properties. From the critical literature review, it is evident that most of the studies limited to observe mechanical properties of hybrid fibers reinforced concrete and dynamic properties that have the most importance in concrete structures are missing. On the other hand, no study is done on the combination of banana fibers and glass fibers along with GGBS. Therefore, detailed investigations need to be concluded on awareness of the behavior of banana fibers and glass fibers along with GGBS.

1.2 Research Motivation and Problem Statement

The construction industry is innovating day by day and there is a huge demand for concrete having good mechanical properties and dynamic properties. The main issue with ordinary concrete is the low energy absorption and formation of cracks during different stages of concrete. Thus, these cracks reduce the performance of concrete, and ultimately contributing towards the failure of structures. So present research is to minimize such type of problems by the addition of hybrid fiber (glass fiber and banana fiber) along with GGBS in the concrete.

Thus the problem statement is as follows:

"Concrete has low resistance to cracks and has low tensile strength. The main problem in ordinary concrete is the cracking, low energy absorption, and low toughness index. Impact resistance of ordinary concrete is also less. So there is a need to enhance the mechanical and dynamic properties of concrete by converting the brittle nature of plain concrete to the tough nature of FRC."

1.2.1 Research Questions

Why hybrid fiber reinforced concrete is more efficient than single fiber reinforced concrete?

Why glass fibers and banana fibers are used in this research?

How the addition of GGBS affect the strength of hybrid fiber reinforced concrete?

1.3 Overall Objective of the Research Program and Specific Aim of this MS Thesis

The overall goal of the research program is to explore the behavior of hybrid fiber (artificial and natural) reinforced concrete under different conditions.

The specific aim of this MS research work is to investigate the mechanical, dynamics and water absorption properties of concrete having glass and banana fibers along with ground granulated blast furnace slag.

This specific objective is to consummate by the following tasks (significant the choice of current investigation work):

i. Mechanical properties (compressive behavior, splitting tensile behavior, flexural behavior, and water absorption), dynamic properties (resonant frequencies, damping ratio, dynamic modulus of elasticity, poisons ratio, and dynamic modulus of rigidity) of plain concrete, concrete having 8% GGBS and hybrid fibers reinforced concrete.

ii. SEM and TGA tests on concrete

iii. Based on the conducted investigation, to recommend suitable HFRC for commercial use.

1.4 Scope of Work and Study Limitations

42 specimens having GGBS and different combinations of banana and steel fibers are cast. Compression, split tensile and water absorption tests are performed on cylinders while flexural testing is performed on beam-lets. The dynamic testing is performed on cylinders and beam-lets. Glass fiber and banana fiber are selected for the manufacturing of hybrid fiber reinforced concrete. Cement is replaced with 8% of GGBS. The physical, dynamic, and mechanical properties of PC and HFRC are investigated. Water absorption tests are performed. Tests are performed on two specimens and the average of these two values is taken. SEM and TGA tests

are performed on HFRC. The length of the fibers is 5cm. The total numbers of specimens are 42. With time dark patches are formed on the surface of concrete due to the addition of GGBS and the study of such behavior is outside the scope of this research.

1.4.1 Rationale Behind Variable Selection

Glass and banana fiber is used in this research because these fibers are easily available and have good properties. Glass fiber has good tensile strength while banana fiber has good bonding properties. From the literature review, it is clear that the combination of natural fiber along with synthetic fiber gives good properties to the concrete. Ground Granulated Blast furnace Slag (GGBS) is a byproduct of the blast furnaces and it is available easily and has good binding properties. The concrete made from the partial replacement of cement with GGBS is cheap and also eco-efficient.

1.4.2 Investigation Methodology

In the present research, the properties of concrete are studied by using glass fibers and banana fibers along with GGBS. Mechanical, dynamic, and water absorption properties of concrete are studied. Mix design ratio is 1:2:3:0.6 (cement, sand, aggregate, and water) for A0 and A1. While mix design for HFRC is 1:2:3:0.7 (cement, sand, aggregate, and water). W/C ratio for PC is 0.6 while the W/C ratio for HFRC is 0.7. The addition of fibers decreases the workability of concrete to make HFRC more workable W/C ratio of HFRC is kept at 0.7 rather than 0.6. GGBS is used in the concrete mixes, 8% of cement is replaced with GGBS along with hybrid fibers or without hybrid fibers. Banana fiber and glass fiber are used in concrete for hybridization, length of fiber is kept 5 cm and 5% contents by mass of cement is added in the concrete mix. Both fibers are used in different ratios along with GGBS to make HFRC. Workability of mixes of PC and HFRCs are computed in a fresh state by using the standard procedure of slump cone test. Specimens are cast in the casting yard and then put in water for 28 days after that different types of mechanical and dynamic tests are performed on the cylinders and beam-lets of PC and HFRC. Mechanical tests include compressive test, split tensile test, water absorption test, and flexural test. Similarly, in dynamic testing resonance frequencies, damping ratio, dynamic modulus of elasticity, dynamic modulus of rigidity, and poisons ratio of PC and HFRC are calculated. SEM and TGA tests are performed on HFRC. The servo-hydraulic testing machine is used for mechanical testing while the resonance frequency apparatus is used for the calculation of dynamic properties.

1.5 Thesis Outline

This research work has six chapters:

Chapter 1. This chapter includes an introduction, research motivation, problem statement, overall objective, specific aim, research methodology, and thesis outline.

Chapter 2. This chapter includes a literature review segment. It explains the background, flaws in concrete, the role of hybrid fiber in concrete, the role of GGBS in concrete performance, the novelty of current work, and a summary.

Chapter 3. This chapter consists of the experimental procedure. This chapter explains the background, material, and mix design, the procedure of casting, testing, and summary.

Chapter 4. This chapter consists of analysis and testing results. This chapter explains the behavior of PC and HFRC during different testing, effects of different fiber concentrations and GGBS on the performance of PC and HFRC, dynamic properties of PC and HFRC, outcomes of water absorption of specimens, SEM and TGA of HFRC, and a summary.

Chapter 5. This chapter contains background, empirical relation, the empirical equation between water absorption and selected strength properties, use of research result in actual Life applications, and a summary.

Chapter 6. This chapter explains the conclusion and recommendations.

References

Chapter 2

Literature Review

2.1 Background

Hybrid fibers are used in the concrete to attain the maximum properties of the concrete. A lot of researches used more than two fibers in concrete for improving the properties of concrete. Cement is the main constituent of concrete and it gives strength and binding properties to the concrete. Concrete made from cement is costly so replacement of cement with admixtures having similar properties to that of cement lessens this problem. Because these admixtures are low cost and easily available. Cracking in ordinary concrete is its main flaw. The cracking pattern in the concrete rigid pavement can be condensed by refining the dynamic properties, compressive, splitting-tensile, and flexure strength of concrete. In this chapter flaws in concrete, the role of hybrid fiber in concrete, and the role of GGBS in concrete performance are discussed.

2.2 Flaws in Concrete

Flaws in concrete are due to several reasons that affect the performance of the structure. Different researchers investigated different flaws in concrete. The main flaw in concrete is the sudden failure of concrete due to external chemical attacks on concrete and different external factors [26]. The cracking pattern in concrete was studied by using different methods. Cracking in concrete was due to shrinkage (plastic and drying) of concrete. The durability of plain concrete was also less due to cracking [27]. Spalling of concrete was investigated by many researchers. This flaw is due to the infiltration of reactive agents from pores of concrete [28]. Cracking in concrete is the most common phenomenon and occurs due to several reasons. Cracking in walls and slabs affect the look of the structure and decreases its strength of bearing load and sometimes, due to the presence of excessive cracking structure doesn't perform well. Figure 2.1 shows the cracking mechanism in rigid pavement or slab.

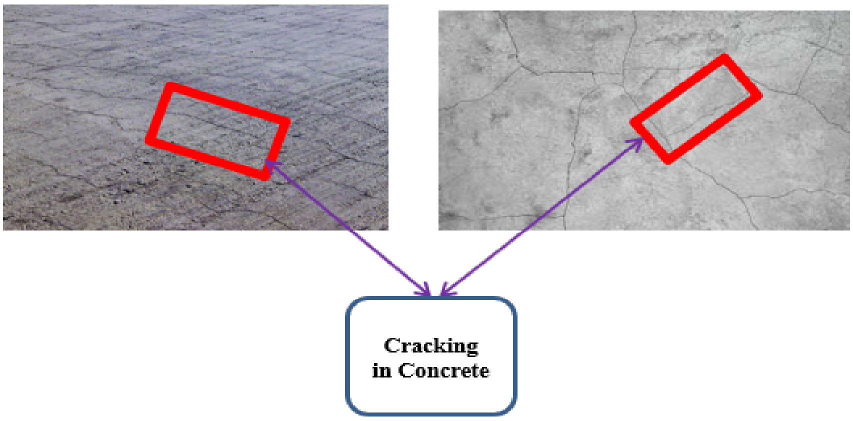


FIGURE 2.1: Cracking in Rigid Pavement

In the fragile stage of concrete, shrinkage and plastic settlement of concrete occurs. This phenomenon along with other factors results in plastic shrinkage of concrete and due to this plastic cracks occur [29]. Plastic cracking is harmful in the bridge deck and rigid pavement having larger surface area [30]. One of the old problems of concrete is plastic shrinkage. Plastic shrinkage occurs due to the settlement of solid particles and evaporation of water from the concrete surface. The problem of plastic shrinkage is minimized by using fibers and super-plasticizer [31].

2.3 Potential of Hybrid Fibers and GGBS as Construction Material

Concrete is generally used in mega projects all around the world. By suitable addition of hybrid fibers and admixture increases the properties of concrete to a larger extent. Mechanical and dynamic properties of concrete can be improved by using different types of fibers and admixtures. With time concrete is innovating day by day. Different types of fibers and admixtures are used to improve the properties of concrete. There is a lot of work done on FRC due to the increment in properties of concrete by using fibers and admixtures. Two types of different fibers in concrete give attractive properties as compared to single fiber reinforced concrete. This concept of hybridization (using two fibers in concrete) was given by different researchers for the better performance of concrete. Hybrid fibers give the smart working properties because one fiber improves the properties of other fiber for the better performance of concrete [32]. Combination of two fibers in which one is durable and hard increases the durability properties and strength of the concrete. While another fiber improves other properties of concrete. Hybrid polymer fiber concrete is mostly lightweight concrete having improved mechanical and dynamic properties.

The use of stiff and flexible fibers enhances the strength of first crack and post-crack toughness [33]. The stiff fiber in concrete increases the strength properties of concrete. Moreover, the use of two fibers increases the toughness indices of the concrete [2]. Characteristics of concrete by the limited replacement of steel and polypropylene with common aggregate were examined. Some proportion of cement with fly ash was replaced, toughness and ductility of concrete were increased [34]. Properties of hybrid fibers concrete (glass fiber and steel fiber) were studied. The bridging effect in HFRC was more as compared to plain concrete. In this way, sudden failure due to impact loading was minimized by using steel and glass fiber [35]. Properties of banana fiber reinforced concrete (BFRC) were studied in the presence of admixture. Banana Fibers had a good tensile and bond strength, hence could reduce the different types of cracking [36].

Characteristics of hybrid fiber reinforced concrete along with GGBS were studied. Two types of fibers (banana and polypropylene fibers) were incorporated along with GGBS in concrete to boost the strength of concrete without upsetting the workability. The compressive strength, flexural toughness index, and damping ratio were enhanced when 1.5% of banana fibers and 2% of polypropylene fibers along with 8% of GGBS were added to the concrete mix [37]. Experimental analysis of HFRC having GGBS was performed. This admixture reduced the water requirement during curing stages and also prevents plastic shrinkage during the pre-hardening stage of concrete [38]. High-strength concrete having steel and polypropylene fiber was prepared. Results showed that the addition of silica fume enhanced the toughness and mechanical properties of concrete [39].

2.3.1 Role of Hybrid Fibers in Concrete

Concrete made up of two or more fibers is hybrid fiber reinforced concrete. The performance of hybrid fiber concrete with glass fiber and steel fibers was considered. Various models of concrete having glass and hybrid fibers were made. The use of fibers minimized the cracking and hence increased the flexural strength of concrete [40]. Properties of concrete by using coir fiber and banana fiber in the presence of admixture were calculated. Different combination of hybrid fiber reinforced concrete was made and the characteristics of concrete were studied. The split tensile strength and ductility of concrete were increased [41]. Addition of 1800g/cm^3 of glass fibers increased 31.5% of compression strength, 29.9% of flexural strength and 97% of split-tensile strength respectively [42]. Mechanical properties and energy absorption capacity of concrete were checked by incorporating glass fibers at a percentage level of 1%, 2%, 3%, and 4% by weight of cement in concrete mixes. Split-tensile strength and flexural energy absorption of concrete were increased at a percentage of 4% of glass fibers [43].

Properties of concrete were studied by adding glass fibers content in the ratio of 0, 0.5, 1, and 1.5% by volume of cement along with aluminum oxide nanoparticles contents of 0, 0.5, 1, 1.5, 2, and 3 % by weight of cement. Compressive and tensile strength was increased when 2% aluminum oxide nanoparticles and 1% of glass fiber were added [44]. The addition of glass fibers in concrete improved the flexural strength and split tensile strength of the concrete. Plastic and drying shrinkage could be minimized by adding glass fibers in concrete [45]. The strength and durability of glass fiber reinforced concrete was compared with ordinary concrete. Glass fibers concentration varied from 0-1% and compression strength, split tensile strength and flexural strength of GFRC were investigated. After 7 and 28days compression strength was increased when 1% of glass fibers were added in concrete [46].

Properties of high-strength concrete were determined by using banana fibers and wood bottom ash. Cement is replaced with wood bottom ash and 0.5% to 2.5% of banana fibers content was used in concrete. Results showed that desired properties were obtained when cement is replaced with 10% of wood bottom ash and 1.5% of fiber content [47]. High-strength concrete was prepared by using palm fibers and jute fibers. Both of these fibers were added 6% content by mass of cement to check the properties of concrete. Hybridization of these fibers at 3.5% of palm fibers and 2.5% of jute fibers gave good mechanical properties, flexural toughness index, and flexural strength as compared to that of ordinary concrete [48]. Other researchers increased the value of natural fiber from 0% to 6% to enhance the properties of concrete [49]. In this study, banana fibers are added 4.5% by mass of cement in concrete to check the properties of concrete at higher concentrations of banana fibers. Reinforced concrete beams having banana fiber bars were prepared and mechanical properties were studied. Using banana fiber bars in concrete minimized cracking and spalling in concrete, the flexural strength of concrete beams was increased up to 25% as compared to PC [50].

When steel fiber was added by 5% mass of cement to the concrete slump value was decreased but the tensile and flexural strength of concrete was increased [51]. The result of the experiment showed that the impact energy absorption and ductility of concrete were increased when polypropylene fiber and glass fiber were added [52]. Properties of concrete by adding an equal amount of fibers (steel and polypropylene fiber) were analyzed. Results indicated that strength properties were increased by adding steel fiber as compared to polypropylene fiber [53]. Glass and banana fiber are used in current research and it is important to discuss the mechanical properties of glass and banana fiber. **Table 2.1** discusses the mechanical properties of banana and glass fiber.

TABLE 2.1: Mechanical Properties of Banana and Glass Fiber

Sr. No.	**Fibers**	**Fiber Diameter(in)**	**Specific Gravity**	**Tensile Strength (Ksi)**	**Elastic Modulus (Ksi)**	**Water Absorption(%)**	**Source**
1	Banana	0.14-0.14	1.32	275–350	1900-3585	55-65	[7]
2	Glass	0.3-0.8	2.5	220-580	10,400-11,600	-	[71]

Note in= inch, ksi= kilopound per square inch, %= Percentage.

The concrete beam was made by using banana fiber bars, the use of banana fiber bars in concrete beams reduced cracking and spalling [54]. From the earlier learning, it was clear that fiber length and volume fraction affect the properties of concrete. Higher compressive and flexural strength was obtained by adding steel fiber and glass fiber [55]. Characteristics of concrete having GGBS and hybrid fibers (carbon and glass fibers) were investigated. Properties of concrete were calculated by MATLAB software. The mechanical properties after 28, 56, and 90 days were compared, and an increase in flexural strength was observed at a higher concentration of glass fibers [56].

2.3.2 Role of GGBS in Concrete Performance

Characteristics of hybrid fiber reinforced concrete with GGBS were studied. Cement was replaced with 5%, 10%, 15%, 20%, and 25% of GGBS. The toughness index of hybrid fibers reinforced concrete was enhanced in the presence of 10% of GGBS [57]. The effect of GGBS on the properties and setting time of concrete was studied. The central composite design method was used to design the mixture. By adding GGBS in one-part geopolymer binders setting time and compressive strength was enhanced [38].

GGBS and metakaolin were partially replaced with cement and the respective properties were studied [58]. The behavior of hybrid fiber concrete along with GGBS was studied. Steel fiber and banana fiber were used in the concrete. Properties of hybrid fibers concrete were compared and it was shown that workability was decreased so a super-plasticizer was added. Compressive strength and crack resistance were increased [59]. Toughness load-deflection behavior and stiffness of the hybrid fiber concrete having GGBS were investigated. Cement is replaced with 12% of GGBS. Steel and polypropylene fibers were used in different concentrations. Compressive strength was improved when cement was replaced with 1% of GGBS [60]. Mechanical and physical properties of the concrete by using hybrid slag were considered. The sand was replaced by different concentrations of ferrochrome slag and cement was replaced by 25% of GGBS. Different types of tests were performed, GGBS along ferrochrome considerably increased compressive strength but voids ratio was decreased [61]. The industrial waste product is mainly used in concrete to minimize the cost of concrete. Because these wastes are cheap and easily available and have the potential to be used as aggregate in the concrete. Properties of concrete having glass and steel fibers in the presence of GGBS were investigated. Cement was replaced with 5%, 10%, 15%, 20%, 25% and 30% of GGBS. Compressive strength and toughness index of concrete increased when cement was replaced with 5% and 10% of GGBS respectively [62]. To have both parameters favorable, 8% GGBS is selected for this study. For many years, a lot of researchers is working to replace cement partially or fully with alternative materials. The industrial waste product is mainly used in concrete to minimize the cost of concrete. Because these wastes are cheap and easily available and have the potential to be used as aggregate in the concrete. The chemical composition of GGBS is quite similar to that of cement comparison of the chemical properties of cement and GGBS is discussed in table 2.2 [7].

TABLE 2.2: Chemical and Mechanical Properties of GGBS

	Cement (%)	**GGBS (%)**
CaO	64.64	36.62
Al_2O_2	5.6	14.73
SiO_2	21.28	33.86
Fe_20_3	3.36	0.48
MgO	2.06	6.33
SO_3	2.14	2.1
Specific gravity	3.15	2.88
Bulk density (kg/m^3)	1400	1200
Color	Grey	Black

2.4 Novelty of Current Work

To the best of the author's knowledge, no study is being conducted on the combined use of glass and banana fibers along with GGBS in concrete for improving its different properties. Using dissimilar types of natural fibers in the concrete has been studied by many researchers in past decades but no one used banana fiber and glass fiber along with GGBS in concrete.

2.5 Summary

From the above discussion, it is conducted that the use of hybrid fibers along with admixture gives better properties as compared to that of single fiber reinforced concrete. To minimize the cracking pattern of concrete, it is necessary to improve the dynamic and mechanical properties of concrete. From the literature review, it is clear that banana fiber has higher bonding strength and it is also easily available. On the other hand, glass fiber has good tensile strength. The combination of natural and synthetic fibers in concrete improves the performance of the concrete. From the past study, it is concluded that GGBS has the potential to replace cement in concrete.

Chapter 3

Experimental Program

3.1 Background

Natural fibers along with artificial fibers are used in concrete for the last two decades. Increasement in mechanical properties, toughness index, and damping ratio are the main outcomes of using hybrid fiber in concrete. In this chapter material properties, mix design, casting procedure, and testing procedures are discussed in detail.

3.2 Material Properties and Fibers Treatment

Locally available ordinary portland cement, lawarnacpur sand, coarse aggregates (13mm), and water are used for manufacturing plain concrete. To prepare HFRC, glass fibers and banana fibers are used with cement, sand, crush, and water. GGBS is used in all combinations of the HFRC and one combination of PC. Figure 3.1 shows banana fibers, glass fibers, and GGBS in raw form and treated form. Length of fiber is kept 5cm by keeping in mind the literature review because during the complete failure of a concrete half portion of the fiber remains embedded in the concrete [36]. Banana fiber and glass fiber are available in raw form, first of all, these fibers are washed and then dried for 24hr to remove impurities from them. Fibers are properly combed and cut into 5cm length. GGBS is obtained from the iron manufacturing factory near Rawat. In the same way, GGBS is also treated before using it in concrete.

FIGURE 3.1: Raw Form and Treated Form Pictures of (a) Banana Fiber (b) Glass Fiber (c) GGBS

3.3 Mix Design and Casting Procedure

According to the literature review available on HFRC, fiber length and content have an important role to achieve desired properties of concrete, the fiber length and fiber content should be kept in mind during the preparation of HFRC. There are many literature reviews available that tell higher energy absorption is more important rather than increasing the strength of concrete. A higher energy absorption value is achieved by selecting a proper length of fiber in concrete and it is useful in the bridge deck and another such type of structure in which impact loading is a very important parameter. So to gain the required goals lot of researchers are working to obtain higher energy absorption along with maximum compressive strength. All the constituents are in the dry state and added in the foam of layers in the mixer machine. First of all coarse aggregates are taken and one-third of these aggregates are added to the mixer machine then fiber is added in a layer above coarse aggregates. Similarly, a one-third layer of sand is also prepared and added to the mixer machine, above this layer again a layer of fiber is laid. The same process is repeated one more time then the mixer is rotated for 5 min. During 3 min of rotation, one-third of more layers of aggregates along with fibers are added to the mixer machine. During rotation required amount of water is also added. When all material is added mixer is left for 2 min rotation. The amount of aggregates used for the preparation of PC and HFRC is discussed in table 3.1. The densities of banana fiber and glass fiber are 1.35 g/cm^3 and 2.44 g/cm^3, respectively. The addition of these fibers (being less dense) reduces the amount of binders (Cement and GGBS), sand and coarse aggregates for producing the same number of samples.

Workability of PC and HFRC is checked by slump test according to ASTM C143/ C143M-15a [63]. To determine the mechanical behavior of HFRC cylinders of size 100 mm x 200mm and beam-lets of size 100 mm x 100 mm x 450 mm are filled according to the standard given. The mix proportion is given in table 3.1.

Proper cleaning and oiling of molds are required. Each cylinder and beam-let is filled in three layers; in each layer 25 blows of the tamping rod are given for smooth compaction of concrete. These casted specimens are then de-molded after 24hrs and placed in water for 28 days according to the ASTM C192/C192M [64]. After this, mechanical testing is performed on these specimens according to ASTM C 215-02 [65]. The loading rate is different for different specimens, for compression loading rate applied on specimens is according to the ASTM standard C39/C39M-18 [66]. Loading rate applied in case of split tensile and flexure is according to ASTM standard C496/C496M-17 [67] and C78/C78M-15b [68]. Water absorption capacities of specimens are calculated per ASTM C642-13 [69]. Dynamic properties are calculated per ASTM standard C215-02 [70].

Table 3.1: Mix Proportion

Index	Fiber(%)	Binders		Sand	Crush (kg)	Banana Fiber (%)	Glass Fiber (%)	W/C	Slump (mm)	Density (kg/m^3)
		GGBS	Cement							
A0	0	0	1	2	3	-	-	0.6	44	2477
A1	0	0.08	0.92	2	3	-	-	0.6	41	2471
A2	G0.5,B4.5	0.08	0.92	2	3	4.5	0.5	0.7	21	2299
A3	G1.5,B3.5	0.08	0.92	2	3	3.5	1.5	0.7	24	2331
A4	G2.5,B2.5	0.08	0.92	2	3	2.5	2.5	0.7	25	2324
A5	G3.5,B1.5	0.08	0.92	2	3	1.5	3.5	0.7	29	2458
A6	G4.5,B0.5	0.08	0.92	2	3	0.5	4.5	0.7	32	2369

Note kg= kilogram, %= Percentage, mm= millimeter, m= meter.

Table 3.1 shows the slump values and densities for PC and HFRC. Slump value of A0, A1, A2, A3, A4, A5, and A6 are 44 mm, 41 mm, 21 mm, 24 mm 25 mm, 29 mm 32 mm, respectively. The FRCs are less workable when compared with PC for the same W/C ratio. The workability of HFRC is not good due to the higher water absorption capacity of fibers and the w/c ratio for HFRC is kept at 0.7 to increase the workability of HFRC but still slump value is lesser so it is recommended to use a super-plasticizer to enhance the workability of HFRC. Due to the retention and confinement effect of fibers, reduced values of a slump are observed in the case of FRCs than that of PC. The value of slump for A1, A2, A3, A4, A5 and A6 is 6.8%, 52%, 45%, 43%, 34% and 27% less than that of PC. Other researchers also reported that the incorporation of fibers in concrete decreased workability [71]. If some admixture is added to the concrete then workability of concrete gets increased. Concrete mix without hybrid fibers having only GGBS has good workability as compared to HFRC.

Table 3.1 also displays the densities of the specimens of hardened PC and HFRC. Densities of A0, A1, A2, A3, A4, A5 and A6 are 2477 kg/m^3, 2471 kg/m^3, 2299 kg/m^3, and 2331 kg/m^3, 2324 kg/m^3, 2458 kg/m^3 and 2469 kg/m^3 respectively. Hence, the densities of HFRC are condensed by 0.2%, 7%, 5%, 6%, 0.7% and 4% in comparison with PC. The inclusion of fibers in FRCs caused a decrease in densities of FRCs as compared to that of PC due to fiber's low unit weight.

3.4 Specimens

Cylinders and beam-lets are used for all types of testing. Dynamic properties of cylinders and beam-lets are calculated by using resonant frequency apparatus. Water absorption test is performed on the cylinders. Compressive, splitting tensile and flexural properties of cylinders and beam-lets are determined. One thing that should be noted that all the tests are performed on two specimens of the same combination and the average of these two values is taken. Other researchers also take an average of two values [72]. Total 42 specimens are prepared for determining the required properties of concrete. Out of 42 specimens, 28 are cylinders and 14 are beam-lets. Specimens are labeled as A0, A1, A2, A3, A4, A5, and A6 for easy identification during testing. Table 3.1 shows the labeling scheme of specimens. Fibers and GGBS are not added in the A0 combination, while the A1 combination has 8% of cement replaced with GGBS. A2, A3, A4, A5, and A6 combinations have fibers 5% content by mass of cement and all these mixes have 8% of cement replaced with GGBS.

3.5 Testing Procedure

Cylinders and beam-lets were cast in casting yard. The testing procedure is adopted according to the ASTM standards. Servo testing machine is used for the determination of strength, energy absorption, and toughness index while resonant frequency apparatus is used for measuring dynamic parameters of cylinders and beamlets.

3.5.1 Testing for Mechanical Properties

STM standard C143/C143M-15a is used for finding the workability of PC and HFRC. Dry densities of both PC and HFRC are checked by using ASTM standard C642-13 [73]. Slump and density of HFRC are measured by the same standard that is used for PC. The reason is that no separate standard is available for the calculation of slump and density for HFRC. A servo-hydraulic testing machine is used for determining the mechanical properties of PC and HFRC. ASTM standard C39 / C39M-17 is used for the calculation of mechanical properties. Capping of cylinders is required before testing and smooth capping is possible with the plaster of Paris. Mechanical testing depends upon capping of specimens.

Mechanical properties include compressive tests, split-tensile and water absorption tests while in dynamic testing resonant frequencies, dynamic modulus and damping ratios of specimens are calculated according to the standard. ASTM standard C293 / C293M-16, 3.4.2 is used for calculating flexural strength of PC and HFRC.

Servo hydraulic testing machine is used for this purpose. Maximum strength, deflection, total energy absorbed and flexural toughness index is calculated.

3.5.2 Testing for Dynamic Properties

Oscillation of the system without any external force is called resonant frequency. During different storage modes, when a system can store or transfer its energy like kinetic energy and potential energy then oscillation of the system occurs. The resonant frequency of concrete is measured by apparatus called resonance frequency apparatus. Damping ratio, dynamic modulus of elasticity, dynamic modulus of rigidity, and poisons ratio is calculated from these resonant frequencies.

The unit of dynamic modulus of elasticity is Pascal. If transverse frequency, mass of cylinder, and beam-lets are given we can find the dynamic modulus of elasticity by using the following equation [ASTM C215-14].

$$E_{dyn} = CMn^2 \tag{3.1}$$

Where: M= Mass of beam-let or cylinder in kg, n = Fundamental transverse frequency in Hz,

C= 1.6067 (L3 T/d4), m^{-l} for a cylinder, C = 0.9464 (L^3 T/bt^3), m^{-l} for beam-lets.

Dynamic modulus of rigidity (G) is calculated from the torsional frequency [ASTM C215-14]. Unit of dynamic modulus of rigidity is Pascal and formula for calculation of G is

$$DynamicG = BM(n") \tag{3.2}$$

Here n"= Fundamental Torsional frequency in Hz,

M= Mass of beam-let or cylinder in kg,

B= (4LR/A), m^{-l}, R = 1 for circular cylinder and 1.183 for beam-lets

L = length of the specimen, m, A= Cross-sectional area of tested specimens, m^2

The dynamic poison ratio of concrete depends upon dynamic loading and its value varies from 0.20 to 0.25. For different types of concrete, its value is different. For high strength concrete, its value is 0.1 and its value is 0.2 for low strength concrete. A lot of researchers are taking the value of the dynamic Poisson ratio as 0.2. Poisson ratio is very important in the design of concrete structure usually it is defined as the ratio of change in width per unit width of a material, to the change in length per unit length of material, due to strain. Dynamic poisons ratio is calculated by using ASTM C215-14. Flexible materials have more poison ratio and rigid materials have less poison ratio. The equation for the calculation of the Dynamic poison ratio is

$$Dynamic\ poison\ ratio = (E_{dyn}/2G) - 1 \tag{3.3}$$

Where E_{dyn} = Dynamic modulus of elasticity, G= Dynamic modulus of rigidity.

The damping ratio is a material property, represented by ζ (zeta), if the value of ζ is equal to 0 then the system is un-damped if its value is less than 1 then the system is under-damped and if its value exceeds from 1 then the system is over-damped. Damping is applied to the vibratory system and it minimizes, reduces, or even stops the motion of the system. The behavior of damping ratio on RC structure by using seismic response record was considered. Relation between peak ground acceleration and damping ratio was given [74]. Three main properties of concrete should be kept in mind while studying the dynamic properties of concrete and these three properties of concrete are dynamic modulus of elasticity, dynamic modulus of rigidity, and damping ratio. These three properties are co-related with each other. Damping as discussed earlier depends on the energy dissipation of the system or material. Most of the researchers are working on the importance of vibrational damping because it is very useful for the structure due to its ability to overcome hazards and thus improves the comfort for the users. In somatic systems, damping is created by methods that waste energy deposited in the swinging system. Examples include sticky drag in automated structures, opposition in electronic oscillators, concentration, and a sprinkling of dainty in visual oscillators. Damping is not only important in concrete structures but it also has a huge impact on the biological field and in other daily life studies.

Dynamic characteristics of rubberized concrete were calculated and dynamic properties of rubberized concrete were compared with the ordinary concrete. Beam element and elastic wave method was applied to decide the dynamic characteristics of concrete. The crumpled rubberized solid had improved damping characteristics as compared to plain concrete [75]. The mechanical and dynamic behavior of coconut fiber reinforced concrete was studied. The addition of coconut fiber improved the damping ratio and dynamic modulus of elasticity of concrete [76]. The damping ratio is dimensionless that tells how the system stops its motion when an external force acts upon it. Usually, the damping ratio (ζ) is calculated from typical logarithmic decrement tests.

3.5.3 Testing for Water Absorption Properties

ASTM standard C642-13 [56] is used for finding the water absorption capacity of specimens. Water absorption test is performed on cylinders only because cylinders are hard and there is no apparent crack on the surface of the cylinders. For each mix, only one cylinder is taken and dry weight is measured. After measuring the weight of cylinders, the same cylinders are put into water for 24hrs. After one day these cylinders are taken out from the water and again the weight of the cylinders is measured. The weight of the cylinders is increased to the water absorption quantity of concrete. All those mixes that have fiber absorbed more water.

3.5.4 SEM and TGA Testing

Concrete is the combination of microstructures. These microstructures make concrete very hard and dense. To study the properties of concrete, these microstructures are intensely studied. SEM is very useful for the study of the microstructure of concrete. SEM is the part of the electron microscope in which usually a beam of light falls on the surface of specimens and images are formed.

High-performance concrete was prepared by the limited replacement of cement with silica fume and fly ash. SEM analysis showed that the microstructure behavior of concrete was enhanced by the addition of admixtures. The replacement of concrete ingredients changed the behavior of concrete and its microstructure [77].

Thermogravimetric analysis (TGA) is thermal analysis in which with time mass of specimen is measured. Time, mass, and temperature are the main measurement of the specimens while other small measurements are derived from these main measurements. This test is conducted on an instrument named a thermogravimetric analyzer. With the passage of time mass is measured on this instrument in variable temperature. Impact characteristics of hybrid fibers reinforced concrete were considered. Thermal properties of hybrid fibers were studied which showed that the addition of admixture and fibers in concrete improved the thermal properties of the concrete [66]. TGA gives information about that type of specimen that changes its mass during cooling or heating. For TGA the max temperature is 1000 °C.

3.6 Summary

Specimens of PC and HFRC are cast; cement, sand, coarse aggregates, and water has a mix proportion of 1, 2, 3, and 0.6, while in the case of HFRC mix ratio is 1:2:3:0.7 (cement, sand, crush, and water). 5 cm length of fibers with 5% content by mass of the cement are used in concrete and 8% of cement is replaced with GGBS in A1, A2, A3, A4, A5, and A6 mixes. Mechanical properties, resonant frequencies, damping ratios dynamic modulus of elasticity, dynamic modulus of rigidity, and poisons ratio of PC and HFRC are determined. SEM and TGA tests on HFRC are performed. All the testing is performed according to ASTM standards. Results obtained from the testing are compiled and discussed in the coming chapter.

Chapter 4

Results and Analysis

4.1 Background

All the mechanical and dynamic testings are performed according to ASTM standards and properties of HFRC are compared with the properties of PC. In this chapter, mechanical, dynamic, and water absorption properties of PC and HFRC are studied experimentally. Characteristics of HFRC are discussed by SEM and TGA analysis.

4.2 Mechanical Properties of PC and HFRC

4.2.1 Properties Under Compressive Loading

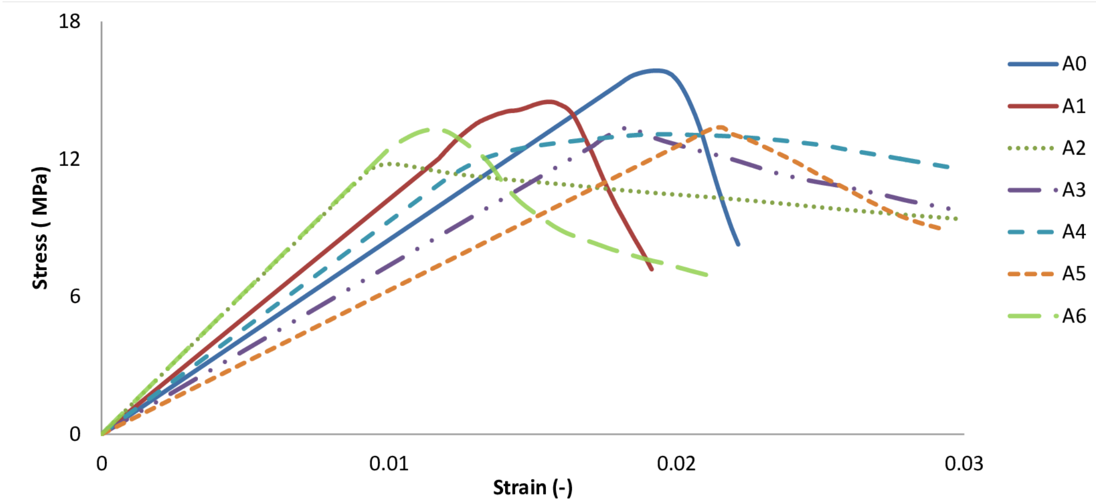
Figure 4.1 shows the stress-strain curve for A0, A1, A2, A3, A4, A5, and A6 mixes3wq. In this figure, the scenario for first crack, maximum load crack, and ultimate load crack is seen. Properties that are required during testing are crack location, crack length, and the number of cracks during maximum and ultimate loading. First crack for A0, A1, A2, A3, A4, A5, and A6 is observed at 82%, 80%, 95%, 92%, 90%, 88%, and 86% of their peak load. In the A0 combination, no GGBS is present but in the A1 combination, 8% of cement is replaced with GGBS. The presence of GBBS in concrete has caused the first crack to appear at

80% of its respective maximum load. The crack length of HFRC mixes is less as compared to PC due to the presence of fibers that absorb load and reduce cracking patterns to some extent. Length of crack mainly depends upon the ingredients present in concrete. Crack length and width for A0 and A1 is more as compared to other mixes. Length of crack for A0, A1, A2, A3, A4, A5, and A6 are 41 mm, 38 mm, 24 mm, 27 mm, 28 mm, 30 mm, and 33 mm respectively. A2 combination has a small crack length because the banana fiber is present 4.5% by mass of cement. Banana fiber has more resistant to control cracking than glass fiber, therefore the lesser the concentration of banana fiber more the crack length. During peak loading conditions crack lengths for A0, A1, A2, A3, A4, A5, and A6 and 83 mm, 81 mm, 52 mm, 58 mm, 61 mm, 65 mm, and 70 mm, respectively. Again cracking length trend is the same. This phenomenon is shown in figure 4.1.

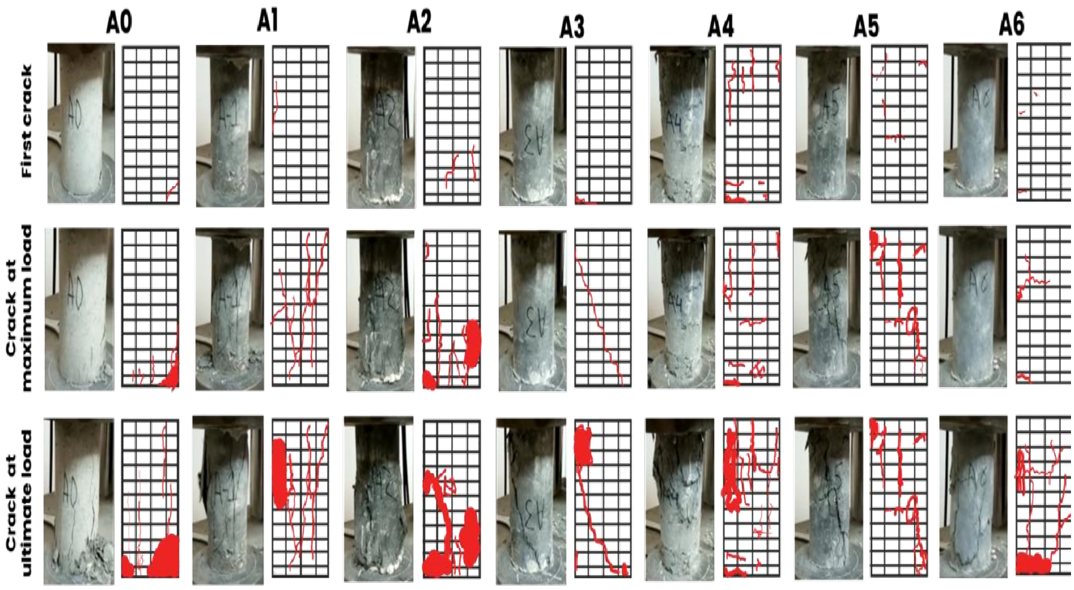
While in case of final loading, the length and width of cracks for HFRC are increased to maximum values (refer to top respective photos in **Figure 4.1**). At ultimate load specimens of A0 and A1 are fragmented in two equal parts while specimens of HFRC don't break into two separate pieces and they show tough and ductile behavior during compressive loading. These two fibers bind cracks and control the deformation of the concrete. During ultimate strength, A0 and A1 mixes are fully broken into two equal parts. While in case of HFRC, a lot of de-bonding is observed in glass fiber while no fiber is broken. Small fracture and more bonding are observed in banana fiber is observed while more de-bonding and less fracture of glass fiber is observed due to greater tensile strength of glass fiber and low tensile strength of the banana fiber.

The maximum load applied on the cylinder is divided by its area is equal to the compressive strength of the cylinder. While a change in length over the original length is a strain (δ). The zone beneath the stress-strain curve from start to the initial crack is compressive pre-crack absorbed energy (Eα). The sum of pre-cracked energy and post-crack energy gives total compressive energy absorbed by cylinders (ET). When total energy is divided by initial energy (i.e. ET/ Eα) then compressive toughness index (CTI) is obtained. **Table 4.1** shows the values of

P_{max}, δ, Δ, $E\alpha$, $E\beta$, ET, and TI, respectively. At ultimate load specimens of A0 and A1 are fragmented in two equal parts.



(a)



(b)

FIGURE 4.1: Mechanical Properties Under Compressive Loading (a) Stress-Strain Curve (b) Tested Specimens

The value of load for A0, A1, A2, A3, A4, A5, and A6 mixes are 177 kN, 162 kN, 61 kN, 71 kN, 73 kN, and 72 kN respectively. The reasons for decreasing load caring capacity of cylinders are due to the presence of GGBS and hybrid fibers. GGBS has low strength properties as compared to cement. Moreover, additions of less dense fibers decrease the compressive strength of the concrete. Values of strain for A0, A1, A2, A3, A4, A5 and A6 are 0.019, 0.015, 0.010, 0.018, 0.019, 0.21 and 0.31, respectively. The strain at maximum load for all combinations varies significantly indicating that tough behavior depending upon the percentage contents of BF and GF.Fibers are lightweight and less dense so the strengths of HFRC are less while the addition of fibers makes concretes tough. It is shown in SEM images that, due to the addition of fibers, small cavities are formed inside the concrete, and the slippage of fiber from concrete causes energy dissipation. This is also evident from the calculated toughness index shown in table 4.1. Compressive pre-cracked energy for A0, A1, A2, A3, A4, A5 and A6 are 0.07 MJ/m^3, 0.08 MJ/m^3, 0.063 MJ/m^3, 0.12 MJ/m^3, 0.16 MJ/m^3, 0.14 MJ/m^3 and 0.13 MJ/m^3 respectively. Compressive cracked absorbed energy ($E\beta$) for A0, A1, A2, A3, A4, A5 and A6 are 0.09MJ/m^3, 0.10 MJ/m^3, 0.20 MJ/m^3, 0.19 MJ/m^3, 0.26 MJ/m^3, 0.24 MJ/m^3 and 0.268 MJ/m^3 respectively. Total compressive energy (ET) absorbed by A0, A1, A2, A3, A4, A5 and A6 are 0.16 MJ/m^3, 0.18 MJ/m^3, 0.27 MJ/m^3, 0.31 MJ/m^3, 0.42 MJ/m^3, 0.38 MJ/m^3 and 0.398 MJ/m^3 respectively. An increase of 0.02 MJ/m^3, 0.11 MJ/m^3, 0.15 MJ/m^3, 0.26 MJ/m^3, 0.22 MJ/m^3, and 0.238 MJ/m^3 is observed in total compressive energy of A1, A2, A3, A4, A5, and A6 respectively, as compared to that of PC.

Toughness index (TI) of A0, A1, A2, A3, A4, A5 and A6 are 2.28, 2.25, 4.1, 2.55, 2.61, 2.71 and 3.05, respectively. The toughness index (TI) of all the mixes is more than that of PC. Cement is replaced with 8% by mass of GGBS, as GGBS has greater energy absorption properties so the toughness index of mix A1 is more than that of PC. Moreover, mixes having hybrid fibers have more toughness index and a greater toughness index is shown for A2 and A6 because of more concentration of single fiber. The presence of both fibers in different concentrations provides resistance against internal stresses during the propagation of cracks. Incorporation of fibers in concrete increases its energy absorption capacities along with the increment of toughness index. By using two types of fibers in concrete required properties are more enhanced as compared to single fiber reinforced concrete.

Table 4.1: Mechanical Properties of PC and HFRC under Compression Loadings

Property	**Index**	**P_{max} (kN)**	**δ (MPa)**	εo	**Eα (MJ/m^3) (-)**	**Eβ (MJ/m^3) (-)**	**ET (MJ/m^3) (-)**	**TI (-)**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	A0	177.86±6.4	15.85±1.41	0.019±0.003	0.07±0.002	0.09±0.002	0.16±0.01	2.28±0.13
	A1	162.6±8.2	14.5±1.04	0.015±0.01	0.08±0.007	0.10±0.004	0.18±0.02	2.25±0.15
	A2	61.14±12.1	11.8±2.1	0.010±0.02	0.063±0.002	0.20±0.03	0.27±0.05	4.1±0.02
Compression	A3	73.6±8.2	13.38±1.9	0.018±0.04	0.124±0.009	0.19±0.005	0.31±0.1	2.55±0.1
	A4	71.3±4.6	13.1±3.1	0.019±0.07	0.16±0.0013	0.26±0.008	0.42±0.08	2.61±0.03
	A5	73.7±13.1	13.39±4.6	0.021±0.01	0.14±0.005	0.24±0.009	0.38±0.03	2.71±0.17
	A6	72.91±9.2	13.28±2.6	0.031±0.04	0.13±0.003	0.268±0.006	0.398±0.3	3.05±0.12

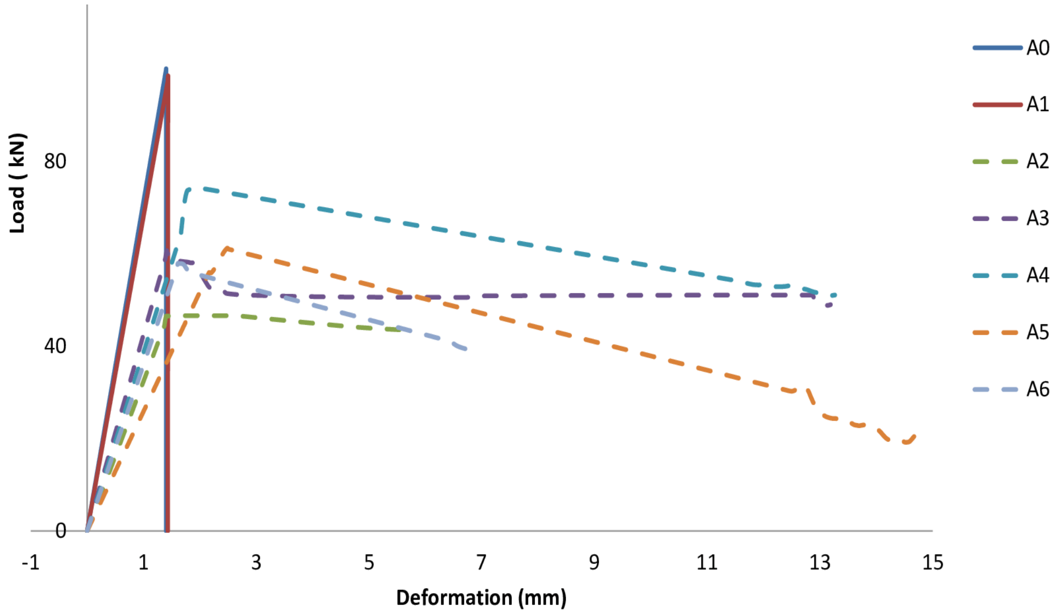
4.2.2 Properties Under Splitting Tensile Loading

Figure 4.2 shows the load-deformation curve under split-tensile loading for A0, A1, A2, A3, A4, A5, and A6 mixes. In this figure, the scenario for the first crack, maximum load crack, and ultimate load crack is seen. Properties that are required during the testing are (1) crack location, (2) crack length, and a number of cracks during maximum and ultimate loading. Split-tensile behaviors of all specimens are studied throughout the test. First crack for A0, A1, A2, A3, A4, A5 and A6 mixes are seen at 100%, 90%, 85%, 82%, 80%, 78% & 66% of their peak load. Length of crack mainly depends upon the ingredients present in concrete. The length and width of cracks for different types of mixes are different. Crack length and width for A0, A1 is more as compared to other mixes. The length of the first crack for A0, A1, A2, A3, A4, A5, and A6 is 73 mm, 78 mm, 44 mm, 57 mm, 58 mm, 60 mm, and 63 mm, respectively. Existence of fibers in concrete decreases cracking arrangement in concrete.

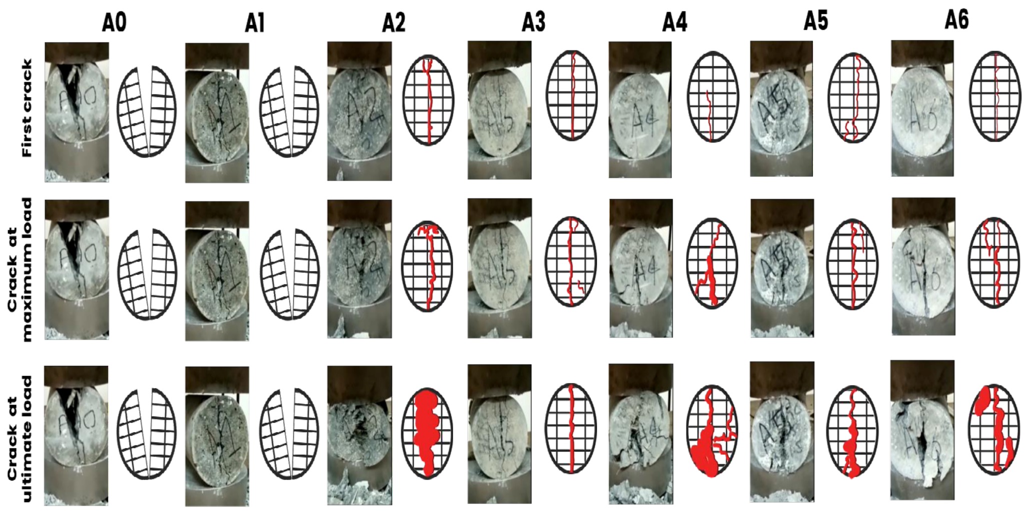
During peak loading conditions, crack length for A0, A1, A2, A3, A4, A5, and A6 is 83 mm, 81 mm, 62 mm, 68 mm, 71 mm, 75 mm, and 80 mm, respectively. Again cracking length trend is the same. At ultimate load, the specimens of A0 and A1 are converted into two equal parts, while specimens of HFRC don't break into two separate pieces. The presence of fibers in concrete resists cracking due to the bridging effect of fibers. Natural fiber has more potential to resists cracking as compared to artificial fiber.

The zone under the load-deformation curve from start to initial crack is equal to splitting tensile pre-crack absorbed energy (Eα). While zone beneath the load-deformation curve from the initial crack to failure load is equal to splitting tensile cracked absorbed energy (Eβ). The sum of these two energies gives total splitting tensile energy absorbed by cylinders (ET). When total energy is divided by initial energy (i.e. ET/ Eα) then splitting tensile toughness index (STI) is obtained. Table 4.2 shows the values of P_{max}, δ, Eα, Eβ, ET, and TI. It is noted that the split tensile cracked absorbed energy of A0 and A1 mixes are zero because specimens of these mixes are split into two equal parts when maximum load is applied on it. Values of maximum load for A0, A1, A2, A3, A4, A5, and A6 are

100.1 kN, 98.1 kN, 46.5 kN, 60.8 kN, 74.5 kN, 81.3 kN, and 59.9 kN, respectively. Maximum load is seen for A5 mix in case of HFRC.



(a)



(b)

Figure 4.2: Mechanical Properties Under Split Tensile Loading (a) Load-Deformation Curve (b) Tested Specimens

Values of maximum load of A2, A3, A4, A5, A6 mixes are less than that of A0. The reason for the decrement of load in the case of HFRC is due to the addition of fibers and GGBS in the mixes, as mentioned earlier GGBS has low strength properties and fibers used in concrete are lightweight. Hybridization of banana and glass fibers at a ratio of 3.5% and 1.5% absorbed maximum load in case of HFRC because glass fiber is stiff and has good tensile strength while banana fiber has good bonding properties due to its rough surface. When the concentration of glass fiber further increases load-carrying capacity of the specimens decreases because of the poor bonding properties of glass fibers. Minimum load is absorbed for A3 mix because in this mix concentration of banana fiber is more. The reason for the low strength of the A3 mix is due to the low tensile strength of the banana fiber.

Splitting tensile strength for A0, A1, A2, A3, A4, A5, and A6 mixes are 3.2 MPa, 3.1 MPa, 1.48 MPa, 2.02 MPa, 2.4 MPa, 2.6 MPa, and 1.8 MPa, respectively. Reduction of the strength of A1, A2, A3, A4, A5, and A6 mixes are 0.1 MPa, 1.72 MPa, 1.18 MPa, 0.8 MPa, 0.6 MPa, and 1.4 MPa as compared to that of PC. A possible reason for the reduction of strength in the case of HFRC is due to low density and more volume of fibers present in concrete. Values of deformation (Δ) for A0, A1, A2, A3, A4, A5, and A6 are 1.4 mm, 1.4 mm, 1.91 mm, 1.87 mm, 1.71 mm, 1.68 mm, and 1.6 mm, respectively. Deformation in HFRC is more than that of PC because fibers grasp concrete constituents at the time of propagation of cracks.

Mixes having a maximum concentration of banana fiber has more value of deformation because banana fiber has a rough surface and holds the ingredients of concrete even after the application of maximum load. Deformation value is less for the mixes having a higher concentration of glass fiber because of the weaker bonding properties of glass fibers with concrete. Splitting tensile pre-cracked absorbed energy (Eβ) for A0, A1, A2, A3, A4, A5, and A6 mixes are 2.2 MJ/m^3, 2.1 MJ/m^3, 1.5 MJ/m^3, 1.6 MJ/m^3, 2.1 MJ/m^3, 2.5 MJ/m^3 and 1.6 MJ/m^3 respectively. Splitting tensile pre-cracked energy absorption for A0 and A1 and same because chemical properties of GGBS is similar to cement, metakolin and fly ash.

TABLE 4.2: Mechanical Properties of PC and HFRC Under Splitting Tensile Loadings

Property	**Index**	$\mathbf{P}_{max}$ **(kN)**	δ **(MPa)**	Δ **(mm)**	**E**α **(MJ/m^3) (-)**	**E**β **(MJ/m^3) (-)**	**ET (MJ/m^3) (-)**	**TI (-)**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	A0	100.1±4.9	3.2±0.67	1.4±0.27	2.2±0.9	0	2.2±0.9	1±0
	A1	98.1±7.1	3.1±0.56	1.4±0.23	2.1±0.4	0	2.1±0.4	1±0
	A2	46.5±2.1	1.48±0.2	1.71±0.1	1.5±0.24	1.9±0.6	3.4±1.2	2.26±0.9
Splitting tensile	A3	60.8±3.9	2.02±0.5	1.41±0.2	1.6±0.1	2.1±1.9	3.7±1.01	2.3±0.54
	A4	74.5±9.1	2.4±0.23	1.91±0.4	2.1±0.4	2.9±0.8	5±1.01	2.4±0.7
	A5	81.3±11.3	2.6±0.14	2.5±0.7	2.5±0.1	5±0.97	7.5±1.8	3±0.4
	A6	59.9±12.2	1.8±0.3	1.6±0.5	1.6±0.34	7.4±1.01	9±1.4	5.62±0.45

In case of HFRC, A5 mix has maximum value of pre-cracked energy absorption.

An increase of 0.3 MJ/m^3 of pre-cracked energy absorption for A5 is observed as compared to PC. While pre-cracked energy absorption for other mixes is decreasing. Specimens of A0 and A1 are broken into two equal pieces so cracked energy absorption for A0 and A1 are zero. Cracked energy absorption for A2, A3, A4, A5, and A6 are 1.9 MJ/m^3, 2.1 MJ/m^3, 2.9 MJ/m^3, 5 MJ/m^3, and 7.4 MJ/m^3 respectively. Cracked energy absorption for A5 and A6 are mixed more because glass fiber has more tensile strength as compared to banana fiber. Total energy absorption for A0, A1, A2, A3, A4, A5 and A6 is 2.2 MJ/m^3, 2.1 MJ/m^3, 3.4 MJ/m^3, 3.7 MJ/m^3, 5 MJ/m^3, 7.5 MJ/m^3 and 9.01 MJ/m^3 respectively.

Total splitting tensile energy absorption of HFRC specimens is more as compared to that of PC. Splitting tensile toughness index for A0, A1, A2, A3, A4, A5, and A6 are 1, 1, 2.26, 2.3, 2.4, 3, and 5.62, respectively. An increment in toughness index is observed in the case of HFRC mixes. A6 mix has an increased toughness index having a higher concentration of glass fibers. The presence of both fibers in different concentrations provides resistance against internal stresses during the propagation of cracks. In short, the incorporation of fibers in concrete increases its energy absorption capacities along with the increment of toughness index. Mix having 4.5% glass fiber by mass of cement has greater toughness index because energy absorption capacity of glass fiber is more under split loading and tensile strength of glass fiber is also good.

4.2.3 Properties Under Flexural Loading

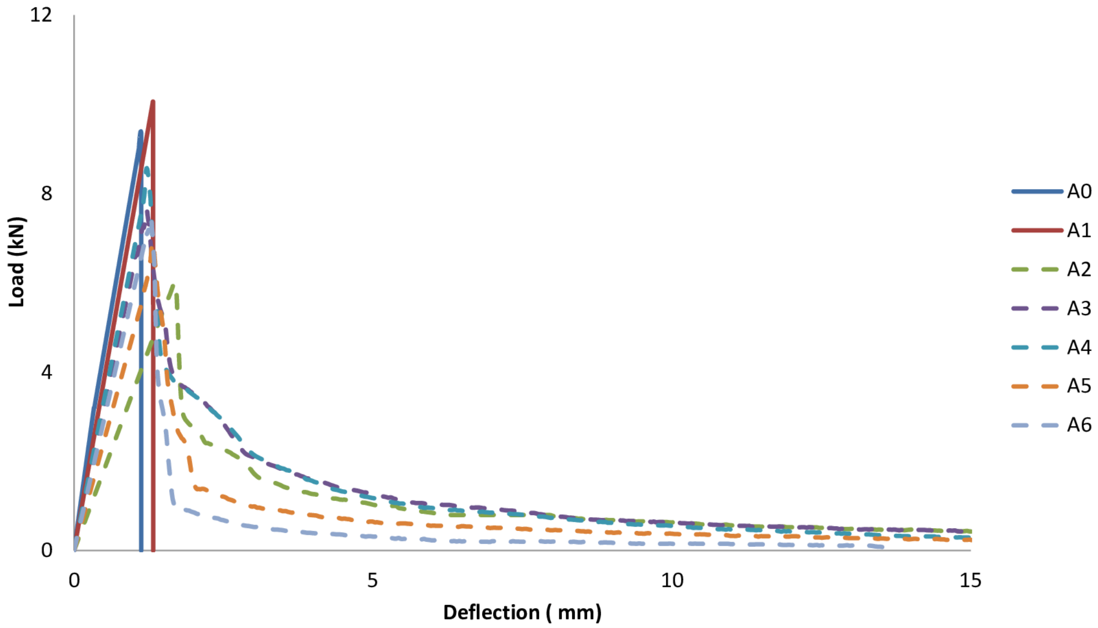
Figure 4.3 shows the load-deflection curve for A0, A1, A2, A3, A4, A5, and A6. In this figure scenario for the first crack, maximum load crack and ultimate load crack are seen. Properties that are required during testing are (1) crack location, (2) crack length (3) number of cracks during maximum and ultimate loading. First crack for A0, A1, A2, A3, A4, A5 and A6 are observed at 100%, 100%, 97%, 95%, 93%, 91% and 86% of their peak load. The length and width of cracks for different types of mixes of beam-lets are different. Cracks in all types of specimens are started from the bottom middle of the beam-lets. Crack length and width for A0 and A1 is more as compared to other mixes.

Length of crack for A0, A1, A2, A3, A4, A5, and A6 are 51mm, 54mm, 28 mm, 32 mm, 38 mm, 40 mm, and 43 mm, respectively. During peak loading conditions the crack length for A0, A1, A2, A3, A4, A5, and A6 are 83 mm, 81 mm, 54 mm, 59 mm, 63 mm, 65 mm, and 75 mm, respectively. Again cracking length trend is the same and this phenomenon is shown in figure 4.3. While in the case of final loading the width and length of the cracks for HFRC are increased to maximum values (refer to bottom respective photos in Figure 4.3). At ultimate load specimens of A0 and A1 are broken into two equal parts, while the specimens of HFRC don't break into two separate pieces and they show tough and ductile behavior during flexural loading. Fiber fractured and fiber pull-out behavior is shown in SEM images.

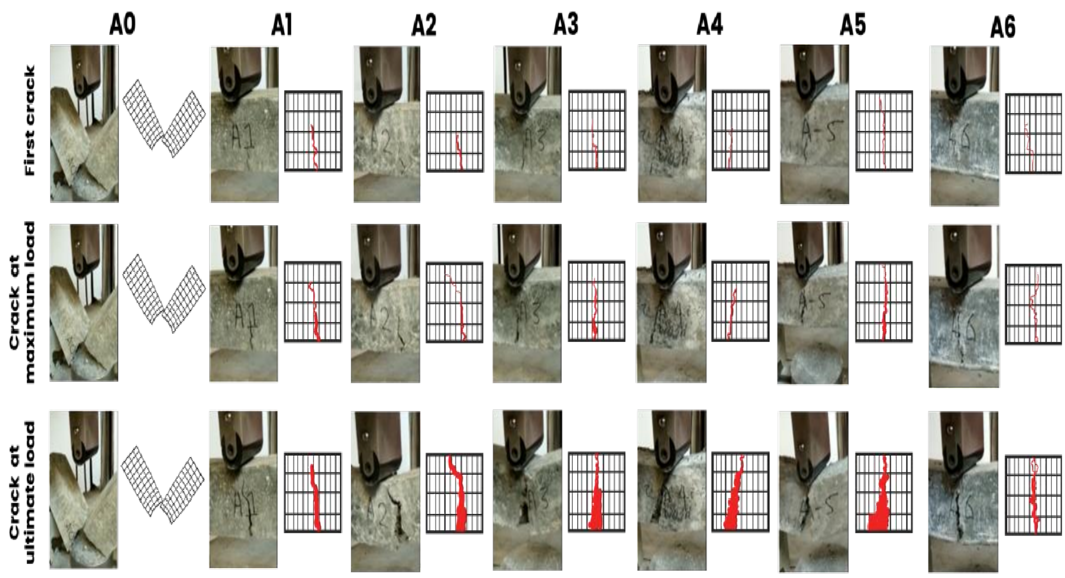
Flexural pre-crack absorbed energy (Eα) is calculated from the area beneath the load-deflection curve from start to the initial crack. While zone under the load-deflection curve from the initial crack to failure load is flexural cracked absorbed energy (Eβ). The sum of these two energies gives the total flexural energy absorbed by cylinders (ET). When total energy is divided by initial energy (i.e. ET/ Eα) then flexural toughness index (STI) is obtained. α shows the values of P_{max}, δ, Δ, Eα, Eβ, ET, and TI, respectively. Values of maximum load for A0, A1, A2, A3, A4, A5, and A6 are 9.39 kN, 10.1 kN, 6 kN, 7.6 kN, 8.6 kN, 7 kN, and 7.4 kN, respectively. The load-bearing capacity of the A2 mix is increased up to 0.71kN than that of PC. The increment in the load-bearing capacity of A2 is due to the good flexural behavior of ground granulated blast furnace slag (GGBS). GGBS has more SiO_{max} and CaO that enhance the flexural properties of A1.

The load-bearing capacity of mixes having hybrid fibers is less than that of PC. Decrement of 3.39 kN, 1.79 kN, 0.79 kN, 2.39 kN, and 1.99 kN of P_{max} is observed in A2, A3, A4, A5, and A6 mixes as compared to PC. Due to the presence of less dense and low strength fibers in the concrete flexural strength is reduced. The perfect result is obtained by hybridization of glass and banana fibers in an optimum range. Values of flexural strength for A0, A1, A2, A3, A4, A5, and

A6 are 6.3 MPa, 6.4 MPa, 4 MPa, 5.1 MPa, 5.8 MPa, 4.6 MPa, and 5.0 MPa, respectively. Flexural strength of A2 mix is increased up to 0.1 MPa than that of PC.



(a)



(b)

FIGURE 4.3: Mechanical Properties Under Flexural Loading (a) Load-Deflection Curve (b) Tested Specimens

The increment in the flexural strength of A2 is due to good flexural behavior of the ground granulated blast furnace slag (GGBS). Decrement of 2.3 MPa, 1.2 MPa, 0.5 MPa, 1.7 MPa, and 1.3 MPa of flexural strength is observed in A2, A3, A4, A5, and A6 mixes as compared to PC. Deflection for A0, A1, A2, A3, A4, A5, and A6 mixes are 1.1 mm, 1.3 mm, 1.6 mm, 1.2 mm, 1.2 mm, 1.3 mm, and 1.2 mm, respectively. Deflection in the A1 mix is more than that of PC due to the presence of GGBS that enhances the elastic properties of concrete. Deflection in A2 mix having 4.5% of banana fibers by the total weight of the fiber is more because of larger bridging effect in banana fiber.

Flexural pre-crack absorbed energy (Eα) of A0, A1, A2, A3, A4, A5, and A6 mixes are 7.35 MJ/m^3, 6.21 MJ/m^3, 5.13 MJ/m^3, 4.11 MJ/m^3, 4.9 MJ/m^3, 4.2 MJ/m^3 and 3.9MJ/m^3 respectively. Flexural post-crack absorbed energy (Eβ) for A0 and A1 mixes are zero because beam-lets are separated into two equal segments after implementation of maximum load. Flexural post-crack absorbed energy (Eβ) of A2, A3, A4, A5, and A6 mixes are 20 MJ/m^3, 17.1 MJ/m^3, 16.8 MJ/m^3, 8.3 MJ/m^3, and 4.9 MJ/m^3 respectively.

Values of flexural post-crack absorbed energy (Eβ) is decreased from A2 to A6 mix. Total flexural energy (ET) absorbed by beam-lets of A0, A1, A2, A3, A4, A5, and A6 are 7.35 MJ/m^3, 6.21 MJ/m^3, 25.1 MJ/m^3, 21.2 MJ/m^3, 21.7 MJ/m^3, 12.5 MJ/m^3 and 9.9 MJ/m^3 respectively. The total energy absorption capacity of HFRC is greater than PC due to the presence of fibers in concrete that absorb energy. Fibers grasp cracks and enhance the load-carrying capacity of concrete.

Total energy absorption of mixes having more concentration of banana fiber in case of flexural loading is more because the bridging effect in banana fiber is more as compared to that of glass fibers. The lesser the concentration of banana fibers in concrete lesser is the total energy absorption behavior of the HFRC. Flexural toughness index (FTI) for A0, A1, A2, A3, A4, A5, and A6 mixes are 1.1 4.9, 5.1, 4.4, 3, and 2.27, respectively. Flexural toughness index (FTI) is more for A3 and decreasing from A3 to A6 because the concentration of banana fiber is decreasing. Lower the concentration of banana fibers in concrete lower is the value of total energy absorption and toughness index of concrete in case of flexural loading.

Table 4.3: Mechanical Properties of PC and HFRC Under Flexural Loadings

Property	**Index**	$\mathbf{P}_{max}$ (**kN**)	δ (**MPa**)	Δ (**mm**)	**E**α (**MJ/m**^{3}) (-)	**E**β (**MJ/m**^{3}) (-)	**ET** (**MJ/m**^{3}) (-)	**TI** (-)
1	2	3	4	5	6	7	8	9
	A0	9.39±0.2	6.3±0.02	1.1±0.1	7.35±1.6	0	7.35±1.6	1±0
	A1	10.1±0.3	6.4±0.02	1.3±0.2	6.21±0.8	0	6.21±0.8	1±0
	A2	6±0.7	4±0.01	1.6±0.2	5.13±0.5	20±1.3	25.1±1.1	4.9±0.6
Flexural	A3	7.6±1.2	5.1±0.0	1.2±0.1	4.11±0.6	17.1±0.2	21.2±1.23	5.1±0.3
	A4	8.6±1.3	5.8±0.1	1.2±0.2	4.9±0.7	16.8±0.7	21.7±1.14	4.4±0.6
	A5	6.9±0.	4.6±0.4	1.3±0.5	4.2±0.13	8.3±0.5	12.5±1.2	3±0.9
	A6	7.4±0.8	5.0±0.3	1.2±0.3	3.9±0.2	4.98±0.1	9.9±0.6	2.27±0.8

Compressive toughness index (CTI) for A0, A1, A2, A3, A4, A5 and A6 are 2.28, 2.25, 4.1, 2.55, 2.61, 2.71 and 3.05, respectively. CTI of A1 is 1% less than that of PC, while CTI for A2, A3, A4, A5 and A6 mixes are 79%, 11%, 14%, 18% and 33% more than that of PC. Splitting tensile toughness index for the A0, A1, A2, A3, A4, A5 and A6 are 1, 1, 2.26, 2.3, 2.4, 3 and 5.62, respectively. The increment in splitting toughness index is observed in case of HFRC mixes. Flexural toughness index (FTI) of mixes A0, A1, A2, A3, A4, A5 and A6 are 1, 1, 4.9, 5.1, 4.4, 3 and 2.27, respectively. Flexural toughness index (FTI) of mixes is decreasing from A2 to A6 because concentration of banana fiber is decreasing.Flexural toughness index (FTI) of A2 and A3 mixes is more because banana fiber concentration in these mixes is maximum.

4.3 Dynamic Properties Analysis

Values of fundamental frequencies, damping ratio, dynamic elastic modulus, and dynamic modulus of rigidity for cylinders and beam-lets are shown in table 4.4. Dynamic properties of cylinders of concrete having GGBS, glass, and banana fiber are compared with PC. The longitudinal frequency of concrete having 8% of GGBS has the same value as that of PC. But the longitudinal frequency of the A2 mix is 3595Hz which is 1.23% more than that of PC. Longitudinal frequencies of A5 and A6 mixes are slightly less than that of PC longitudinal frequency. Transverse and rotational frequencies of all mixes having hybrid fibers have more value than that of PC and the same trend is seen in the case of beam-lets resonant frequencies. A relative comparison between longitudinal frequencies of the cylinder is shown in **Figure 4.4**.

The damping ratio of an ordinary concrete cylinder is 2.01. For A1, A2, A3, A4 A5, and A6 mixes damping ratios are 9%, 59%, 14%, 12%, 48%, and 54% more than that of PC. For ordinary concrete beam-lets, the damping ratio is 2.91, while other mixes have a more damping ratio than that of PC. Comparisons of damping ratio between different concrete mixes are shown in **Figure 4.4**. The dynamic

Table 4.4: Dynamic Properties of PC and HFRC

Specimens	Index	RFl (Hz)	RFt (Hz)	RFr (Hz)	ξ	E_{dyn} (GPa)	G_{dyn} (GPa)	Poisons Ratio
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Cylinders	A0	3551±412	1164±310	1178±512	2.01±0.3	3.94±1.2	2.84±0.1	0.30±0.03
	A1	3551±315	1164±456	1167±402	2.21±0.5	3.9±1.3	2.85±0.4	0.31±0.03
	A2	3595±512	1420±209	1422±119	3.2±0.2	4.5±1.01	3.6±0.3	0.37±0.02
	A3	3537±608	1422±309	1443±208	2.3±0.5	4.6±1.1	3.78±0.5	0.39±0.05
	A4	3551±543	1437±259	1487±245	2.26±0.3	4.7±0.7	3.82±0.8	0.38±0.02
	A5	3506±432	1437±321	1422±298	2.98±0.1	4.72±0.4	4.76±0.3	0.5±0.01
	A6	3506±409	1443±276	1487±208	3.1±1.2	4.81±0.5	4.78±0.4	0.49±0.03
Beam lets	A0	1686±346	1231±367	1234±209	2.91±0.4	4.14±1.4	3.03±1.7	0.31±0.02
	A1	1795±678	1235±564	1236±108	3.3±0.3	4.08±2.1	3.11±0.7	0.34±0.03
	A2	1376±208	1420±432	1420±215	6.5±1.8	4.45±0.5	4.34±0.8	0.28±0.01
	A3	1509±312	1409±674	1509±346	4.2±0.8	4.36±0.9	5.1±0.4	0.58±0.05
	A4	1469±456	1376±432	1464±654	3.6±0.3	4.2±1.1	4.91±0.2	0.5±0.02
	A5	1376±187	1509±234	1465±243	4.5±482	5.73±0.6	4.99±0.7	0.42±0.06
	A6	1745±98	1539±107	1563±267	3.5±0.3	6.07±0.4	5.42±0.9	0.4±0.034

elastic modulus for cylinders is very important parameter during dynamic testing of concrete. E_{dyn} for PC is 3.94 GPa and E_{dyn} for A1 mix is similar to that of PC. While E_{dyn} of A2, A3, A4, A5, and A6 mixes are 14%, 16%, 18%, 19%, and 22% more than that of PC. For ordinary concrete beam-lets E_{dyn} for PC is 4.41 GPa. E_{dyn} of A1 is 1% less than that of PC. While A2, A3, A4 and A5 mixes have E_{dyn} 7%, 5%, 1%, 38%, and 46%, more than that of PC.

Dynamic modulus of rigidity is calculated from the torsional frequency of concrete. G_{dyn} for ordinary concrete cylinders is 2.84 GPa. G_{dyn} for A1 mix is 0.85% more than that of PC. On the other hand, values of G_{dyn} for all A2, A3, A4, A5 and A6 mixes are 26%, 33%, 34%, 67%, and 68% more than PC. For beam-lets G_{dyn} of PC is 3.03 GPa. All G_{dyn} values of A1, A2, A3, A4, A5, and A6 mixes are more than that of PC. Dynamic poison ratio for cylinders and beam-lets are shown in **Table 4.4**.

The values of poisons ratio for cylinders of PC is 0.30. Value of poisons ratio for A1, A2, A3, A4, A5, and A6 mixes are 3%, 23%, 30%, 26%, 66%, and 63% more than that of PC. Poisons ratio for beam-lets of PC is 0.31. Value of poisons ratio of A2 mix is less than that of PC. For A1, A3, A4, A5, and A6 mixes poison ratio is 9%, 87%, 61%, 35%, and 29% more than that of PC. A relative comparison between dynamic modulus of elasticity and dynamic modulus of rigidity, resonant Frequency, the damping ratio is shown in **Figure 4.4**.

4.4 Water Absorption

In the lab, a water absorption test is performed on cylinders of PC and HFRC. These cylinders are weighted before putting them in water and placed in water for 24 hrs. After taking out cylinders from the water again weight is calculated for all these cylinders and a percentage increase of weight is calculated as shown in table 4.5. Weight increase by cylinders of A0, A1, A2, A3, A4, A5 and A6 are 0.77%, 1.28%, 2.77%, 3%, 3.56%, 2.33% and 3.56%, respectively.

A1, A2, A3, A4, A5, A6 mixes absorb 66%, 259%, 289%, 362%, 202% and 388% more water than PC. The water absorption capacity of HFRC is more because

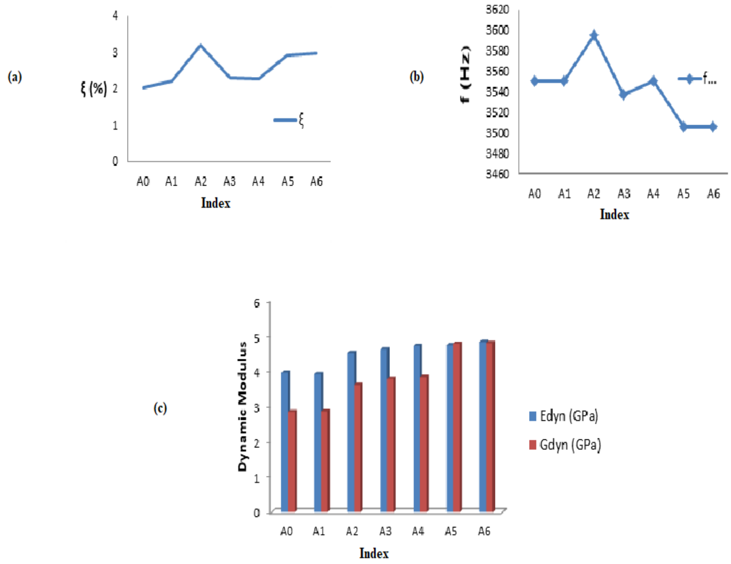


FIGURE 4.4: Influence of GGBS and Fiber Content on (a) Damping Ratio (b) Resonant Frequency (c) Dynamic Modulus of Elasticity and Dynamic Modulus of Rigidity

of the greater water absorption capacity of fibers. The water absorption capacity of mixes having more glass fiber is greater because glass fiber is stiff and cannot cover all the voids so water enters in voids of concrete and hence water absorption capacity of such mixes having a greater concentration of glass fibers are more.

TABLE 4.5: Water Absorption of PC and HFRC

Index	**W (kg)**	**W_W (kg)**	**Water Absorption (%)**
A0	3.89	3.92	0.77
A1	3.88	3.93	1.28
A2	3.61	3.71	2.77
A3	3.66	3.77	3
A4	3.65	3.78	3.56
A5	3.86	3.95	2.33
A6	3.72	3.86	3.76

Figure 4.5 shows the water absorption capacity of different mixes of PC and HFRC. Similar working was made by many researchers. Results indicated that

adding fibers having minimum water absorption capacity could be useful in lowering the vessel permeability and conductivity between the holes [78 and 79].

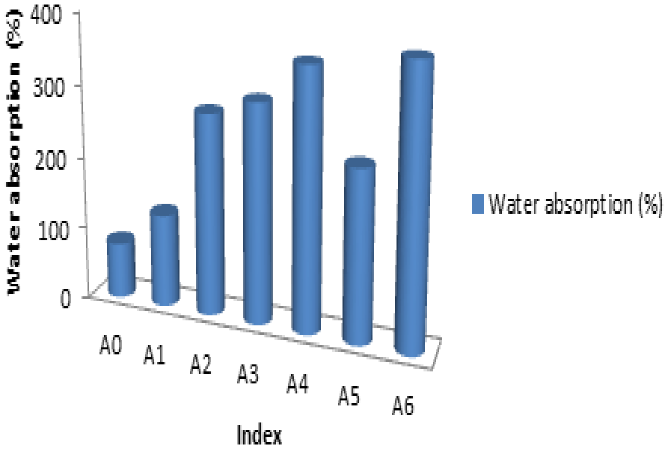


FIGURE 4.5: Influence of GGBS and Fiber Content on Water Absorption

4.5 SEM and TGA Analysis for Broken HFRC Specimens

Figure 4.6 shows the broken images of HFRC specimens. When mechanical

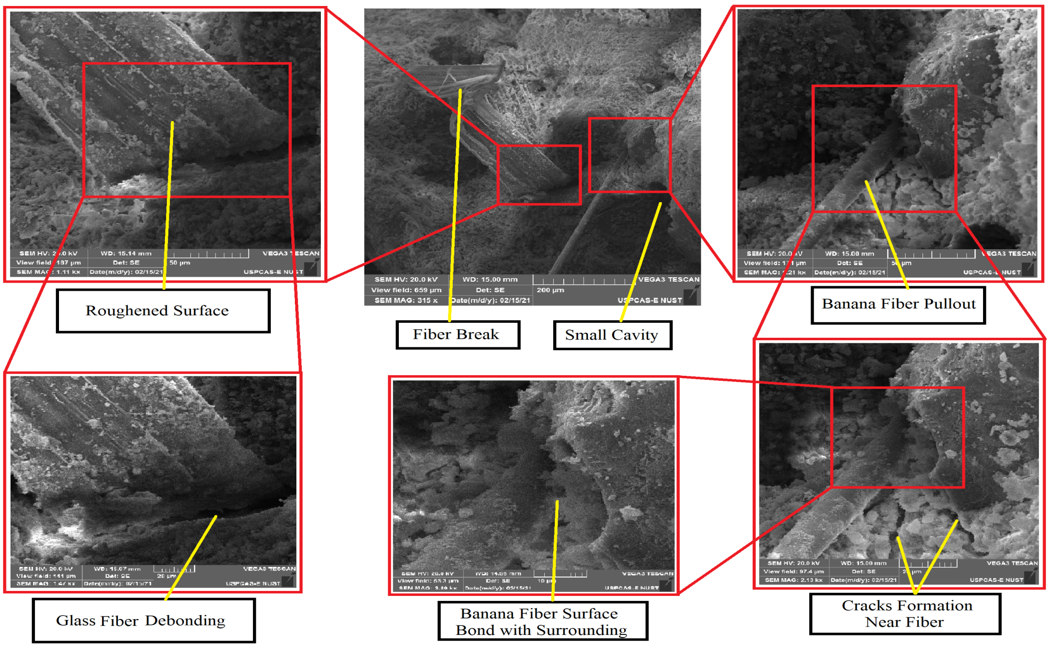


FIGURE 4.6: SEM of HFRC

loading is applied on specimen's breakage of fibers and small cavity formation occurs inside the concrete. The Shearing and splitting of fibers are shown in **Figure 4.6**. Banana fiber pullout is seen in a top-right image while the rough surface is seen in the top left image and the rough surface is due to the addition of GGBS. Good bonding of concrete with banana fiber is seen and de-bonding of glass fiber can be seen in a bottom left image due to the smooth surface of glass fiber. When the load is applied to the HFRC specimen's slippage of glass fibers is seen in SEM images. Cracks are not formed in presence of fibers because the primary aim of using fibers in concrete is to minimize cracking in concrete but small cracks are formed near the fiber and it is seen in the bottom right image of SEM.

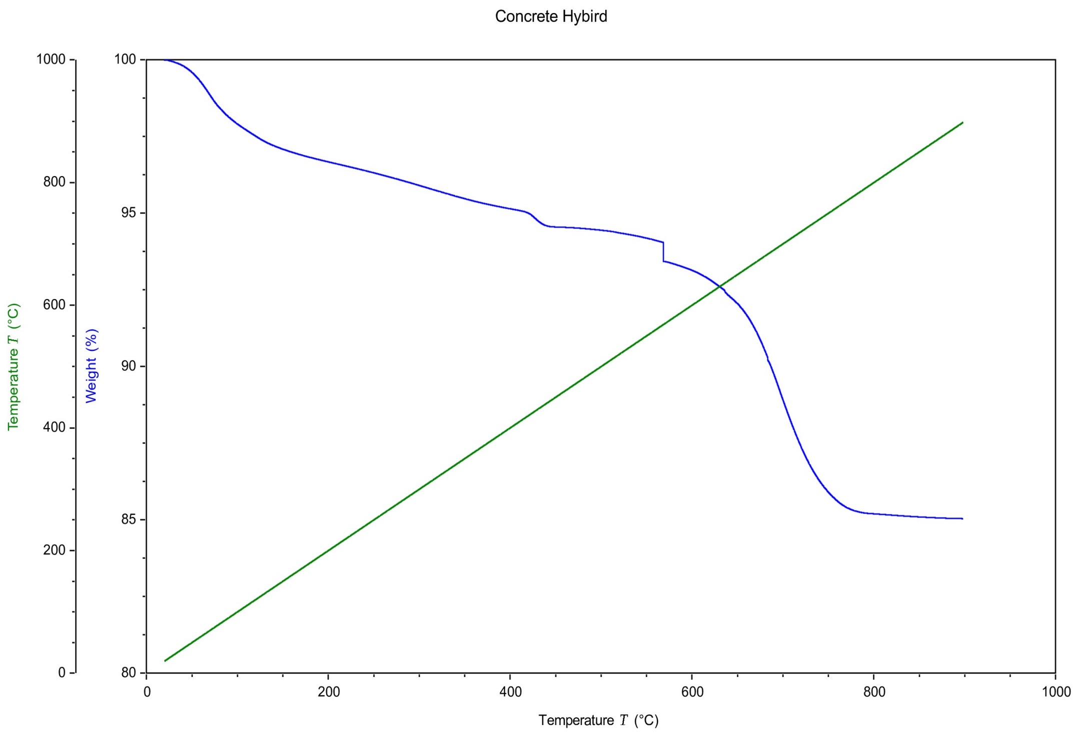


FIGURE 4.7: TGA of HFRC

Figure 4.7 shows the TGA analysis for broken specimens of HFRC. The maximum temperature for the TGA test is kept 900 oC and specimens of HFRC are crushed into powdered foam. The weight of the specimens is 12.8mg and the temperature is increased from 0 oC. When the temperature is increasing the weight of the specimen is decreasing. When the temperature is increased up to 700 oC no further decrease in mass is seen.

4.6 Summary

Mechanical, dynamic, and water absorption properties of PC and HFRC with mixed design ratio of 1:2:3 and W/C ratio of 0.6 and 0.7 are determined. Values of slump and densities of HFRC are lower than values of PC. Compressive, split-tensile, and flexural properties are determined and compared with PC. Compressive strength, split tensile strength test and flexural strength of HFRC is less than that of PC. Dynamic properties of PC and HFRC are also studied. The damping ratio for HFRC is more than that of PC. Dynamic elastic modulus and dynamic rigidity modulus and dynamic poisons ratio also increases for HFRC.

Chapter 5

Discussion

5.1 Background

Mechanical properties including compressive, split tensile, and flexural properties of PC and HFRC are studied in chapter 4. Some of the properties of concrete are increased by the addition of hybrid fibers and GGBS. In this chapter, the empirical equation for water absorption (WA) is discussed and values of water absorption are calculated by using this equation and obtained values are co-related with the experimental values. Consequences of mechanical and dynamic properties are discussed and HRFC for commercial use is recommended.

5.2 Optimization of HFRC

Fibers are lightweight and less dense so the strengths of HFRC are less while the addition of fibers makes concretes tough. It is shown in SEM images that, due to the addition of fibers, small cavities are formed inside the concrete, and the slippage of fiber from concrete causes energy dissipation.**Fig 5.1** displays the comparison of compressive strength and compressive toughness index of the A0, A1, A2, A3, A4, A5, and A6 mixes. Compressive strength for A0, A1, A2, A3, A4, A5, and A6 mixes are 15.85 MPa, 14.5 MPa, 11.8 MPa, 13.1 MPa, 13.29MPa, 13.32MPa and 13.48MPa, respectively. Strength of A1, A2, A3, A4, A5, and

A6 mixes is 8.5%, 25%, 15%, 17%, 16% and 16% less than that of PC. The incorporation of GGBS in the A1 mix reduced its compressive strength, while the compressive strength of other mixes having hybrid fibers and GGBS is less than that of A0. In the case of HFRC, compressive strength is increasing when the concentration of glass fiber is increasing as shown in figure 5.1 and the reason is that glass fiber is dense and has good strength properties as compared to banana fiber. Compressive toughness index (CTI) for A0, A1, A2, A3, A4, A5, and A6 mixes are 2.28, 2.25, 4.1, 2.55, 2.61, 2.71 and 3.05, respectively. TI of A1 is 1% less than that of PC while TI of A2, A3, A4, A5, and A6 are 79%, 11%, 14%, 18%, and 33% more than that of PC. Moreover, a greater toughness index is shown for A2 and A6 mixes because of more concentration of single fiber in these two combinations. Mix having 4.5% banana fiber by mass of cement has greater toughness index because energy absorption capacity of banana fiber is more as compared to banana. On the other hand, a mix having 4.5 % glass fiber gives maximum TI because glass fiber is stiff and has larger tensile strength.

Fig. 5.1 displays the judgment of tensile strength and splitting toughness index of the A0, A1, A2, A3, A4, A5, and A6 mixes respectively. Tensile strength for A0, A1, A2, A3, A4, A5, and A6 mixes are 3.2 MPa, 3.1 MPa, 1.48 MPa, 2.02 MPa, 2.4 MPa, 2.6 MPa, and 1.8 MPa, respectively. Tensile strength of A1, A2, A3, A4, A5 and A6 mixes are 3%, 53%, 36%, 25%; 18% and 43% less than that of PC. Incorporation of GGBS in the A1 mix reduced its split-tensile strength, while other mixes having hybrid fibers and GGBS, split-tensile strength is less than that of A0. In the case of HFRC, tensile strength is increasing when the concentration of glass fiber is increasing up to 3.5% of total fiber weight as shown in figure 5.1. The tensile strength of concrete is low for the A6 mix because the glass fiber is mixed in a larger amount and the bonding strength of glass is low. The hybridization of glass and banana fiber in optimum amount increases the tensile strength of concrete. Splitting tensile toughness index for A0, A1, A2, A3, A4, A5, and A6 mixes are 1, 1, 2.26, 2.3, 2.4, 3, and 5.62, respectively. An increment in toughness index is observed in the case of HFRC mixes. More the concentration of glass fiber more is the split-tensile toughness index of the concrete. Maximum toughness index gains by A6 mix having a higher concentration of glass fibers.

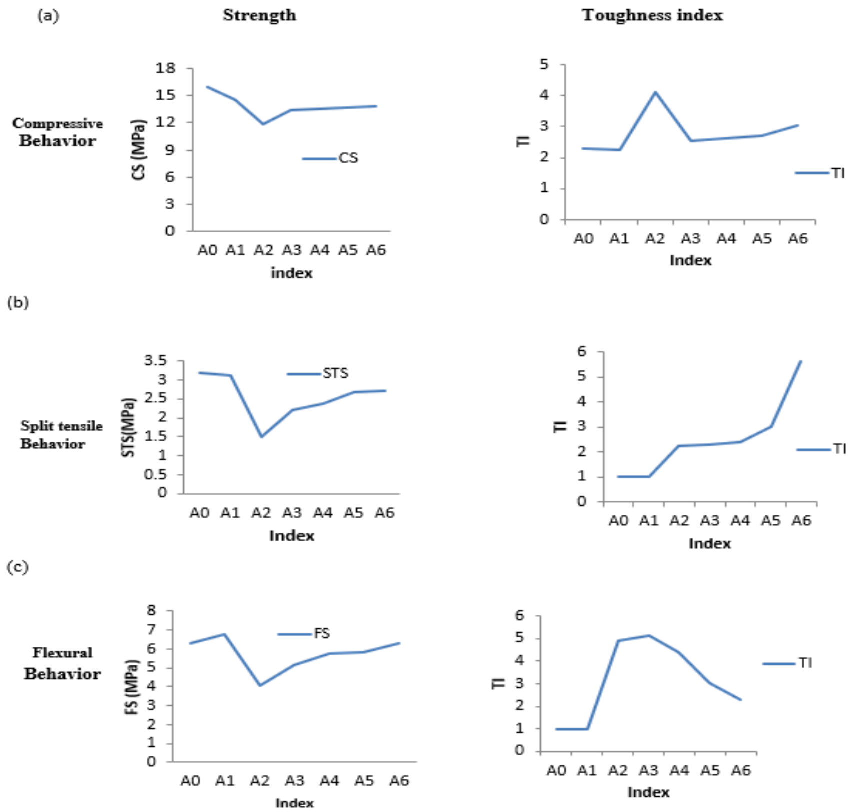


FIGURE 5.1: Comparison of Strength and Toughness index of PC and HFRC under Mechanical Loading

Fig.5.1 shows the comparison of flexural strength and flexural toughness index (FTI) of A0, A1, A2, A3, A4, A5, and A6 mixes respectively. Flexural strength for A0, A1, A2, A3, A4, A5, and A6 mixes are 6.3 MPa, 6.4 MPa, 4 MPa, 5.1 MPa, 5.8 MPa, 4.6 MPa, and 5.0 MPa respectively. Flexural strength of A1 mix is 0.01% more than that of PC and flexural strength of A1, A2, A3, A4, A5, and A6 mixes are 36%, 19%, 7.9% 26%, and 20% less than that of A0. Flexural toughness index (FTI) of mixes A0, A1, A2, A3, A4, A5, and A6 is 1, 1, 4.9, 5.1, 4.4, 3 and 2.27 respectively. The flexural toughness index (FTI) of mixes is decreasing from A2 to A6 because the concentration of banana fiber is decreasing. Flexural toughness index (FTI) of A2 and A3 mixes are more because banana fibers concentration in these mixes are maximum, as banana fiber has a greater bridging effect and excellent bonding strength as compared to glass fiber. All the combinations of HFRC have more value of TI in split and flexural due to the addition of fibers, converting the brittle nature of plain concrete to the tough nature of FRC.

TABLE 5.1: Consequences of HFRC for Mechanical Properties and Dynamic Properties

	Compression				**Splitting Tensile**			
Concrete Type	**P_{max} (kN)**	**Δ (mm)**	**ET (MJ/m^3)**	**TI**	**P_{max} (kN)**	**Δ (mm)**	**ET (MJ/m^3)**	**TI (-)**
HFRC with minimum value	61.14±12.1 (A2)	-	0.27±0.08 (A4)	2.55±0.1 (A3)	46.5±2.1 (A2)	1.41±0.2 (A3)	3.4±1.01 (A2)	2.26±0.9 (A2)
HFRC with maximum value	73.7±13.1 (A5)	-	0.42±0.1 (A4)	4.1±0.12 (A2)	81.3±11.3 (A5)	2.5±0.7 (A5)	9.01±1.4 (A6)	5.62±0.45 (A6)
Recommended HFRC	(A5) (Compression)					(A5) (Splitting Tensile)		
	Flexural				**Dynamic Properties**			
Pmax (kN)	**Δ(mm)**	**ET (MJ/m^3)**	**TI**	ξ	**RFl (Hz)**	**Poisons Ratio**	**E_{dyn} (GPa)**	**G_{dyn} (GPa)**
6±0.7 (A2)	1.2±0.1 (A3)	9.9±0.6 (A6)	2.27±0.8 (A6)	2.2±0.5 (A4)	3506 (A6)	0.06±0.1 (A5)	4.5±1.01 (A2)	3.6±0.3 (A2)
8.6±1.3 (A4)	1.6±0.2 (A2)	25.1±1.1 (A2)	4.91±0.6 (A2)	3.2±0.2 (A2)	3595±512 (A2)	0.94±0.5 (A3)	4.81±0.5 (A6)	3.82±0.8 (A4)
	A4 (Flexural)					A6		

Table 5.1 shows the minimum, maximum and recommended value of HFRC for mechanical and dynamic properties. A5 mix having 3.5% glass fiber weight and 1.5% banana fiber weight gives good properties under compression and split-tensile loading, so the recommended HFRC under compression and split-tensile loading for commercial use is A5 A5 combination gives better properties due to the addition of the larger amount of glass fiber because fibers diameter, tensile strength and specific gravity of glass fiber are more than that of banana fibers. In case of flexural loading, recommended HFRC is A4 (2.5% glass and 2.5% banana fiber). A6 mix having 4.5% glass and 0.5% banana fiber gives good dynamic properties.

5.3 Empirical Equation between Water Absorption and Selected Strength Properties

Empirical equations are formed from the data obtained after the experiment and by using the best-fit curve method in which the value of R_2 is between 0.65 to 0.80. The empirical equations between water absorption and selected strength properties are shown here. Water absorption is calculated by using the following single equation.

$$Y = 0.9e^{0.2217X_n} \tag{5.1}$$

(Where Y = Water absorption and X_n = X_1, X_2 and X_3)

X_1=P*C, X_2=Q*S and X_3=Experimental values of flexural strength.

P and C are constants, the value of P is calculated by dividing flexural strengths of the mixes with their compressive strengths and the average of these values is taken. Similarly, the value of P is calculated by dividing flexural strengths of the mixes with their split-tensile strength and the average of these values is taken.

The equation is made against compressive strength, split tensile strength, and flexural strength. Table 5.2 displays the investigational and theoretical values

Table 5.2: Investigational and Theoretical Values of WA for A0, A1, A2, A3, A4, A5 and A6

	WA (γ) $Y = 0.9e^{0.2217X_n}$				
Specimens	**Exp**	$\mathbf{X_1}$	$\mathbf{X_2}$	$\mathbf{X_3}$	**Recommended Condition**
A0	0.77	2.1	2.9	3.6	X_1
A1	1.28	1.8	1.7	3.75	X_2
A2	2.77	2.32	2.7	2.2	X_2
A3	3	2.8	2.9	2.8	X_2
A4	3.56	3.7	2.7	3.2	X_3
A5	2.33	2.6	2.9	2.5	X_3
A6	3.76	3.5	2	3	X_1

of WA (%). Values of water absorption are calculated by using these equations and it is seen that if the strength of specimens is more then water absorption capcity of concrete specimens will be reduced. Figure 5.2 shows the comparison of water absorption of PC and HFRC obtained from experimental test and empirical equation, experimental value of water absorption for A3 mix is very close to its empirical water absorption values.

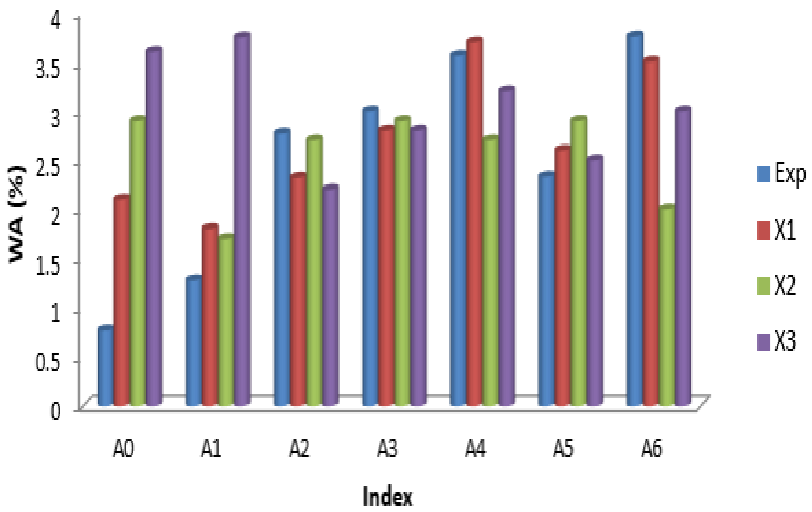


Figure 5.2: Comparison of values of WA of PC and HFRC Obtained from Experimental Test and Empirical Equation

5.4 Use of Research Result in Real Life Applications

Concrete manufacture from fibers and admixture is cheap and eco-efficient. It is clear from previous chapters that HFRC has better mechanical and dynamic properties. Greater values of toughness index, damping ratio, dynamic elastic modulus, and dynamic rigidity modulus are observed in the case of HFRC. The use of hybrid fibers gives better properties having a good bond between concrete mix and fibers, impact bearing capacity of concrete is also improved by using banana and glass fiber. Proper bonding of fibers with concrete control cracking and prevents concrete from spalling. HFRC having GGBS has higher moment capacity so flexural resistance of such type of concrete is more against impact loading.

Cracking in ordinary concrete is more due to its brittle nature. The bending stresses occur due to the differential settlement of concrete structures and cracking due to differential settlement is minimized by improving the flexural strength of concrete. The brittle nature of concrete is also responsible for cracking in different concrete structures for this purpose it is required to enhance the energy absorption capacity and toughness of concrete by changing the brittle nature of concrete to the tough nature of FRC. In the present research, the experimental behavior of PC and HFRC for controlling the cracking and spalling of concrete are studied. The presence of GGBS in concrete improves the flexural strength of concrete and differential settlement of concrete is minimized by the limited replacement of cement with GGBS. HFRC having more value of toughness index and less value of water absorption can overcome the problem of cracking in rigid pavements. Mix A5 having 3.5% of glass and 1.5% of banana fiber performs well under compression loading and splitting loading. The column is the compression member and using the A5 mix in column improves its properties under compression loading. Similarly, the A2 mix having 4.5% banana fiber and 0.5% glass fiber is used in foundations, slabs, and bridge decks where flexural loading is very essential. To overcome the problem of cracking and spalling of concrete, the A6 mix can be used.

5.5 Summary

The relationship between water absorption of PC and HFRC is developed by discussing CS, STS, and FS and an empirical equation is formed. The experimental and empirical relation between water absorption is discussed and a good relationship is seen. If the strength of specimens will be more the water absorption capacity of specimens will be less. The practical implementation of current research along with its use in daily life is discussed. HFRC gives better performance to control cracking than PC because of its improved energy absorption capacity. By keeping in mind all properties, HFRC with different proportions of fibers is recommended for commercial use.

Chapter 6

Conclusion and Future Work

6.1 Conclusions

Performance of concrete is improved by hybrid fibers because presence of one fiber enhances the properties of other fiber. Combination of natural and artificial fibers plays a vigorous role in refining the properties of concrete. In this study mechanical, dynamic and water absorption properties of HFRC are studied experimentally. Glass fiber and banana fiber is used 5% content by mass of cement having length of 5cm in the mix design of 1:2:3. GGBS is used as an admixture, 8% of cement is replaced with GGBS. Properties of HFRC are compared with properties of PC. Following conclusions are drawn from the research.

- Values of slump for A1, A2, A3, A4, A5 and A6 are 6.8%, 52%, 45%, 43%, 34% and 27% less than that of PC. Densities of HFRC are condensed by 0.2%, 7%, 5%, 6%, 0.7% and 4% than that of PC.
- Compressive strength of A1, A2, A3, A4 and A5 are 8.5%, 25%, 15%, 17%, 16% and 16% less than that of PC. Tensile strength of A1, A2, A3, A4, A5 and A6 mixes are 3%, 53%, 36%, 25%; 18% and 43% less than that of PC. Flexural strength of A1 is 0.01% more than that of PC. Flexural strength of A2, A3, A4, A5 and A6 mixes are 36%, 19%, 7.9% 26% and 20% less than that of A0.

- Value of total compressive energy absorbed by cylinders (ET) of A1 is 0.02 MJ/m^3 less than that of PC. While for A2, A3, A4, A5 and A6 value of total compressive energy absorption are 0.27 MJ/m^3, 0.31 MJ/m^3, 0.42 MJ/m^3, 0.38 MJ/m^3 and 0.398 MJ/m^3 more than that of PC. Improvement of splitting tensile energy absorption for A2, A3, A4, A5 and A6 are 0.1 MJ/m^3, 1.2 MJ/m^3, 1.5 MJ/m^3, 2.8 MJ/m^3, 5.3 MJ/m^3 and 6.81 MJ/m^3 as compared to PC. Values of total flexural energy absorbed by beam-lets of A2, A3, A4, A5 and A6 are 241%, 188%, 196%, 70% and 34% more than PC.

- Compressive toughness index (CTI) for A0, A1, A2, A3, A4, A5 and A6 are 2.28, 2.25, 4.1, 2.55, 2.61, 2.71 and 3.05, respectively. CTI of A1 is 1% less than that of PC, while CTI for A2, A3, A4, A5 and A6 mixes are 79%, 11%, 14%, 18% and 33% more than that of PC. Splitting tensile toughness index for the A0, A1, A2, A3, A4, A5 and A6 are 1, 1, 2.26, 2.3, 2.4, 3 and 5.62, respectively. The increment in splitting toughness index is observed in case of HFRC mixes. Flexural toughness index (FTI) of mixes A0, A1, A2, A3, A4, A5 and A6 are 1, 1, 4.9, 5.1, 4.4, 3 and 2.27, respectively. Flexural toughness index (FTI) of mixes is decreasing from A2 to A6 because concentration of banana fiber is decreasing. Flexural toughness index (FTI) of A2 and A3 mixes is more because banana fiber concentration in these mixes is maximum.

- In case of cylinders, for A1, A2, A3, A4 A5 and A6 mixes damping ratio are 9%, 59%, 14%, 12%, 48% and 54% more than that of PC. For ordinary concrete beam-lets damping ratio is 2.91, while damping ratio for A1, A2, A4, A5 A3 and A6 mixes are 13%, 123%, 44%, 23% , 54% and 20% more than that of PC.

- In case of cylinders, E_{dyn} of A2, A3, A4, A5 and A6 are 14%, 16%, 18%, 19% and 22% more than PC. For ordinary concrete beam-lets E_{dyn} for PC is 4.14GPa. A1 has similar value of E_{dyn} as that of PC and A2, A3, A4, A5 have E_{dyn} 7%, 5%, 1%, 38% & 46% more than that of PC.

- For cylinders, G_{dyn} for A1 mix is 0.85% that is slightly more than that of PC. On the other hand, value of G_{dyn} for all A2, A3, A4, A5 and A6 are 26%, 33%, 34%, 67% and 78% more than that of PC. For beam-lets, G_{dyn} of PC is 3.03GPa. G_{dyn} for A1 mix is slightly more than that of PC. All G_{dyn} values of A2, A3, A4, A5 and A6 are 2%, 43%, 68%, 62%, 64% & 78% more than PC.

- Value of poisons ratio for cylinders of PC is 0.30. Poisons ratio for beam-lets of PC is 0.31 and A1 mix has poison ratio equal to 0.34 that is 9% more than that of ordinary concrete.

- Water absorbed by A0, A1, A2, A3, A4, A5 and A6 mixes are 0.77%, 1.28%, 2.77%, 3%, 3.56%, 2.33% and 3.56% respectively.

- A5 combination is best among all because this combination performs well under compression and split-tensile loading.

- Relationship between water absorption of PC and HFRC is developed by discussing CS, SS & FS and empirical equation is formed. Experimental and empirical relation between water absorption is discussed and good relation is seen.

- A5 combination is best among all, because this combination performs well under compression and split-tensile loading.

Based on the above conclusions it is clear that HFRC gives better properties and it has a potential to reduce cracking and overcome deterioration of concrete. Combination of natural fibers and artificial fibers improve some of required properties of concrete.

6.2 Recommendations

Followings are the recommendations

- Experimental work may be carried out by changing the length of two fibers or by using two types of admixtures along with hybrid fibers.
- Hybridization of fibers is improved by the proper surface treatment of the fibers.
- HFRC along with admixture has greater moment capacity so it can provide flexural resistance against the impact loading.

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