CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Influence of Varying Length Hybrid Fibers and Ground Granulated Blast Furnace Slag on Properties of Concrete

by

Ijlal

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Civil Engineering

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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

Influence of Varying Length Hybrid Fibers and Ground Granulated Blast Furnace Slag on Properties of Concrete

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Acknowledgement

In the Name of Allah, The Most Gracious, The Most Merciful. Praise be to God, the Cherisher and Sustainer of the worlds. All thanks to Almighty Allah, The Lord of all that exist, who bestowed me with His greatest blessing i.e. knowledge and Wisdom to accomplish my task successfully.

Thousands of salutations and benedictions to the Holy prophet **Hazrat Muhammad (PBUH)** the chosen-through by whom grace the sacred Quran was descended from the Most High.

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Abstract

Concrete is widely utilized in constructing all over the world because it is widely accessible, economical, and resistant to severe weather. Concrete provides a number of benefits but it also has some limitations. Concrete cracking is a relatively frequent occurrence. The performance of concrete is degraded by cracking. By converting the brittle nature of ordinary concrete into the tough nature of FRC fiber additions prevent cracking. The key ingredients in concrete are cement, aggregates, and water, and these are something mostly influence how much concrete needs. The cement which significantly contributes to the greenhouse gas emissions is a key component of concrete. The global warming is an induced by greenhouse gases. Therefore a cement replacement is most needed to reduce this issue. GGBS can be used in place of cement in concrete and it is a waste product produced by iron manufacturing plants. The aforementioned issues can be reduced by using concrete that also contains banana fiber and glass fiber.

In this research, hybrid fiber reinforced concrete along with admixture explored the mechanical properties, dynamic behavior, and water absorption properties. Glass and banana fibers are utilized as reinforcement in the concrete while GGBS is used as an additive. While the mix design for HFRC is the same as that of plain concrete (PC) in which the water-cement ratio is maintained at 0.75. The mix design for plain concrete (PC) is 1:2:3:0.6 (cement: fine aggregate: coarse aggregates: water). Different varying lengths of Banana and glass fiber are maintained at 2.5 cm, 5 cm and 7.5 cm respectively with a 5% mass of cement fiber content. In the current facility a total of 42 specimens are cast and they are immersed in water for 28 days. Tests are carried out on specimens for dynamic, mechanical, and water absorption properties.

PG, PG11, PG12, PG13, PG21 and PG31 mixes having compression strength are 9.77 MPa, 5.51 MPa, 9.74 MPa, 11.76 MPa, 11.43 MPa and 10.36 MPa are less than PC respectively. PG, PG11, PG12, PG13, PG21 and PG31 mixes having tensile strength are respectively 2.11 MPa, 2.34 MPa, 2.14 MPa, 1.64 MPa, 2.16 MPa and 1.51 MPa equal or greater than PC as compare to compression. Set PG has a 0.5% stronger flexural strength than PC. PC has a flexural strength

less than the 2.87 MPa, 3.89 MPa, 3.37 MPa, 3.44 MPa, 3.40 MPa and 3.35 MPa mixes of PG, PG11, PG12, PG13, PG21 and PG31. For P, PG, PG11, PG12, PG13, PG21 and PG31 mixtures the corresponding compressive toughness index (CTI) are 1.08, 1.78, 2.97, 2.23, 3.27, 3.02 and 2.10. The compressive toughness index (CTI) of PG mix is 0.7 greater than PC but the CTI of PG11, PG12, PG13, PG21 and PG31 mixes are 2.97, 2.23, 3.27, 3.02 and 2.10 higher than that of PC respectively. While HFRC mixes have better split-tensile toughness and flexural toughness index than that of PC. According to the results HFRC mixes perform with PC in terms of the water absorption, damping ratio, dynamic modulus of elasticity and dynamic modulus of rigidity. By analyzing CS, STS, and FS a relationship between PC and HFRC water absorption is established and also an empirical equation is established. The empirical and experimental relationships between water absorption are explored; the empirical and experimental results show a strong correlation. It is observed that adding glass and banana fibers having varying length along with GGBS in concrete enhances the concrete properties. As a result, it is recommended to utilize hybrid fiber i.e. glass fiber and banana fiber concept along with GGBS in concrete for commercial use.

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Abbreviations and Symbols

BF	Banana Fiber
BFRC	Banana Fiber Reinforce Concrete
CE	Compression Energy
CEα	Compression Energy Absorption till Maximum Load
CEβ	Compression Cracked Energy Absorption till Ultimate Failure
CTI	Compressive Toughness Index
ET	Total Energy Absorption
Edyn	Dynamic Modulus of Elasticity
Exp	Experimental
FEα	Flexural Energy Absorption till Maximum Load
FEβ	Flexural Cracked Energy Absorption till Ultimate Failure
FE	Flexural Energy
FTI	Flexural Toughness Index
Gdyn	Dynamic Modulus of Rigidity
GF	Glass Fiber
GFRC	Glass Fiber Reinforce Concrete
GGBS	Ground Granulated Blast Furnace Slag
GPa	Giga Pascal
HFRC	Hybrid Fibers Reinforced Concrete
kN	Kilo-Newton
mm	Millimeter
MPa	Mega Pascal
PG	8% GGBS
P or PC	Plain Concrete

PG11	Banana = 2.5 cm ; Glass = 2.5 cm; 5% fiber content; 8% GGBS
PG12	Banana = 2.5 cm ; Glass = 5 cm ; 5% fiber content; 8% GGBS
PG13	Banana = 2.5 cm ; Glass = 7.5 cm; 5% fiber content; 8% GGBS
PG21	Banana = 5 cm ; Glass = 2.5 cm ; 5% fiber content; 8% GGBS
PG31	Banana = 7.5 cm ; Glass = 2.5 cm ; 5% fiber content; 8% GGBS
Pmax	Maximum Load
RFl	Resonance Frequency Longitudinal
RFr	Resonance Frequency Rotational
RFt	Resonance Frequency Transverse
SE	Split Tensile Energy
SEα	Split Tensile Energy Absorption till Maximum Load
SEβ	Split Tensile Cracked Energy Absorption till Ultimate Failure
STI	Split-tensile Toughness Index
W/C	Water Cement Ratio
WA	Water Absorption
σ	Strength
δ	Deformation
$\triangle$	Deflection
ϵ	Strain
ζ	Damping Ration

Chapter 1

Introduction

1.1 Background

Concrete is a significant building material that is utilized globally. Although concrete provides many benefits, there are also many drawbacks to evaluate. The development of cracks during the lifetime of concrete of varying ages is one of the most concerning situations that might arise in it. Several factors can cause crack formation. The use of a single fiber strengthened the attributes of concrete, but the hybridization of fibers in concrete strengthened the concrete capacity to perform sensibly. As due the production of cement produces the production of greenhouse gases, fly ash, GGBS, and metakaolin are used in place of cement. GGBS has a greater influence on the strength of the concrete than other admixtures. Metakaolin was used to investigate the characteristics of hybrid fiber reinforced concrete [1]. Other admixtures, such as silica fume and rice husk, enhanced the concrete's cracking behaviour and thus enhanced its split-tensile characteristics [2]. Since the utilization of cement in the concrete manufacturing process results in the emitting of greenhouse gases, fly ash, GGBS, and metakaolin are used in its replacement. Compared to other admixtures, GGBS has a larger influence on the strength of the concrete [3]. Typically, admixture and hybrid-fiber concrete was lightweight, used to have a lower density, and contained a higher flexural strength [3 and 4]. Compressive strength improved from 58.735 MPa to 65.2 MPa by raising the percentage of glass fibre from 0% to 1.2%. Flexural strength increased from 5.215 MPa to 7.21 MPa and tensile strength improved from 3.25 MPa to 4.5 MPa [4]. Evaluating the impact resistance behaviour of steel-sisal and steel-polypropylene fibre in concrete, it was revealed that the former performed best under compressive loading than the earlier [5]. Mono and hybrid fibres were utilized to examine the properties of high-strength lightweight aggregate. There were debates on the concrete's water absorbing attributes, compressive performance, flexural performance, split tensile performance, and stress-strain curve. If compared to concrete containing mono fibres, concrete with hybrid fibres exhibited greater attributes. Using two distinct types of fibers increased both the dynamic qualities of the concrete and the efficiency of single BF as it accelerated [6]. Concrete compressive strength was enhanced by incorporating different amounts of fibre, 20% metakaolin, and 10% GGBS [6]. Concrete is being used more and more frequently as a result of building innovation. Concrete with a high strength is utilized in construction. In order to reduce the size of structural elements and save natural resources, there is a significant demand for high-strength concrete as a result of rising urbanization [7]. Utilizing hybrid fibres, the properties of high-strength concrete were explored. Hybrid fibre concrete was produced combining steel and palm fibres. Utilizing these fibres enhanced flexural toughness and durability. The calculations were performed on the properties of ternary mixed high routine concrete with banana and steel fibres. In substitution of cement, 5% to 10% of GGBS and silica fume were added. Study demonstrated that workability decreased while mechanical properties increased [8]. The flexibility and impacts absorbed energy of concrete were both enhanced with the help of polypropylene fibre [9]. It was investigated that high-strength concrete performed while incorporating hybrid fibres. In varying ratios, hybrid fibres were utilized in addition to metakaolin and micro silica. Hybrid fibers material characteristics and concrete ductility have both increased by up to 25% compared to PC [10]. Plastic cracks arise in concrete during the pre-hardening phase, while shrinkage cracks make an appearance after the concrete has fully hardened. These flaws expand during time when the concrete's microstructure is exposed to precipitation and other toxic components including silicate, calcium, and bromide. Cracking is the cause of several different kinds of structural collapse.

The GGBS and metakaolin in concrete, as well as glass and steel fibre, improved the thermal characteristics of concrete. The concrete was given a larger dose of super-plasticizer to make it more flexible. According to previous studies, adding steel fibre to concrete containing natural fibre minimizes slump values while enhancing flexural and split tensile properties [8]. The addition of glass fibre to concrete minimized the occurrence of rapid cracks, enhancing the ductility of the material [10]. Steel fibers were added to concrete which improved its mechanical characteristics post-cracking flexural resistance, and durability. Maximized mechanical performance for both single and hybrid fibre RPCs was achieved by 1%Steel fiber and 1% carbon fiber hybridization [11]. The researcher noted that utilizing steel and polypropylene fibers may minimize cracking by up to 1.5%. HyFRC workability can be enhanced by substituting graded length fibres for single length fibres at greater volume proportions. This optimizes fiber dispersion, which increases the concrete's pre-peak and post-peak performance [12]. Hybridization of natural fiber and their mechanical properties of composites have been interfacial adhesion of fiber and matrixes were influenced by banana and sisal fiber [13]. Up to 40% of the fibre volume, it was established that increasing the fiber volume and length strengthened the flexural and thermal properties; however, at 50% of the fiber volume, these advantages began to decrease. The thermal properties are adversely affected by the fiber length, but the flexural properties are significantly affected [14]. The concrete properties were enhanced when SF or GGBS was utilized instead of ordinary Portland cement (OPC). The drying shrinkage and creep coefficients of high performance hybrid fiber reinforced composites were significantly lowered with the addition of fibers. Applications should consider creep behavior into consideration because it is a vital aspect of HPC. The drying shrinkage of high performance hybrid fiber reinforced composites was not severely impacted by the fiber volume fraction. Among all of the models examined in this study involves predicting the time-dependent behavior of concretes [15]. The hybrid double-layer fibers mat composites provide the highest tensile and flexural performances in the longitudinal direction [16]. Investigating the impact resistance performance of steel-sisal and steel-polypropylene fibre in concrete, it was revealed that it also performs better under compressive loading than the steel-sisal fiber. Steel, polypropylene, and sisal fibers used in hybrid fiber reinforced concrete were compared to PC in terms of mechanical strength characteristics. Other admixtures, such as silica fume and rice husk, enhanced the concrete cracking behavior and thus enhanced its split-tensile characteristics. The results show that a weight fraction with 40% or more fiber performance was better than other weight fractions. It is also observed that caryota fiber characteristics exceed other natural fibers in terms of results [17]. The best mechanical performance was achieved by hybrid fibre RPC with 2% SF-1% GF at both low and high temperatures. At both high and low temperatures, a single 3% SF-RPC performed significantly better than a single 3% GF-RPC [18]. Dune sand and steel fibres added combined massively reduced the workability. As the pace of the sand dunes grows, the tensile and flexural strength reduces [19]. The researchers examined about how steel and polypropylene fiber influenced the mechanical characteristics of concrete. When the steel fibers were added to the concrete matrix, the compressive and flexural behavior of the concrete was enhanced. The hybrid fibers are an exciting concept and switching out a portion of the steel fiber along with palm fiber can significantly reduce density while improving toughness and flexural strength. Additionally, the research shows that using hybrid fiber 1.5% steel fiber and 0.5% palm fiber in specimens substantially enhances the toughness index [21]. Steel, polypropylene, and sisal fibres used in hybrid fibre reinforced concrete were compared to PC in terms of the mechanical properties. Results revealed that combining steel and polypropylene fibres might minimize cracking up to some extent [23]. Polypropylene fibers were used to analyze the behaviour of high-performance self-compacting concrete beams without coarse materials. High-performance self-compacting concrete beams compressive strength was enhanced [24 and 25].

According to the review of relevant literature, utilizing hybrid fibers and admixtures results in engineering materials with admirable characteristics. The critical assessment of the literature makes it clear that the majority of research have been focused to examining at the mechanical characteristics of hybrid fibre reinforced concrete, while excluding the dynamic properties that are essential for concrete structures. On the other hand, no research has been done on the combination of banana and glass fibers having different varying lengths in addition to GGBS admixture. As a result, significant research is needed to investigate exactly banana and glass fiber having varying length along with GGBS.

1.2 Research Motivation and Problem Statement

There has been massive construction around the global and concrete is one of the frequently used materials for many civil engineering applications. A lot of research has been done to further improve the performance of concrete by various means. One of such efforts is the use of locally available small fibers and admixtures (for cement replacement) in concrete. It may be noted that many properties can be improved with some little compromise on few properties. Depending upon the application, such concrete can be used safely and their detail evaluation. Therefore, the performance of concrete having fiber addition and for cement replacement should be explored.

Consequently, the following is the problem statement:

Concrete is widely used construction material. It inherits certain flaws like brittle nature, less tensile strength etc. There has been a growing trend in use of fibers and admixtures in concrete. But there is little or no knowledge about the performance of concrete having such additions/replacement. In a recent research, fixed length of BF, GF and GGBS were used in concrete and favorable results were reported. The performance of concrete having varying length of BF, GF and 8% GGBS is unknown.

1.2.1 Research Questions

- How much compressive strength would be compromised with some gain in tensile and flexural strength with the use of varying length hybrid fiber and 8% GGBS?

- How much damping energy absorption and toughness can be enhanced with the use of varying length hybrid fiber and 8% GGBS?
- How much WA would be increased with the use of varying length hybrid fiber and 8% GGBS?

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

The overall objective of the research program is to evaluate hybrid fibers reinforced concrete (containing both natural and/or artificial fibers) along with admixture for partial cement replacement under various conditions for recommending optimized HFRC for civil engineering application.

The specific aim of this MS research study is to analyze the mechanical, dynamic, and water-absorbing characteristics of concrete (containing both glass and banana fibers having varying lengths along with ground-granulated blast furnace slag.

1.4 Scope of Work and Study Limitations

There are 42 hybrid fiber reinforced concrete specimens utilizing different combinations of banana and glass fibers having different lengths along with a GGBS admixture. Flexural testing is carried out on beam-lets while the compression, split tensile, and water absorption tests are performed on cylinders. For dynamic testing, both beam-lets and cylinders are used. For mechanical properties two samples were analyzed, and the average of these two results is used for a particular property as per [59].

Single percentage of GGBS is used in current research only two fibers (i.e. one natural and one artificial) are used. Average of two is taken to represent a specific mentioned property.

1.4.1 Rationale Behind Variable Selection

The research utilized banana and glass fibers because these are both readily available. Banana fiber has high bonding characteristics [57] and glass fiber has a strong tensile strength [58]. The 8% of GGBS is used to replace cement because in literature, the researchers have used different percentages (3%, 5% and 8% of GGBS was recommended [30]. So 8% GGBS is used in current research. Many researchers used different percentages but in hybrid fiber 50:50 used for the optimum result [59].

1.5 Brief Methodology

In the current study, glass fibres and banana fibres are used with GGBS to study the characteristics of concrete. The concrete dynamic, mechanical and water-absorbing characteristics are investigated. For set 1 and 2 (cement, sand, aggregate, and water) mix design ratio is 1:2:3:0.6. While the HFRC mix design is 1:2:3:0.75, (cement, sand, aggregate, and water). PC has a W/C ratio of 0.6, whereas HFRC has a W/C ratio of 0.75. To make HFRC better workable, fibers are added to concrete, which reduces the durability of the material. The HFRC W/C ratio is maintained at 0.75. In the concrete mixtures, GGBS is utilized to replace 8% of the cement, either with or without hybrid fibres. In order to achieve hybridization, glass and banana fibers are utilized in concrete. The length of the hybrid fibers having different varying lengths i.e. the combination of both fibers of 2.5 cm, 5 cm, 7.5 cm and 5% by mass of cement is added to the concrete mixture. To create HFRC, both fibers are mixed with GGBS admixture in various ratios. Using the industry-standard slump cone testing methods, the workability of PC and HFRC mixtures is evaluated in a fresh condition. The cylinders and beamlets of PC and HFRC are subjected to various dynamic and mechanical tests after being cast in the designated location and placed in water for 28 days. Calculations are conducted for PC and HFRC, related to poisons ratio, dynamic testing resonance frequencies, damping ratio, dynamic modulus of elasticity, and dynamic modulus of rigidity. Similar to this, mechanical tests include the compression test, splitting tensile strength test, test for water absorption and flexural test of PC and HFRC. The resonance frequency tool is utilized to calculate the dynamic parameters, while the servo-hydraulic testing machine is used for mechanical testing.

1.6 Research Novelty and Significance

To the author's knowledge, no research is being conducted on the combined usage of glass and banana fibers having varying length and GGBS in concrete to enhance its various attributes with some compromise on compressive strength.

This research will help in contributing towards the production of sustainable concrete using GGBS, glass fiber and banana fiber. This will help the end user to select the optimized combinations for different applications like compression, flexural etc.

1.7 Thesis Outline

The research work having six chapters:

Chapter 1. It includes an introduction section having research motivation, problem statement, overall objective, specific aim, research methodology and the thesis outline.

Chapter 2. It includes the literature review section in which the explanations of background, flaws in concrete, the role of hybrid fiber in concrete performance, the role of GGBS in concrete performance, research novelty & significance of current study and a brief summary.

Chapter 3. It includes the experimental procedure in which the explanations of background, material, mix design, the procedure of casting, testing and a brief summary.

Chapter 4. It includes the analysis and testing results in which the explanations of behavior of PC & 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 and a brief summary.

Chapter 5. It includes the discussion section contains background, optimization of HFRC, use of research result in actual life applications, and a brief summary.

Chapter 6. It includes the explanations of conclusion and recommendations.

References are presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

Concrete is a common building material that is utilized all over the world. Concrete offers a number of advantages, but it also has a number of drawbacks. The formation of fractures in concrete at various ages is one of the most alarming problems that might occur. Cracking can occur for a variety of causes. Plastic cracks form during the pre-hardening stage of concrete, whereas shrinkage fractures appear after the concrete has fully set. The microstructure of concrete is exposed to rain and other hazardous elements such as silicate, calcium, and bromide as these cracks grow in size over time. Cracking is responsible for a variety of structural failures. Concrete built with additives and hybrid fibers was usually light and had a lower density. The use of a single fiber improved the qualities of concrete, but the hybridization of fibers in concrete provided the concrete with more intelligent working properties. The qualities of one fiber were boosted as the performance of another fiber accelerated, and the dynamic properties of concrete were improved by using two types of fibers. Hybrid fibers were used to examine the properties of high-strength concrete. For the preparation of hybrid fiber concrete, palm and steel fibers were employed. Flexural toughness and rigidity were improved when these fibers were employed. The goal of this research is to figure out what the mechanical properties of hybrid fibre reinforced concrete.

Furthermore, the thermal characteristics of concrete were improved by including glass and steel fibre, as well as GGBS and metakaolin. To make the concrete more workable, a larger dose of super-plasticizer was added. The compressive strength of concrete was enhanced using various quantities of fibre, 20% metakaolin, and 10% GGBS [1]. Hybrid fibers were used to examine the behavior of high-strength concrete. In addition to GGBS and micro silica, hybrid fibers were employed in various ratios.

2.2 Flaws in Concrete

The increase of economic, social and environmental issues necessarily needs low cost and sustainable construction materials [2]. Concrete has a lot of advantages but in the same manner, there are a lot of flaws in concrete as well. Concrete deficiencies can occur for a variety of reasons all of which have an impact on the structures performance. Various studies looked into various defects in concrete. The most serious fault in concrete is its rapid collapse due to external chemical attacks and other external forces [26]. The tensile strength and fracture toughness of glass fiber reinforced composite is 36.54% and 33.34% higher than banana fiber composite respectively [60]. Similarly, one of the most alarming conditions that appear in the concrete is the generation of cracks during its different stages. Durability of concrete may be defined as the ability of concrete to resist weathering action, chemical attack and abrasion while maintaining its desired properties [27]. The most consequence is cracking in concrete which can occur for a variety of reasons.

The appearance of the structure is affected by cracking in the walls and slabs, which further reduce the buildings load-bearing strength and can occasionally, cause the structure to perform adversely [27]. Plastic expands as a response of water evaporating from the concrete surface and solid particles settling on the concrete surface. The utilizing of fibers and super-plasticizer helps to reduce the issue of plastic shrinking.

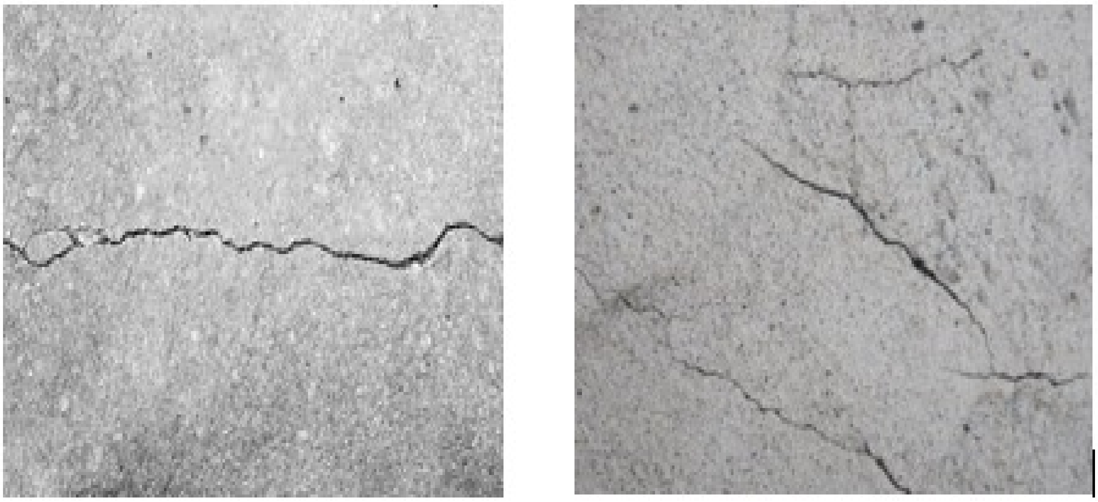

FIGURE 2.1: Cracking in Concrete Structures [27].

2.3 Prospects of Hybrid Fibers and GGBS as Construction Material

Globally, most large-scale construction projects use concrete. The characteristics of concrete can be enhanced to a greater extent by the appropriate combination of hybrid fibres and additives. Concrete may have its mechanical and dynamic characteristics enhanced by adding various fibre and additive combinations. Concrete is improving day by day all over time. To enhance the characteristics of concrete, various fiber and admixtures are incorporated. Due to the improvement in concrete characteristics it was carried by the addition of fibers and admixtures, significant study is being done on FRC. When compared to reinforced concrete made with a single fiber, concrete reinforced with two different types of fibers has more desirable properties. The energy absorption and toughness of concrete can be significantly enhanced with the use of hybrid fibers. Tensile and flexural strengths can also be improved. However, compressive strength is reported to be compromised in many cases, especially with flexible fibers. For concrete to perform efficiently, many researchers suggested the hybridization (using two fibers) concept [28]. Concrete strength and durability are enhanced by merging multiple fibers, one of which is strong and resilient. While a different fiber increases other concrete attributes. The majority of hybrid polymer fiber concrete is lighter weight concrete with enhanced mechanical and dynamic performance. shows compressive strength of mixtures 15 at the age of 7 days, 28 days and 91 days.

Figure 2.2 illustrates that at 91 days age, compressive strength decreases as GGBS replacement percentage increased. Compressive strength decreases with aging [3].

Concrete strength and durability are enhanced by merging multiple fibers, one of which is strong and resilient. While a different fiber increases other concrete attributes. The majority of hybrid polymer fiber concrete is lighter weight concrete with enhanced mechanical and dynamic performance.

It was conducted an experimental study of HFRC with GGBS. The use of less water during the curing process and a reduction in plastic shrinkage during the pre-hardening stage of concrete are both benefits of this additive. Concrete with high strength that contains steel and polypropylene fiber was developed [28]. It indicated that silica fume increased the concrete toughness and mechanical characteristics. Banana fibers could minimize the different forms of cracking due to their strong tensile and adhesive strength [29]. The addition of 2% banana fiber and 4% steel fiber was optimal for improving mechanical qualities [61]. When 1.5% of banana fibres, 2% of polypropylene fibres, and 8% of GGBS were added to the concrete mix, the compressive strength, flexural toughness index, and damping ratio were all increased [30].

Glass fiber and steel fiber hybrid concrete properties were investigated. HFRC has a greater bridging impact than regular concrete. By using steel and glass fiber quick failure due to impact loading was mitigated [31]. The characteristics of GGBS and hybrid fibre reinforced concrete were examined. In order to increase concrete strength without compromising its workability, two types of fibers polypropylene and banana fibers were added together with GGBS. This was conducted an experimental evaluation of HFRC with GGBS. The use of less water during the curing process and a reduction in plastic shrinkage during the pre-hardening phase of concrete are both features of this additive.

2.3.1 Role of Hybrid Fibers in Concrete Performance

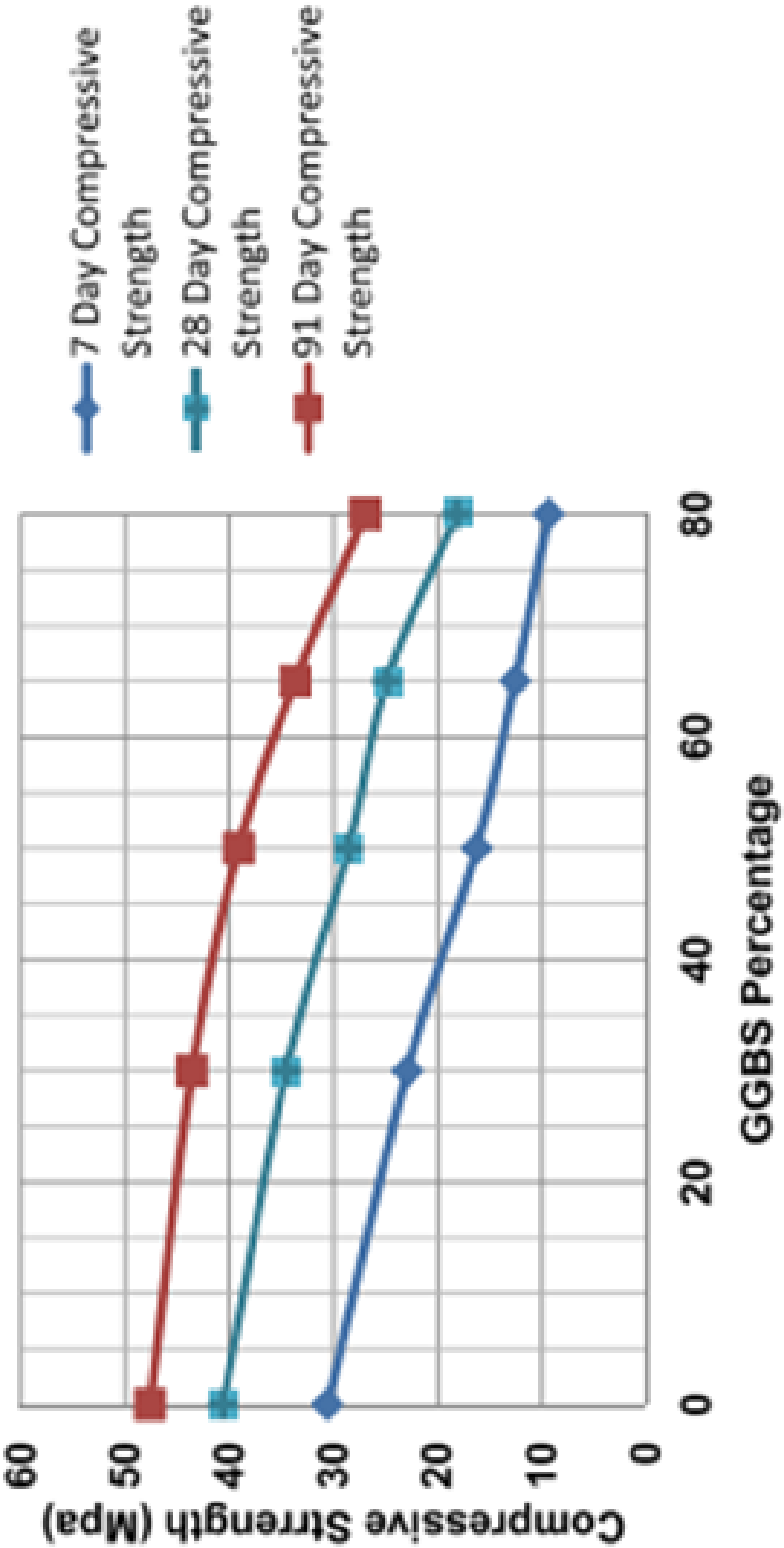

FIGURE 2.2: Compressive strength variation of SCC mixtures with different GGBS replacement percentage for 7, 28, 91 days [3]

Fibers were utilized to prevent cracking enhancing the flexural strength of concrete [31]. Calculations were performed on the properties of concrete produced utilizing coir and banana fibres along with an admixture. The properties of concrete were examined while a few hybrid fiber reinforced concrete mixtures were developed. Concrete ductility and split tensile strength were both enhanced [32]. Glass fibers weighing 1800 g/cm3 were added and the resulting improvement in compression strength, split-tensile strength and flexural strength was 31.5%, 29.9%, and 97% respectively [33]. By adding glass fibers to concrete mixtures at percentage levels of 1%, 2%, 3% and 4% by weight of cement, mechanical characteristics and energy absorption capacity were evaluated. Concrete split-tensile strength and flexural energy absorption were enhanced by adding glass fibers at a proportion of 4% [34]. Glass fibers were added to cement in proportions of 0, 0.5, 1 and 1.5 percent by volume and aluminum oxide nanoparticles in proportions of 0, 0.5, 1, 1.5, and 3 percent by weight to examine the properties of concrete. When 2% aluminum oxide nanoparticles and 1% glass fiber were added compressive and tensile strength enhanced [35]. Concrete with and without glass fiber reinforcement was compared for strength and durability. Compression strength, split tensile strength, and flexural strength of GFRC were investigated with glass fiber varying concentrations from 0% to 1%. When 1% of glass fibers were added to concrete after 7, and after 28 days, compression strength enhanced [36]. Alkali treatment reduces contaminants and exposes small pores on banana fibers. Revealed small pores on treated banana fiber acquire better bonding between fiber content. Banana fiber composites generally have the range of tensile strength showed in fig. 2.3 [38]. Banana fibers and wood bottom ash were utilized to evaluate the properties of high-strength concrete. In place of cement, wood bottom ash is used, and 0.5% to 2.5% of banana fibers are incorporated to the concrete mix. Results showed that replacing cement with 10% wood bottom ash and 1.5% fiber content provided the necessary characteristics [38]. The tensile and flexural strength of concrete enhanced while the slump value decreased when steel fibre was added to it at a rate of 5% of the cement mass [39]. The effect of fiber hybrid mode and bending loading on the long-term property evolution mechanism were revealed [59]. The

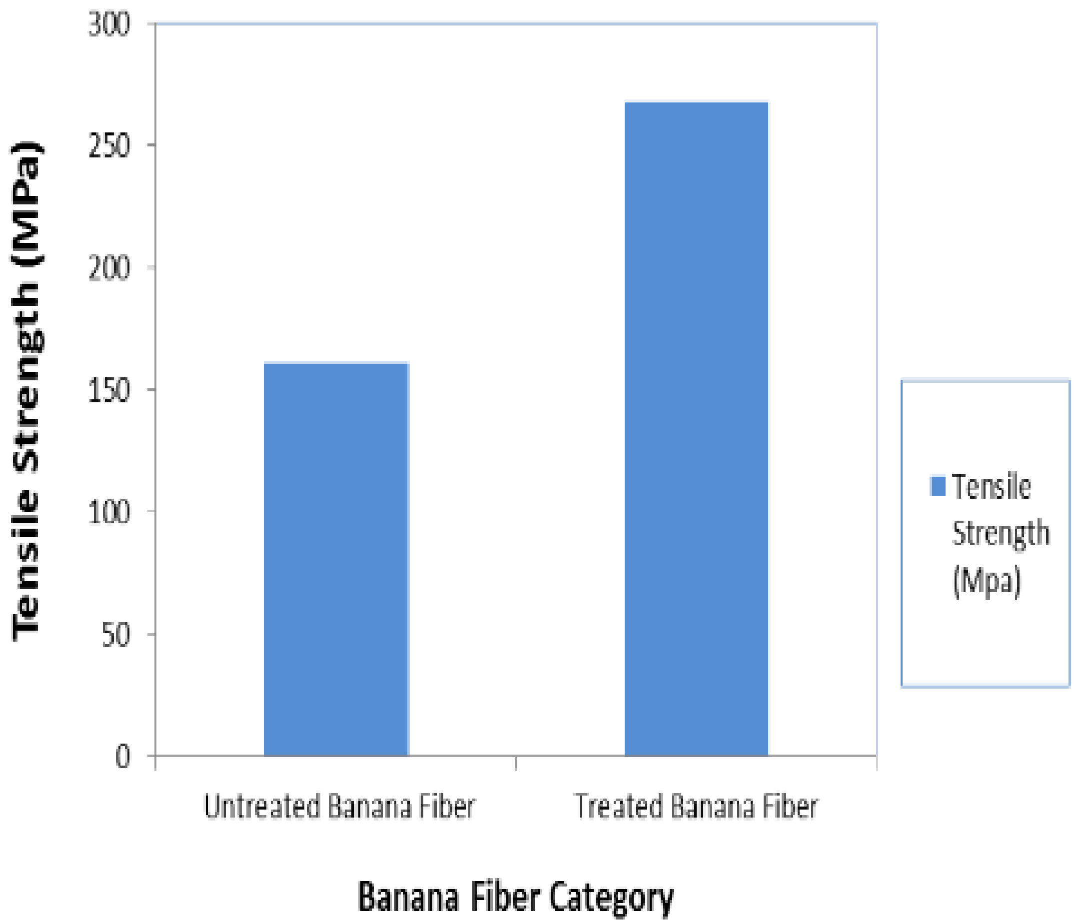

FIGURE 2.3: Tensile strength of raw and alkali treated banana fibers

preparation of high-strength concrete comprised the use of jute and palm fibers. To test the characteristics of concrete, each of these fibers were added at 6% of the cement mass. In comparison to regular concrete, these fibers hybridization at 3.5% palm fibers and 2.5% jute fibers provided materials with high mechanical characteristics, flexural toughness index and flexural strength [40]. Banana fiber reinforced concrete beams were developed, and their mechanical characteristics were investigated. The flexural strength of concrete beams was enhanced by up to 25% compared to PC by using banana fiber bars in concrete, which decreased cracking and spalling in concrete. We investigated the properties of concrete by adding an equivalent amount of steel and polypropylene fiber. Results showed that including steel fiber enhanced strength properties compared to adding polypropylene fiber [41]. Banana fiber bars were incorporated in the construction of the concrete beam to minimize cracking and spalling [42].

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The presence of two type of fiber in concrete may improve the performance. Hybrid fibers were used to examine the properties of high-strength concrete. For the preparation of hybrid fiber concrete, palm and steel fibers were employed. Flexural toughness and rigidity were improved when these fibers were employed. When compared to mono fiber concrete, hybrid fiber concrete should have better characteristics. The properties of low weight aggregate concrete with additives were investigated. As mono and hybrid fibers were employed in concrete, there was a significant improvement in splitting tensile behaviour and flexural strength when compared to PC. The table 2.1 discuss the mechanical properties of hybrid fibers i.e. banana and glass fiber. The qualities of concrete were investigated using various combinations of hybrid fiber reinforced concrete. Hybrid fiber i.e. banana and

Table 2.1: Mechanical properties of banana and glass fiber [57-58]

S. No.	Fiber	Fibers diameter (in)	Specific gravity	Tensile strength (ksi)	Elastic modulus (ksi)	Water absorption
1.	Banana	0.14-0.14	1.32	275-350	1900-2585	55-60
2.	Glass	0.3-0.8	2.5	220-580	10,400-11,600	-

glass fiber is added in concrete to enhance its properties. Hybrid fibre reinforced concrete is made up of two or more fibers. Steel and polypropylene fiber was used to make high-strength concrete [23]. The addition of silica fume to concrete improved the toughness and mechanical qualities of the material. The performance of glass fibre and steel fibre hybrid fibre concrete was studied. Glass and hybrid fibers were used to create a variety of concrete models [35]. The introduction of fibers reduced cracking and hence increased concrete flexural strength.

2.3.2 Role of GGBS in Concrete Performance

To make the concrete more workable, a larger dose of super-plasticizer was added. When 1.5 percent banana fibers and 2% polypropylene fibers were added to the concrete mix with 8% GGBS, the compressive strength, flexural toughness index, and damping ratio were all improved. The properties of concrete were estimated using coir fiber and banana fibre in the presence of admixture. The compressive strength of concrete was enhanced with various percentages of fibre, 20% metakaolin, and 10% GGBS. Fly ash and ground-granulated blast-furnace slag (GGBS) uses to reduce air pollution by eliminating carbon dioxide and carbon monoxide from the surroundings [62]. The presence of glass fiber in concrete reduced the occurrence of abrupt cracks, increasing the ductility of the concrete and the behaviour of high-strength concrete [36].

The thermal characteristics of concrete were improved by including glass and steel fiber as well as GGBS and metakaolin. It was explored both hybrid fiber concrete and GGBS performed. The concrete incorporated steel and banana fibers. Comparing the properties of hybrid fibers in concrete showed that workability was reduced leading to the use of a super-plasticizer. Significant increase was obtained in compressive strength and fracture resistance [43]. By utilizing hybrid slag, the mechanical and physical properties of the concrete were taken into consideration. Different ferrochrome slag concentrations were utilized in place of the sand, and 25% GGBS was utilized in place of cement. Several experiments were conducted; GGBS with ferrochrome significantly enhanced compressive strength while minimizing voids ratio [44]. In order to reduce the expense of concrete, the industrial waste product is mostly utilized in concrete because these wastes might ultimately be utilized as aggregate in concrete and are cheap and readily available. Investigated were the properties of concrete incorporating GGBS and fibres made of glass and steel [44]. A study was conducted on how volume fraction and fiber length affected the properties of composite materials. The outcomes demonstrate that the hybrid artificial banana/glass fiber composites mechanical properties are significantly influenced by both volume fraction and fiber length [52]. To identify the important components and their impacts variations are evaluated. The volume portion of fiber with polyester matrix was shown to influence more than other components. Furthermore, it is revealed that glass fiber reinforced composite has tensile strength and fracture toughness which are respectively 36.54% and 33.34% and is better than banana fiber composite [54]. Many researchers have examined the use of various types of natural fibers in concrete throughout the years, but no one has employed banana fibre and glass fibre having a variant length in concrete with GGBS.

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Table 2.2: Chemical and mechanical properties of GGBS

Content	**Cement (%)**	**GGBS(%)**
CaO	64.64	36.62
Al_2O_2	5.6	14.73
SiO_2	21.28	33.86
Fe_2O_3	3.36	0.48
MgO	2.06	6.33
Bulk density (kg/m^3)	1400	1200
Specific gravity	3.15	2.88
SO_3	2.14	2.1
Color	Grey	Black

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The better understanding of damages observed in concrete related to the mechanical properties of concrete under different conditions. In order to reduce the expense of concrete, the industrial waste product is mostly utilized in concrete because these wastes might be ultimately utilized as an aggregate in concrete which are inexpensive and readily available. Comparison of the chemical properties of cement and GGBS is studied because the chemical composition of GGBS and cement are relatively comparable as discussed in table 2.2

2.4 Summary

According to the description above, it is observed that the combination of hybrid fiber along with GGBS admixture provides the better properties than the single fiber reinforced concrete. The dynamic and mechanical characteristics of concrete should be enhanced in order to reduce the cracking pattern. Banana fibre is readily accessible and has a better bonding strength while on the other hand glass fiber has a strong tensile strength, according to the review of the literature. The performance of concrete is enhanced by the use of both natural and artificial fibers. According to previous research, it is observed that GGBS has the ability to substitute the cement in concrete.

Chapter 3

Experimental Program

3.1 Background

Concrete has been manufactured with both natural and synthetic fibers over the past 20 years. The major benefits of utilizing hybrid fiber in concrete are an enhancement in mechanical characteristics, toughness index, and damping ratio. Basically this research work is the continuation of previous research work that is "improvement in properties of concrete using hybrid fiber and ground granulated blast furnace slag (GGBS)". This chapter explores in great depth on material characteristics, mix design, casting process, and testing processes.

3.2 Material Properties and Fibers Treatment

Plain concrete is made utilizing water, locally sourced Portland cement, Lawrencepur sand, and coarse aggregates (13mm). Banana fibers and glass fibers are mixed with cement, fine aggregate, coarse aggregate, and water to produce HFRC. All HFRC set combinations and one PC set combination both use GGBS as an admixture. Figure 3.1 represents banana fibers, glass fibers and GGBS both in fresh and processed forms. The portion of the fiber is left immersed in the concrete after a concrete structure fails completely [20]. the length of hybrid fibers that combine banana and glass fiber in different lengths are the combination of 2.5 cm, 5 cm and 7.5 cm. Glass and banana fibres both seem to be available in raw form. To remove contaminants from them, these fibers are first washed and then dried for 24 hours. The required quantity of fibers are disentangled and cut up in different varying lengths i.e. 2.5 cm, 5 cm and 7.5 cm long fibers which are used. The iron production factory placed near I-9 Islamabad is from where GGBS is acquired. Similar, GGBS is prepared before it can be used in concrete.

Figure 3.1: Images of (a) Banana fiber (b) Glass fiber (c) GGBS in their treated and untreated variants

3.3 Mix Design and Casting Procedure

According to the literature study on HFRC, fiber length and composition play a significant role in achieving the necessary characteristics of concrete, so consideration must be given to them while making HFRC. Previous literature reviews indicate that increased energy absorption is more significant than improving concrete's strength. In the available literature, researchers have used different percentages

TABLE 3.1: Mix Proportion.
Note: *kg = kilogram, % = Percentage, mm = millimeter, m = meter and the dimensions mentioned in [ ] are in inches (1”=25mm). Both the BF and GF are equally added i.e. 2.5% each.*

Index	**Hybrid Fiber (%)**	**Binders**		**Sand (kg)**	**Crush (kg)**	**Banana fiber length (cm)**	**Glass fiber length (cm)**	**W/C**	**Slump (mm)**	**Density (kg/m^3)**
		Cement	**GGBS**							
P	0	1	0	2	3	-	-	0.6	42[2]	2468
PG	0	0.92	0.08	2	3	-	-	0.6	40[2]	2460
PG11	5	0.92	0.08	2	3	2.5	2.5	0.75	22[1]	2302
PG12	5	0.92	0.08	2	3	2.5	5	0.75	26[1]	2322
PG13	5	0.92	0.08	2	3	2.5	7.5	0.75	27[1]	2445
PG21	5	0.92	0.08	2	3	5	2.5	0.75	25[1]	2318
PG31	5	0.92	0.08	2	3	7.5	2.5	0.75	31	2378

and in case of hybrid fibers, 50:50 percentages have been utilized for better results [59]. By determining the perfect length of fiber in concrete, a higher energy absorption value may be obtained. This is essential for bridge decks and other structures of this kind where impact loading is a critical factor. Thus, several researchers are attempting to achieve increased energy absorption as well as optimum compressive strength in order to achieve the desired aims. All of the components are added to the mixer machine surface combination in a dry condition. Following the addition of one-third of the coarse aggregates to the mixer machine, fiber is then placed on top of the coarse aggregates. In a similar manner, a third layer of prepared sand is also added to the mixer machine, and then a layer of fiber is put over this layer once again. After one more round of the same procedure, the mixer spins for 5 minutes. 3 minutes of spinning add further third of an additional layer of aggregates and fibres to the mixer machine. Water is also added as required during rotation. After adding all the material, the mixer is left to spin for 2 minutes. Table 3.1 describes the treated and untreated variants of fibers utilized to produce PC and HFRC. Glass fiber and banana fiber have densities of 2.44 g/cm3 and 1.35 g/cm3, respectively. Due to their lower density, these fibres enable for the production of the same number of samples using reduced adhesives (cement and GGBS), fine aggregate, and coarse aggregates. Slump testing in conformance with ASTM C143/C143M-15a is utilized to examine the workability of PC and HFRC [21]. Cylinders sized 100 mm x 200 mm and beam-lets sized 100 mm x 100 mm x 450 mm are filled in conformance with the specified standard to evaluate the mechanical behavior of HFRC. Table 3.1 shows the mix percentage.

Molds were cleaned properly and oiled. Each cylinder and beam-let is filled in three stages, with 25 tamping rod blows applied to each layer to ensure uniform concrete compaction. According to ASTM C192/C192M, these cast specimens are subsequently demolded after 24 hours and submerged in water for 28 days. These specimens are next subjected to mechanical testing in conformance with ASTM C 215-02 [27]. Variable specimens require a different loading rate, and the compression loading rate used on specimens is in conformance with the ASTM standard C39/C39M-18 [28]. In cases of split tensile and flexure, loading rates are applied in conformance with ASTM standards C496/C496M-17 and C78/C78M-15b [29].According to ASTM C642-13 sample water absorption capabilities are estimated. According to ASTM standard C215-02 dynamic behaviors are estimated [30].

The slump values and densities for P and HFRC are shown in Table 3.1. P, PG, PG11, PG12, PG13, PG21, and PG31 all have a slump value of 42 mm, 40 mm, 22 mm, 25 mm, 26 mm, and 27 mm, respectively. The FRC is less practical than PC for the same W/C ratio. While casting, the concrete was found to be less workable, the possible reason could be the high temperature during casting as this activity was performed in open environment in summer season. So, the w/c ratio was kept 0.6 in case of PC in order to ensure the proper workability of concrete for making the samples. HFRC has poor workability due to the increased water absorption capacity of the fibers. The W/C ratio for HFRC is kept at 0.75 to improve workability but since the slump value is still low, it is advised to add a super plasticizer for the enhancement of HFRC. The reason for variation in WA is the high absorbing capacity of the fibers. To ensure the workable concrete, w/c ratio was kept high in case of fibers combinations to minimize the adverse effect of WA capability of concrete with fibers on the workability of concrete mixes. In the case of FRCs compared to PC, lower values of a slump are shown due to the retention and confinement effect of fibers. The addition of fibers in concrete reduced its workability according to other researchers. The workability of concrete is enhanced if an admixture is added to it. In comparing to HFRC, a concrete mix with no hybrid fibers and solely GGBS provides high workability. The densities of the specimens of hardened PC and HFRC are also shown in Table 3.1. P, PG, PG11, PG12, PG13, PG21, and PG31 have respective densities of 2468 kg/m^3, 2460 kg/m^3, 2302 kg/m^3, 2322 kg/m^3, 2445 kg/m^3, 2318 kg/m^3, and 2378 kg/m^3. The density of GF has been taken from previous studies and it is 2.44kg/m^3 greater than the density of BF. The length of GF in PG13 is greater i.e. increased content than length of GF in other combination which resulted in high density of PG13 because of high density of GF. As a result comparing to PC, the densities of HFRC are reduced due to the low unit weight of fibre, the incorporation of fibres in FRCs resulted in lower densities of FRCs compared to PC.

3.4 Specimens

All kinds of testing involve the use of cylinders and beam-lets. The dynamic characteristics of cylinders and beamlets are evaluated within the use of resonant frequency equipment due to the determination in the longitudinal, transverse and torsional resonant frequency of concrete. A test for water absorption is carried on cylinders. Cylinders and beamlets compressive, splitting tensile and flexural properties are described. One thing to keep in mind is that the average of the two results from each test is taken. All tests are conducted on two specimens of the same combination. Other researchers precede an average of two values as well. To figure out the necessary properties of concrete, a total of 42 specimens are made in which PG13 beam-lets and 28 cylinders were casted. For convenience during testing, specimens are identified as P, PG, PG11, PG12, PG13, PG21, and PG31.

3.5 Testing Procedure

In the casting yard, cylinders and beamlets were cast. The testing technique is followed in conformity with the ASTM standards. Resonant frequency equipment is utilized to measure the dynamic properties of cylinders and beamlets, whereas servo testing equipment is used to evaluate strength, energy absorption, and toughness index.

3.5.1 Testing for Mechanical Properties

The STM C143/C143M-15a standard is used to determine the viability of PC and HFRC. The ASTM standard C642-13 is used to evaluate the dry densities of PC and HFRC, respectively. The same standard that is utilized to examine HFRC density and slump is also used to measure PC. The cause is the lack of a specific standard for the determination of slump and density for HFRC. The mechanical characteristics of PC and HFRC are assessed using a servo-hydraulic testing apparatus. Evaluating the mechanical characteristics is done in accordance with ASTM standard C39/C39M-17. Before testing, a cylinder has to be smooth-capped, which is made attainable with plaster of Paris. Capping of specimens is essential for mechanical testing. Compressive, split-tensile, and water absorption tests are used to evaluate mechanical characteristics, whereas dynamic testing involves calculating the specimens resonant frequencies, dynamic modulus, and damping ratios in conformance with standards. Flexural strength of PC and HFRC is calculated in accordance with ASTM standard C293/C293M-16, 3.4.2.For this, a servo hydraulic testing apparatus is used. Energy absorbed by the samples in different test is observed as the area under the curve. Eα is the energy absorbed by the sample till maximum loading and Eβ is the energy absorbed by the sample after maximum loading till breakage of the sample. Calculations are carried out for maximum strength, deflection, total energy absorbed, and flexural toughness index.

3.5.2 Testing for Dynamic Properties

Resonant frequency characterizes system oscillation that occurs in the absence of any outside influence. When a system transmits or reserve energy kinetic energy as well as potential energy during various storage modes, the system oscillates.

Resonance frequency apparatus is a used to determine the resonance frequency of concrete. These resonant frequencies are used to evaluate the damping ratio, dynamic modulus of elasticity, dynamic modulus of rigidity, and poisons ratio. Pascal is the unit of measurement for dynamic elasticity modulus. The following equation, [ASTM C215-14] can be used to compute the dynamic modulus of elasticity when the transverse frequency, cylinder mass, and beam-lets are available.

$$E_{dyn} = CMn^2$$

Where M is the mass of the cylinder or beam-let in kilograms (kg), n= is the fundamental transverse frequency in hertz (Hz), and C is either 1.6067 (L^3 T/d^4) for cylinders or 0.9464 (L^3 T/bt^3) for beam-lets. The torsional frequency is used to determine the dynamic modulus of rigidity (G) [ASTM C215-14]. Pascal is the unit for the dynamic rigidity modulus, and method for determining G is

$$DynamicG = BM(n^{"})$$

Here n"= Fundamental torsional frequency in Hz, M= Mass of beam-let or cylinder in kg, B= (4LR/A), ml, 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.

Concrete's dynamic poison ratio, which ranges in value from 0.20-0.25, is based on dynamic loading. Its value varies for various varieties of concrete. Its value is 0.1 for high-strength concrete and 0.2 for weak strength concrete. Numerous researchers use 0.2 as dynamic Poisson ratio value. The Poisson ratio, which is typically described as the ratio of a material's change in width per unit width to its change in length per unit length subjected to strain, this ratio is very crucial in the construction of concrete structures. The ASTM C215-14 is used to compute the dynamic poisons ratio. In comparison to rigid materials, flexible materials have a higher poison ratio. The formula for determining the dynamic poison ratio is:

$$Dynamicpoisonratio = (E_{dyn} = 2G)1$$

Where E_{dyn} is dynamic modulus of elasticity and G is dynamic modulus of rigidity, respectively. The material property includes damping ratio which is expressed by the symbol ζ (zeta), when the value of ζ (zeta) equals 0, the system is considered to be un-damped. The system is under-damped if its value is less than 1, and it is over-damped if its value exceeds 1. The motion of the vibratory system is minimized, decreased, or even stopped when damping is enforced. Peak ground acceleration and damping ratio have a relationship according to three main properties of concrete which should be considered 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 [45]. 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 friction in automated structures, resistance in electrical oscillators, intensity, and a hint of daintiness in visual oscillators. Damping is crucial for concrete buildings and also having a significant influence on research in the biological sciences and normal daily life schooling. The computed dynamic properties for rubberized concrete were correlate to that of ordinary concrete. The elastic wave technique and beam element were both utilized to calculate the concrete's dynamic properties. During the comparison with plain concrete, the rubberized solid that had been crushed exhibited improved damping properties. Concrete reinforced with coconut fibres, mechanical and dynamic properties was examined. Concrete dynamic modulus of elasticity and damping ratio both were enhanced by the inclusion of coconut fibre. The damping ratio has no dimension, specified the systems response to an external force influence and ceases its motion. The damping ratio is typically determined using common logarithmic decrement tests.

3.5.3 Testing for Water Absorption Properties

It can be specify to determine a specimen's ability to absorb water using ASTM standard C642-13 [56]. Cylinders are rigid and they don't show any surface cracks, water absorption tests are exclusively conducted on them. Just one cylinder is selected form each combination, and its dry weight is calculated and that cylinder whose dry weight is calculated and being weighted. These cylinders are removed from the water after a day, and their weight is measured, similarly its weight is raised to meet the concrete's water absorption capacity. The fiber-containing mixtures all absorbed more amount of water.

3.6 Summary

The PC and HFRC specimens are mixed with cement, sand, coarse aggregates, and water in proportions of 1, 2, 3, and 0.6, and 1:2:3:0.75 in the case of HFRC (cement, sand, crush, and water). The combination of banana and glass fiber of 2.5 cm, 5 cm, and 7.5 cm long with 5% cement mass content are utilized and the replacement of 8% GGBS with cement in mixes of PG, PG11, PG12, PG13, PG21, and PG31. Determination for PC and HFRC include its mechanical characteristics, resonance frequencies, damping ratios, dynamic modulus of elasticity, dynamic modulus of rigidity, and poisons ratio. All testing is carried out in accordance with ASTM standards. The testing results are summarized and explained in the next chapter.

Chapter 4

Results and Analysis

4.1 Background

All mechanical and dynamic testing are carried out in accordance with ASTM standards, and the characteristics of HFRC and PC are examined. This chapter includes an experimental studies of the mechanical, dynamic, and water absorption characteristics of PC and HFRC.

4.2 Mechanical Properties of PC and HFRC

4.2.1 Properties under Compressive Loading

In Figure 4.1, the stress-strain curves for the P, PG, PG11, PG12, PG13, PG21 and PG31 mixes are provided. The figure illustrates in 4.1: first crack, crack at maximum load and crack at ultimate load. While the cracks for HFRC are expanded to maximum values in the scenario of final loading (refer to bottom respective photos in Figure 4.1. Due to the addition of fibers that absorb stress and rather minimize cracking patterns, Those of HFRC remains intact with compressive loading and exhibit tough and ductile behavior. The specimens of P and PG split into two equal pieces at the point of maximum stress however the specimens of HFRC remain constant. Due to the fibers bridging action, concrete that contains fibers is more resistant to cracking. Natural fiber has a greater ability than artificial to resist cracking.

(a) Keeping BF length constant and GF length varying:

It can be seen that for a constant length of BF and varying length of GF in PG11, PG12 and PG13 there is a decrease in compressive strength of concrete with respect to PC. The compressive strengths are 5.51MPa, 9.74MPa and 11.76MPa for PG11, PG12 and PG13, respectively. Due to the low density and significant amount of fibers present in concrete, this may be a factor contributing to the drop in strength seen in the case of HFRC.

The compressive pre-crack absorbed energy (CEα) is calculated from the area under the load-deflection curve from the maximum load. The compressive cracked absorbs energy (CEβ) in the area under the load deflection curve from the maximum load to failure load. The total split tensile energy absorbed by cylinders is equal to the combination of these two energies (CE). The split tensile toughness index (CTI), which is calculated by dividing total energy by initial energy (i.e. CE/CEα) is the result. P and PG mix split entirely into two equal parts at final strength. In addition, a lot of de-bonding appears in glass fiber but in case of HFRC no fiber is broken. Due to the higher tensile strength and lower compressive strength of fibers, little fracture and more bonding are seen in banana fiber whereas more de-bonding and less fracture are shown in glass fiber. The compressive strength of the cylinder is equal to the highest load divided by the area of the cylinder. While a strain (σ) is an elongation beyond the initial length. Compressive pre-crack absorbed energy (CEα) is present in the region between the beginning and the maximum load along the stress-strain curve. Total compressive energy (CE) absorbed by cylinders is calculated as the pre-cracked energy plus the post-cracked energy (CEβ). Compressive toughness index (CTI) is determined by dividing total energy over initial energy (i.e. ET/Eα). Table 4.1 shows the values of $P_(max)$, σ, δ, CEα, CEβ, CE, and CTI respectively. P and PG specimens split into two equal portions at the ultimate load.

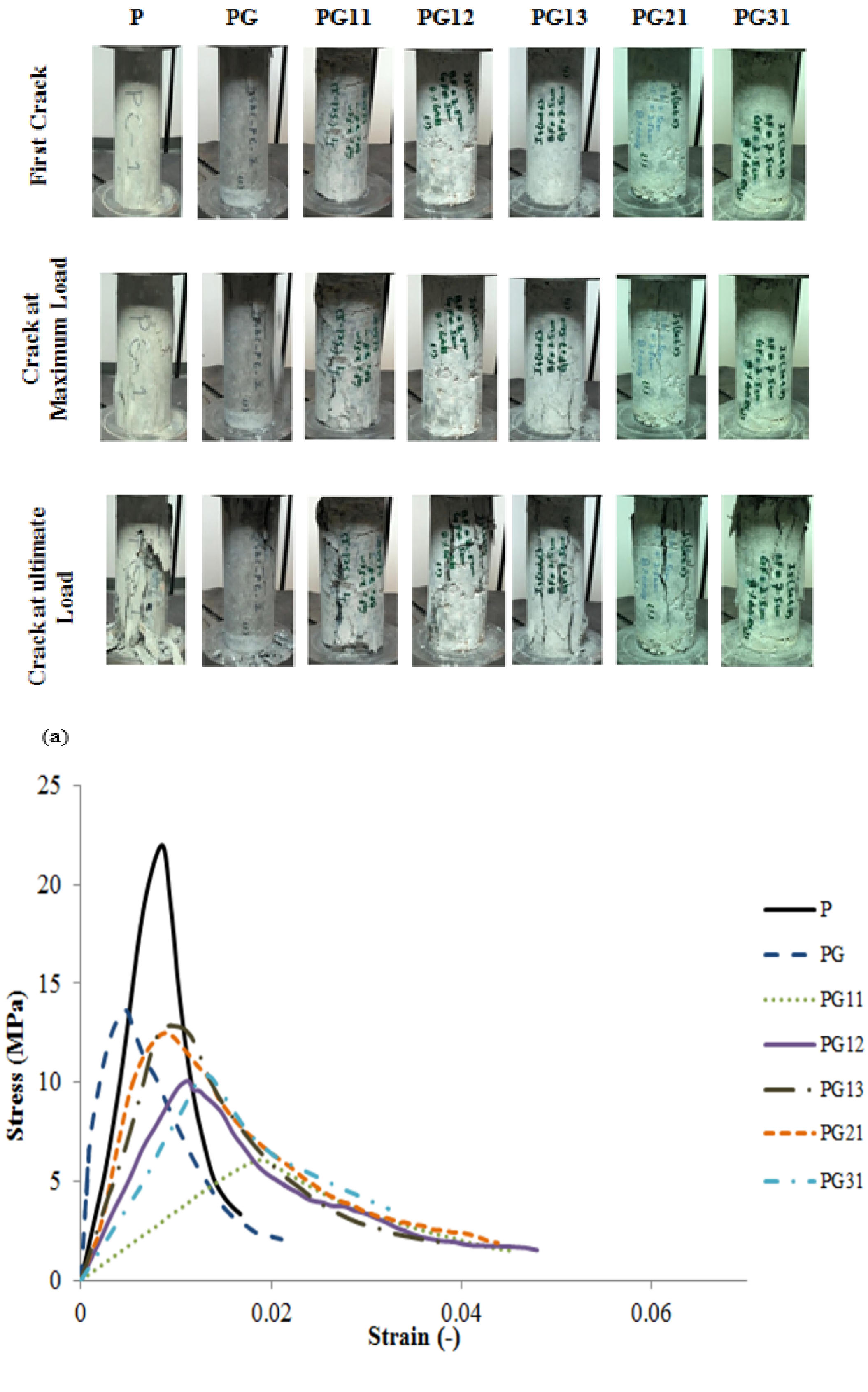


FIGURE 4.1: Mechanical Properties under Compressive Loading (a) Tested Specimens (b) Stress Strain Curve

The maximum loads for the P, PG, PG11, PG12 and PG13 mixtures are respectively 105.49 kN, 75.57 kN, 43.28 kN, 76.53 kN and 92.33 kN. Due to the presence of GGBS and hybrid fibers the load-carrying capacity of cylinders has reduced. GGBS exhibits weaker strength characteristics compared to cement. Additionally, the compressive strength of the concrete is reduced by the insertion of less dense fibers. The values of strain ($\epsilon\circ$) are 0.017 mm, 0.015 mm, 0.082 mm, 0.048 mm and 0.040 mm for P, PG, PG11, PG12 and PG13 respectively. As the fibers hold concrete components when cracks expand, HFRC shows more deformation than PC.

The strain at maximum load changes substantially for all combinations, indicating that tough behavior is dependent on the relative proportions of BF and GF. The fibers are less dense and light as they have lower strengths than PC. Fibers added to concrete make it more durable because of the incorporation of two fibers having different properties which helps to make it durable. This is further confirmed by the toughness index obtained and presented in table 4.1. The compressive pre-cracked energy (CEα) is 0.105 MJ/m^3, 0.033 MJ/m^3, 0.065 MJ/m^3, 0.083 MJ/m^3, 0.069 MJ/m^3, 0.065 and MJ/m^3 for P, PG, PG11, PG12 and PG13 respectively. For P, PG, PG11, PG12 and PG13 the corresponding compressive cracked absorbed energy (CEβ) values are 0.009 MJ/m^3, 0.028 MJ/m^3, 0.132 MJ/m^3, 0.092 MJ/m^3 and 0.146 MJ/m^3 respectively. P, PG, PG11, PG12 and PG13 have absorbed respectively 0.113 MJ/m^3, 0.061 MJ/m^3, 0.197 MJ/m^3, 0.174 MJ/m^3 and 0.211 MJ/m^3 of total compressive energy (CE). Total compressive energy of PG, PG11, PG12, PG21 and PG13 is revealed to enhance by 0.028 MJ/m^3, 0.132 MJ/m^3, 0.091 MJ/m^3, 0.137 MJ/m^3, 0.146 MJ/m^3 and 0.072 MJ/m^3 compared to that of PC.

The combinations of P, PG, PG11, PG12 and PG13 having toughness index (CTI) values of 1.08, 1.78, 2.97, 2.23 and 3.27, respectively. The combination of PG13 have toughness index (CTI) that are better compared to PC. Due to GGBS enhanced energy absorption characteristics, cement is substituted with 8% by mass of GGBS, resulting in mix PG toughness index substantially higher than PC. Additionally, mixes with hybrid fibers have higher toughness index whereas mix with PG13 have higher toughness indicates because of same combination of 2.5cm length of BF and 7.5cm length of GF fiber. When cracks spread resistance to internal pressures is provided by the presence of both fibers at various concentrations. Concrete capacity for absorbing energy enhances along with the toughness index due to the addition of fibers. Compared to single fiber reinforced concrete the needed characteristics of concrete are enhanced more when two types of fibers having varying length are used. The characteristics of concrete are increased and then decrease due the different properties of BF and GF having different lengths.

(b) Keeping BF length varying and GF length constant:

Furthermore, keeping the constant length of GFs and varying length of BFs in PG11, PG21, PG31, there is a decrease in compressive strength of concrete with respect to PC. The compressive strengths are 5.51MPa, 11.43MPa and 10.36MPa for PG11, PG21 and PG31, respectively.

The maximum loads for the P, PG, PG11, PG21 and PG31 mixtures are respectively 105.49 kN, 75.57 kN, 43.28 kN, 89.71 kN and 81.371 kN. Additionally, the compressive strength of the concrete is reduced by the insertion of less dense fibers. The strain values for P, PG, PG11, PG21 and PG31 are respectively 0.017, 0.015, 0.082, 0.051 and 0.035. The strain at maximum load changes substantially for all combinations, indicating that tough behavior is dependent on the relative proportions of hybrid fibers. Hybrid fibers added to concrete make it more durable because of the incorporation of two fibers having different properties which helps to make it durable. This is further confirmed by the compressive toughness index (CTI) obtained and presented in table 4.1. The compressive pre-cracked energy (CEα) is 0.105 MJ/m^3, 0.033 MJ/m^3, 0.065 MJ/m^3, 0.069 MJ/m^3 and 0.066 MJ/m^3 for P, PG, PG11, PG21 and PG31, respectively. For P, PG, PG11, PG21 and PG31 the corresponding compressive cracked absorbed energy (CEβ) values are 0.009 MJ/m^3, 0.028 MJ/m^3, 0.132 MJ/m^3, 0.137 MJ/m^3 and 0.072 MJ/m^3 respectively. P, PG, PG11, PG21, and PG31 have absorbed energy respectively 0.113 MJ/m^3, 0.061 MJ/m^3, 0.197 MJ/m^3, 0.206 MJ/m^3 and 0.138 MJ/m^3 of total compressive energy (ET).

The combinations of P, PG, PG11, PG21 and PG31 having toughness index (CTI) values of 1.08, 1.78, 2.97, 3.02 and 2.10, respectively. The combination of PG13

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

Property	**Index**	**P_{max} (kN)**	**σ (MPa)**	**ϵo**	**CEα (MJ/m^3)**	**CEβ (MJ/m^3)**	**CE (MJ/m^3)**	**CTI (-)**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Compression	P	105.49±38.67	18.49±3.49	0.017±0	0.105±0.009	0.009±0.004	0.113±0.012	1.08±0.030
	PG	75.57±31.59	9.77±4.02	0.015±0.006	0.033±0.014	0.028±0.015	0.061±0.029	1.78±0.147
	PG11	43.28±4.41	5.51±0.56	0.082±0.037	0.065±0.003	0.132±0.078	0.197±0.081	2.97±1.09
	PG12	76.53±2.55	9.74±0.32	0.048±0	0.083±0.021	0.092±0.018	0.174±0.002	2.23±0.523
	PG13	92.33±8.65	11.76±1.11	0.040±0.002	0.065±0.003	0.146±0.026	0.211±0.024	3.27±0.491
	PG21	89.71±8.33	11.43±1.06	0.051±0.007	0.069±0.004	0.137±0.010	0.206±0.006	3.02±0.274
	PG31	81.371±0.16	10.36±0.03	0.035±0.003	0.066±0.004	0.072±0.014	0.138±0.010	2.10±0.274

have toughness index (CTI) that are better compared to PC. Additionally, mixes with hybrid fibers have higher toughness index whereas mix with PG13 have higher toughness indicates because of combination of 2.5cm BF and 7.5cm of GF fibers concentration. When cracks spread resistance to internal pressures is provided by the presence of both fibers at various concentrations compared to single fiber reinforced concrete the needed characteristics of concrete are enhanced more when two types of fibers having varying length are used. The characteristics of concrete are increased due the different properties of BF and GF having different lengths.

PG13 has high compressive strength due to relatively high strength of GF. Other possible reason could be the optimized combination of fibers in PG13. Similarly, PG21 has high compressive strength. The possible reason could be the optimized combination of fibers in PG21. In addition, the further increase in BF content, compressive strength reduced may be due to less compressive strength of BF compared to GF.

4.2.2 Properties under Splitting Tensile Loading

In figure 4.2, the load-deformation curve under splitting tensile loading for the P, PG, PG11, PG12, PG13, PG21 and PG31 mixes are provided. The figure illustrates in 4.3: first crack, crack at maximum load and crack at ultimate load. While the cracks for HFRC are expanded to maximum values in the scenario of final loading (refer to bottom respective photos in Figure 4.2). Concrete cracking is less apparent when fibers are present. The specimens of P and PG split into two equal pieces at the point of maximum stress however the specimens of HFRC remain constant. Due to the fibers bridging action, concrete that contains fibers is more resistant to cracking. Natural fiber has a greater ability than artificial to resist cracking.

(a) Keeping BF length constant and GF length varying:

It can be seen that for a constant length of BF and varying length of GF in PG11, PG12 and PG13. There is an increase in split tensile strength of concrete with respect to PC till GF is 5cm but when the length of GF is 7.5cm i.e. PG13. When compare to PC a decrease of 0.52 MPa, 0.32 MPa, and 0.18 MPa in split tensile

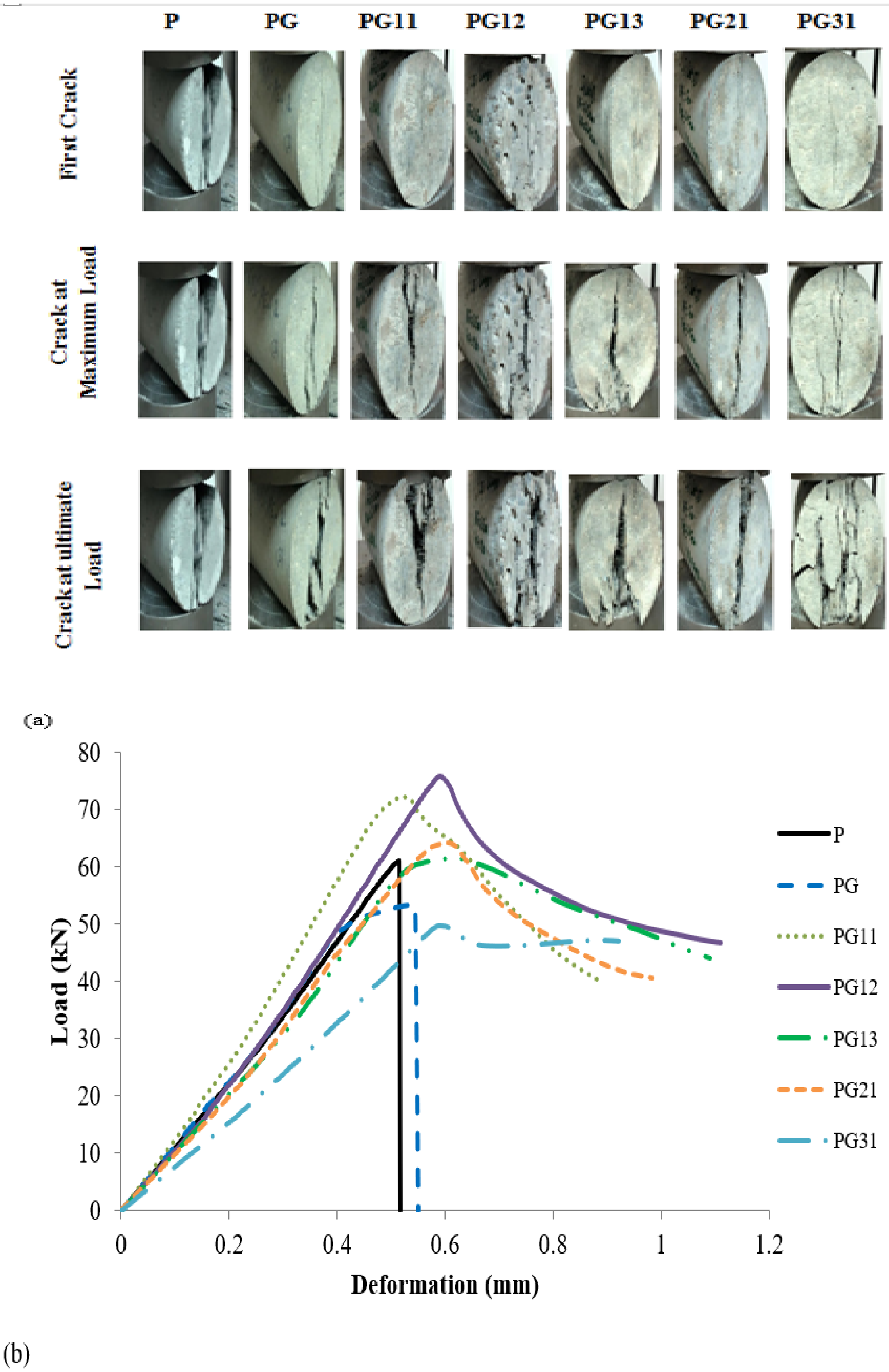


Figure 4.2: Mechanical Properties under Split Tensile Loading (a) Tested Specimens (b) Load Deformation Curve

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

Property	**Index**	**P$_{max}$** (kN)	**STS** (MPa)	δ mm	**SEα** (MJ/m^3)	**SEβ** (MJ/m^3)	**SE** (MJ/m^3)	**STI** (-)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Split Tensile	P	57.23±3.88	1.82±0.12	0.68±0.167	17.03±1.64	0	17.03±1.64	1±0
	PG	66.50±13.15	2.11±4.01	0.52±0.025	17.28±0.38	0	17.28±0.38	1±0
	PG11	73.60±1.356	2.34±0.04	1.02±0.140	19.62±0.59	1.62±0.46	21.23±0.13	1.08±0.03
	PG12	67.41±8.34	2.14±0.27	1.0±0.11	18.25±2.98	9.10±6.32	27.35±3.34	1.57±0.44
	PG13	51.38±10.2	1.64±0.32	1.02±0.07	17.70±3.05	15.65±8.99	33.35±12.02	1.82±0.37
	PG21	65.78±1.52	2.16±0.05	1.1±0.08	19.87±0.02	15.05±3.56	34.92±3.58	1.76±0.18
	PG31	47.38±2.24	1.51±0.07	1.41±0.22	22.59±8.32	8.16±7.34	30.74±0.98	1.56±0.53

strength is observed.The split tensile strengths are 2.34MPa, 2.14MPa and 1.64MPa for PG11, PG12 and PG13, respectively. Due to the low density and significant amount of fibers present in concrete, this may be a factor contributing to the drop in strength seen in the case of HFRC. For P, PG, PG11, PG12 and PG13 the values of deformation (δ) are 0.68 mm, 0.52 mm, 1.02 mm, 1.0 mm and 1.02 mm respectively.

As the fibers hold concrete components when cracks expand, HFRC shows more deformation than PC. The split tensile pre-crack absorbed energy (SEα) is calculated from the area under the load-deflection curve from the maximum load. Split tensile cracked absorbs energy (SEβ) in the area under the load deflection curve from the maximum load to failure load. The total split tensile energy absorbed by cylinders is equal to the combination of these two energies (SE). The split tensile toughness index (STI), which is calculated by dividing total energy by initial energy (i.e. SE/SEα) is the result.

The values of Pmax, STS, δ, SEα, SEβ, SE, and STI are shown in table 4.2 accordingly. The condition in which specimens of the P and PG mixes break into two equal portions when the maximum load is applied to it, the split tensile cracked absorbed energy of these combinations is zero. Maximum load values are 57.23 kN, 66.50 kN, 73.60 kN, 67.41 kN and 51.38 kN for P, PG, PG11, PG12, PG13. In the case of HFRC, the PG11 and PG12 mix is under the most loads. The load in the case of HFRC increased as compared to PC when there is lower length of glass fibers because it is brittle and has significant tensile strength. The banana and glass fiber hybridization at a ratio of 5% having different lengths of both banana and glass fiber i.e. 2.5cm, 5cm and 7.5cm absorbed the maximum load and different varying lengths in the case of HFRC. This is because banana fiber has good bonding characteristics because of its rough surface. Due to the weak bonding characteristics of glass fibers, load-carrying ability of the specimens reduces when glass fiber concentration is further enhanced. PG11 mix absorbed the high amount of load due to the equal percentage and smaller varying length of banana fiber and glass fiber in this mix. The splitting tensile pre-cracked absorbed energy (SEα) values are 17.03 MJ/m^3, 17.28 MJ/m^3, 19.62 MJ/m^3, 18.25 MJ/m^3 and 17.70 MJ/m^3 for the P, PG, PG11, PG12, PG13 mixes respectively. Splitting tensile pre-cracked energy absorption for PC and PG is almost same to same because the chemical characteristics of GGBS are comparable to those of cement, metakaolin, and fly ash. When compare to PC, there is an increase in pre-cracked energy absorption for PG and PG11 of 17.28 MJ/m^3 and 21.23 MJ/m^3 but energy absorption for other combinations is also increasing while pre-cracked. P and PG specimens are split into two equal portions, leading in negligible energy absorption for both components. For PG11, PG12 and PG13 the cracked energy absorption (SEβ) is respectively 1.62 MJ/m^3, 9.10 MJ/m^3 and 15.65 MJ/m^3. The cracked energy absorption for PG13 is more mixed because glass fiber has a higher tensile strength than banana fiber. Total energy absorption (SE) is 17.03 MJ/m^3, 17.28 MJ/m^3, 21.23 MJ/m^3, 27.35 MJ/m^3 and 33.35 MJ/m^3 for P, PG, PG11, PG12 and PG13, respectively. In comparison to PC, HFRC specimens absorbed higher total splitting tensile energy. The equivalent splitting tensile toughness index (STI) are 1, 1, 1.08, 1.57 and 1.82 for P, PG, PG11, PG12, PG21, PG13 and PG31. In the case of HFRC combinations an enhancement in toughness index is shown when the length of GF is maximum i.e. 7.5cm. Because there are more glass fibers in PG13 mix, it has a higher toughness index. When cracks develop, resistance to internal stresses is produced by the existence of both fibers at different concentration. In general, the addition of fibers to concrete enhances its capacity for absorbing energy while also improving its toughness index. The mixes containing 2.5% glass fiber by mass of cement have a higher toughness index because glass fiber may absorbs more energy under split loading and has a strong tensile strength.

(b) Keeping BF length varying and GF length constant:

Furthermore, keeping the constant length of GF and varying length of BF in PG11, PG21 and PG31. There is an increase in split tensile strength of concrete with respect to PC till BF is 5cm but when the length of BF is 7.5cm i.e. PG31 then a decrease of 0.52 MPa, 0.34 MPa, and 0.31 MPa in split tensile strength is observed. The split tensile strengths are 2.34MPa, 2.16MPa and 1.51MPa for PG11, PG12 and PG13, respectively. Due to the low density and significant amount of fibers present in concrete, this may be a factor contributing to the drop in strength seen in the case of HFRC. For P, PG, PG11, PG21 and PG31 the values of deformation (δ) are 0.68 mm, 0.52 mm, 1.02 mm, 1.1 mm and 1.41 mm respectively. As the fibers hold concrete components when cracks expand, HFRC shows more deformation than PC.

The values of Pmax, STS, δ, SEα, SEβ, SE, and STI are shown in table 4.2 accordingly. The condition in which specimens of the P and PG mixes break into two equal portions when the maximum load is applied to it, the split tensile cracked absorbed energy of these combinations is zero. Maximum load values are 57.23 kN, 66.50 kN, 73.60 kN, 65.78 kN and 47.38 kN for P, PG, PG11, PG21, PG31. In the case of HFRC, the PG11 mix is under the most loads. The highest containing length of banana fiber mixes have a higher value of deformation because banana fiber has a rough surface and maintains the elements of concrete even after the application of the maximum load. Due to the weaker bonding characteristics of glass fibers with concrete, deformation value is lower for mixes with a significant concentration of glass fiber. The splitting tensile pre-cracked absorbed energy (SEα) values are 17.03 MJ/m^3, 17.28 MJ/m^3, 19.62 MJ/m^3, 19.87 MJ/m^3 and 22.59 MJ/m^3 for the P, PG, PG11, PG21, PG31 mixes, respectively. Splitting tensile pre-cracked energy absorption for PC and PG is almost same to same because the chemical characteristics of GGBS are comparable to those of cement and fly ash. The cracked energy absorption (SEβ) is respectively 1.62 MJ/m^3, 15.05 MJ/m^3 and 8.16 MJ/m^3 for PG11, PG21 and PG31. The cracked energy absorption for PG21 is more mixed because glass fiber has a higher tensile strength than banana fiber. Total energy absorption (SE) is 17.03 MJ/m^3, 17.28 MJ/m^3, 21.23 MJ/m^3, 34.92 MJ/m^3 and 30.74 MJ/m^3 for P, PG, PG11, PG21 and PG31, respectively.

When compare to PC there is an increase in pre-cracked energy absorption for PG and PG11 of 17.28 MJ/m^3 and 19.62 MJ/m^3 but energy absorption for other combinations is also increasing while pre-cracked. P and PG specimens are split into two equal portions, leading in negligible energy absorption for both components. For PG11, PG21 and PG31 the cracked energy absorption is respectively 1.62 MJ/m^3, 9.10 MJ/m^3 and 15.65 MJ/m^3. The cracked energy absorption for PG11 and PG21 is more mixed because glass fiber has a higher tensile strength than banana fiber. Total energy absorption is 17.03 MJ/m^3, 17.28 MJ/m^3, 21.23

MJ/m^3, 34.92 MJ/m^3 and 30.74 MJ/m^3 for P, PG, PG11, PG21 and PG31, respectively. In comparison to PC, HFRC specimens absorbed higher total splitting tensile energy. For P, PG, PG11, PG21 and PG31 the equivalent splitting tensile toughness index are 1, 1, 1.08, 1.76 and 1.56. In the case of HFRC combinations an enhancement in toughness index is shown. PG11 has high split tensile strength with the increase in BF or GF, the strength reduced. The possible reason could be the relatively less tensile strength of fibers which result a decrease in strength when increase in fibers content.

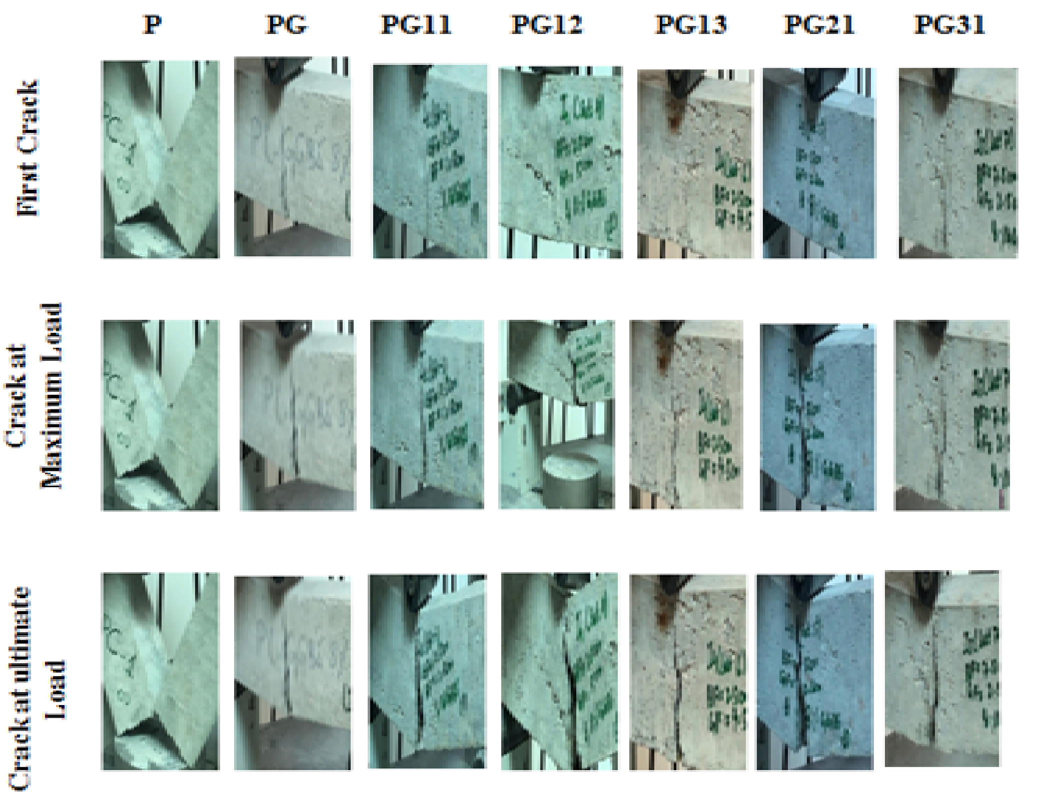
4.2.3 Properties under Flexural Loading

In figure 4.3, the load-deflection curve under flexural loading for the P, PG, PG11, PG12, PG13, PG21 and PG31 mixes are provided. The following characteristics are available in figure 4.3: first crack, crack at maximum load and crack at ultimate load. While the cracks for HFRC are expanded to maximum values in the scenario of final loading (refer to bottom respective photos in Figure 4.3). While the specimens of P and PG crack into two equal portions at the maximum stress, those of HFRC remain constant and respond highly durable and ductile during flexural loading.

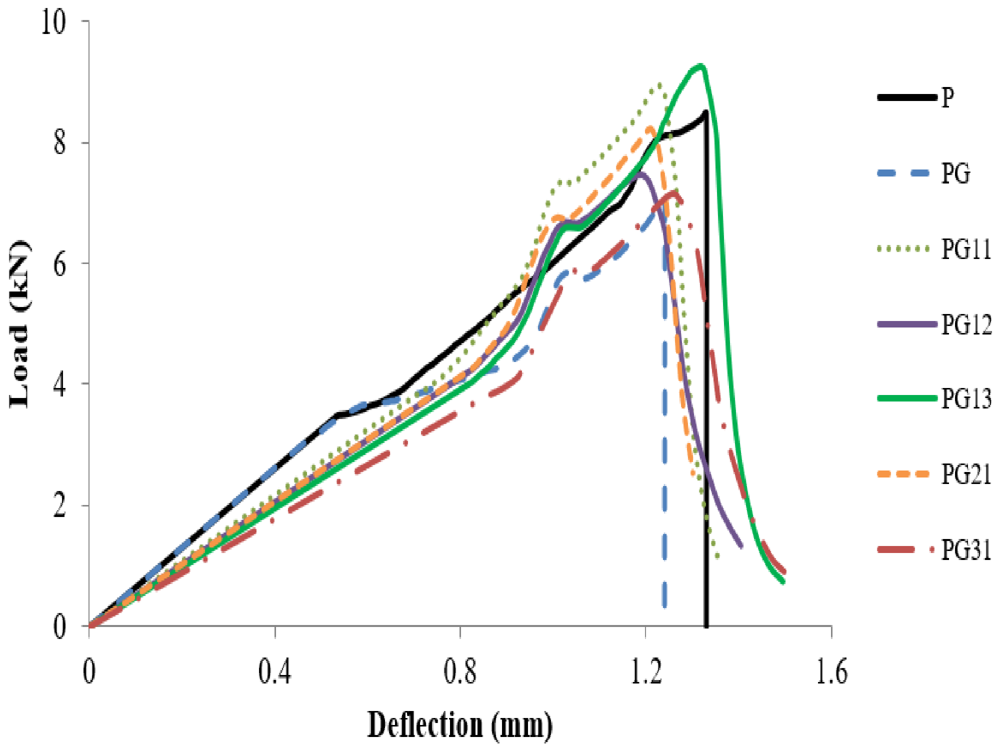
(a) Keeping BF length constant and GF length varying:

It can be seen that for a constant length of BF and varying length of GF in PG11, PG12, PG13, there is an increase in flexural strength of concrete with respect to PC. The flexural strengths are 3.89MPa, 3.37MPa and 3.44MPa for PG11, PG12 and PG13, respectively. The flexural pre-crack absorbed energy (FEα) is calculated from the area under the load-deflection curve from the starting of the maximum load. Flexural cracked absorbs energy (FEβ) in the area under the load deflection curve from the maximum load to failure load. The total flexural energy absorbed by cylinders is equal to the combination of these two energies (FE). The flexural toughness index (FTI), which is calculated by dividing total energy by initial energy (i.e. FE/FEα), is the result.

The values of P$_{max}$, MOR, $\triangle$, FEα, FEβ, FE, and FTI are shown in table accordingly. Maximum load values are 7.51 kN, 6.39 kN, 8.65 kN, 7.50 kN and 7.66 kN for



(a)



(b)

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

P, PG, PG11, PG12, PG13. The PG11 mix has now a load-bearing capability of 1.14kN than the PC. PG11 load-bearing capability has increased GGBS because of the remarkable flexural behavior of ground granulated blast furnace slag (GGBS). More SiO_{max} and CaO in GGBS increase PG flexural characteristics. Combinations containing hybrid fibers have a reduced load-bearing capability than PC. The Pmax of the PG11, PG12 and PG13 mixes reduced by 1.14 kN, 2.26 kN and 1.27 kN as compared to PC. The concrete flexural strength is decreased as a result of the fibers lower strength and less dense composition. Glass and banana fibers are combined in an optimal range to get the best possible outcome. The P, PG, PG11, PG12 and PG13 possess flexural strength values of 3.38 MPa, 2.87 MPa, 3.89 MPa, 3.37 MPa and 3.44 MPa, respectively. Flexural pre-crack absorbed energy (FEα) of P, PG, PG11, PG12 and PG13 mixes are respectively 4.66 MJ/m^3, 3.89 MJ/m^3, 4.83 MJ/m^3, 4.07 MJ/m^3 and 4.09 MJ/m^3. The flexural post-crack absorbed energy (FEβ) is zero for P and PG because the beam-lets are split into two equal segments upon the transmission of a maximum stress. PG11, PG12 and PG13 mixes, respectively have flexural post-crack absorbed energies (FEβ) of 0.73 MJ/m^3, 0.79 MJ/m^3 and 0.91 MJ/m^3. The value of flexural post-crack absorbed energy (FEβ) is decreased as a result of the fibers lower strength and less dense composition from PG11 to PG31 mix. The total flexural energy (FE) absorbed by the beamlets of the openings P, PG, PG11, PG12 and PG13 is 4.66 MJ/m^3, 3.89 MJ/m^3, 5.57 MJ/m^3, 4.87 MJ/m^3 and 5.01 MJ/m^3, respectively. Due to the presence of energy-absorbing fibers in concrete HFRC has a better maximum energy absorption capacity than PC. Fibers make concrete fix cracks and improve its ability to support loads. Mixes with higher glass fiber contents absorb more total energy because glass fiber has a higher bridging effect than banana fibers during flexural stress. The HFRC overall energy absorption performance decreases and then increases with the increase in glass fiber content in concrete. The flexural toughness index (FTI) is 1, 1, 1.15, 1.19, and 1.24 for P, PG, PG11, PG12 and PG13 mixes respectively. The flexural toughness index (FTI) is higher for PG13 and is lower from PG to PG12 because the concentration of banana fiber is increased in PG13. The value of total energy absorption and the toughness index of concrete in the case of flexural loading decreases and then increases as the concentration of banana fibers in concrete increased in PG13.

The P, PG, PG11, PG12 and PG13 have corresponding compressive toughness index (CTI) of 1.08, 1.78, 2.97, 2.23 and 3.27. CTI for PG is 0.7% lower than that of PC. However it is 76%, 17% and 16% higher for PG11, PG12 and PG13 mixes respectively. The P, PG, PG11, PG12 and PG13, respectively the splitting tensile toughness index (STI) is 1, 1, 1.08, 1.57and 1.82. In the case of HFRC mixes an enhancement in splitting toughness index is shown. Mixes P, PG, PG11, PG12 and PG13 having flexural toughness index (FTI) of 1, 1, 1.15, 1.19 and 1.24, respectively.

(b) Keeping BF length varying and GF length constant:

Furthermore, keeping the constant length of GF and varying length of BF in PG11, PG21, PG31, there is an increase in flexural strength of concrete with respect to PC. The flexural strengths are 3.89MPa, 3.40MPa and 3.55MPa for PG11, PG12 and PG13, respectively.

The values of P_{max}, σ, $\triangle$, FEα, FEβ, FE, and FTI are shown in table accordingly. Maximum load values are 7.51 kN, 6.39 kN, 8.65 kN, 7.56 kN and 7.45 kN for P, PG, PG11, PG21 and PG31, respectively. The PG11 mix has now a load-bearing capability of 1.14kN than the PC. PG11 load-bearing capability has increased GGBS because of the remarkable flexural behavior of ground granulated blast furnace slag (GGBS). More GGBS increase PG flexural characteristics. Combinations containing hybrid fibers have a reduced load-bearing capability than PC. The Pmax of the PG11, PG21 and PG31 mixes reduced by 1.14 kN, 1.1 kN and 1.06 kN as compared to PC. Similarly, the P, PG, PG11, PG21 and PG31 possess flexural strength values of 3.38 MPa, 2.87 MPa, 3.89 MPa, 3.40 MPa and 3.35 MPa. The PG11 and PG13 mix does have a 1.03 MPa, 0.58 MPa greater flexural strengths than PC. Flexural pre-crack absorbed energy (FEα) of P, PG, PG11, PG21 and PG31 mixes are respectively 4.66 MJ/m^3, 3.89 MJ/m^3, 4.83 MJ/m^3, 4.29 MJ/m^3 and 4.43 MJ/m^3. The flexural post-crack absorbed energy (FEβ) is zero for P and PG because the beam-lets are split into two equal segments upon the transmission of a maximum stress. PG11, PG21 and PG31 mixes respectively have flexural post-crack absorbed energies (FEβ) of 0.73 MJ/m^3, 0.54 MJ/m^3 and

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

Property	**Index**	**P_{max}**	**MOR**	**△**	**FEα**	**FEβ**	**FE**	**FTI**
		(kN)	**(MPa)**	**mm**	**(MJ/m^3)**	**(MJ/m^3)**	**(MJ/m^3)**	**(-)**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Flexural	P	7.51±1.28	3.38±0.57	1.30±0.18	4.66±1.31	0	4.66±1.31	1±0
	PG	6.39±0.92	2.87±0.41	1.22±0.21	3.89±0.67	0	3.89±0.67	1±0
	PG11	8.65±0.28	3.89±0.12	1.51±0.15	4.83±0.14	0.73±0.16	5.57±0.30	1.15±0.03
	PG12	7.50±0.04	3.37±0.02	1.41±0.01	4.07±0.05	0.79±0.04	4.87±0.01	1.19±0.01
	PG13	7.66±1.57	3.44±0.70	1.41±0.07	4.09±0.83	0.91±0.23	5.01±0.60	1.24±0.11
	PG21	7.56±0.07	3.40±0.30	1.37±0.06	4.29±0.01	0.54 ±0.07	4.83±0.07	1.12±0.02
	PG31	7.45±1.02	3.35±0.20	1.20±0.29	4.43±0.49	0.75±0.07	5.18±0.43	1.17±0.03

0.75 MJ/m^3. The value of flexural post-crack absorbed energy (FEβ) is decreased as a result of the fibers lower strength and less dense composition from PG11 to PG31 mix. The total flexural energy (FE) absorbed by the beamlets of the openings P, PG, PG11, PG21 and PG31 is 4.66 MJ/m^3, 3.89 MJ/m^3, 5.57 MJ/m^3, 4.83 MJ/m^3 and 5.18 MJ/m^3, respectively. Due to the presence of energy-absorbing, fibers in concrete HFRC has a better maximum energy absorption capacity than PC.

Fibers make concrete fix cracks and improve its ability to support loads. Mixes with higher glass fiber contents absorb more total energy because glass fiber has a higher bridging effect than banana fibers during flexural stress. The HFRC overall energy absorption performance decreases and then increases with the increase in glass fiber content in concrete. The flexural toughness index (FTI) is 1, 1, 1.15, 1.19 and 1.24 for P, PG, PG11, PG21 and PG31 mixes, respectively. The flexural toughness index (FTI) is higher for PG31 and is lower from PG to PG21 because the concentration of banana fiber is increased in PG31. The value of total energy absorption and the toughness index of concrete in the case of flexural loading decreases and then increases as the concentration of banana fibers in concrete increased in PG31. The P, PG, PG11, PG21 and PG31 have corresponding compressive toughness index (CTI) of 1.08, 1.78, 2.97, 3.02 and 2.10. CTI for PG is 0.7% lower than that of PC. However it is 76%, 19% and 43% higher for PG11, PG21 and PG31 mixes respectively.

The splitting tensile toughness index is 1, 1, 1.08, 1.76 and 1.56 for the P, PG, PG11, PG21 and PG31 respectively. In the case of HFRC mixes a decrease in splitting toughness index is shown due to lower GF content. Mixes P, PG, PG11, PG21 and PG31 having flexural toughness index (FTI) of 1, 1, 1.15, 1.12 and 1.17, respectively. PG11 has high flexural strength with the increase in BF, the strength reduced. The possible reason could be the relatively less flexural strength of fibers which result a decrease in strength when increase in fibers content. However a little increase was observed in PG13 due to further increase in the content of GF i.e. 7.5cm.

4.3 Dynamic Properties Analysis

Table 4.4 contains the values of the dynamic rigidity, damping ratio, dynamic elastic modulus, and fundamental frequencies for cylinders and beamlets. Concrete cylinders with banana fiber, glass fiber and GGBS are compared to concrete cylinders with PC in terms of their dynamic properties. Concrete with 8% GGBS has a longitudinal frequency that is equivalent to PC value.

The PG13 mix longitudinal frequency is however 3306 Hz, which is greater than PC. The PG21 and PG31 mixes longitudinal frequencies are slightly less than the PC. All mixes with hybrid fibers have higher transverse and rotational frequencies than PC and the behavior is equivalent for beam-let resonant frequencies. a comparative analysis study of the cylinders longitudinal frequencies.

(a) Keeping BF length constant and GF length varying:

An ordinary concrete cylinder has a damping ratio of 2.01. The damping ratios for PG, PG11, PG12 and PG13 mixes are higher than those for PC. The damping ratio for standard concrete beam-lets is 2.7 however some mixes have a damping ratio higher than PC. When evaluating concrete dynamic, a critical characteristic is the dynamic elastic modulus for cylinders. 2.20 GPa is Edyn for PC and 4.90 GPa is Edyn for PG mix. While PC is more expensive than E_{dyn} of PG11, PG12 and PG13 mix. E_{dyn} for PC for ordinary concrete beam-lets is 14.3 GPa. E_{dyn} of PG is 2% greater than PC. While PC has more Edyn than PG12, PG13 respectively by different ratios.

The torsional frequency of concrete is used to evaluate the dynamic modulus of rigidity. G_{dyn} is 2.84 GPa for regular concrete cylinders. G_{dyn} is greater for PG mix than it is for PC. The values of G_{dyn}, however, it is greater than PC for all PG11, PG12 and PG13 mixes, respectively. G_{dyn} of PC for beam-lets is 5.6 GPa. PG, PG11, PG12 and PG13 mixes all have G_{dyn} values that are greater than PC. Table 4.4 illustrates the dynamic poison ratio for cylinders and beamlets.

(b) Keeping BF length varying and GF length constant:

Furthermore, the ordinary concrete cylinder has a damping ratio of 2.01. The damping ratios for PG, PG11, PG21 and PG31 mixes are also higher than those

TABLE 4.4: Dynamic Properties of PC and HFRC

Specimen	**Index**	**RFL**	**RFt**	**RFr**		**E*dyn***	**Gyn**	**Poisons Ratio**
		(Hz)	**(Hz)**	**(Hz)**	**zeta**	**(GPa)**	**(GPa)**	
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Cylinders	P	5615±22	1664.5±66.5	1753±111	2.015±0.2	2.20±1.33	1.22±0.15	0.65±0.01
	PG	2174.5±310	1454±0	1176±421	2.12±0.15	4.90±1.37	0.61±0.39	0.14±0.73
	PG11	1841.5±22.5	1585±25	1787±77	2.3±0.2	3.37±0.08	1.44±0.30	0.64±0.08
	PG12	2307.5±608	1515±35	1712±62	2.3±0.5	6.54±4.2	1.08±0.07	0.59±0.00
	PG13	3306±435	1464±0	1908±482	2.95±0.2	4.82±0.41	6.24±4.08	0.94±0.13
	PG21	1375.5±44.5	1464±0	1863±245	2.26±0.3	1.84±0.11	1.33±0.25	0.68±0.02
	PG31	1575±175	1442±22	1819±133	3.2±1.3	1.38±0.4	0.90±0.12	0.56±0.06
Beam Lets	P	2440±976	1575±66	1509±0	2.81±0.3	14.3±1.9	5.6±1.6	0.88±0.28
	PG	3772±399	1575±111	1442±22	2.7±0.23	31.7±4.45	5.11±0.15	1.94±0.70
	PG11	1242±133	1553±44	1531±22	3.5±1.8	3.47±0.65	5.81±0.16	0.71±0.05
	PG12	2419±910	1486±22.5	1464±0	3.2±0.8	13.3±8.8	5.1±0.4	0.58±0.05
	PG13	1642±89	1642±1000	1509±243	4.5±482	21.38±1.7	5.3±0.7	1.00±0.06
	PG21	1642±133	1642±44	1642±89	3.4±0.2	20.78±1.3	5.4±0.41	0.91±0.02
	PG31	3329±00	1642±133	1642±222	3.7±0.2	21.9±00	5.18±0.46	1.13±0.19

for PC. The damping ratio for standard concrete beam-lets is 2.7 however some mixes have a damping ratio higher than PC. When evaluating concrete dynamic, a critical properties is the dynamic elastic modulus for cylinders. 2.20 GPa is E_{dyn} for PC and 4.90 GPa is E_{dyn} for PG mix. While PC is more expensive than E_{dyn} of PG11, PG12, PG21, PG13, and PG31 mix. E_{dyn} for PC for ordinary concrete beam-lets is 14.3 GPa. E_{dyn} of I is 2% greater than PC. While PC has more E_{dyn} than PG12, PG21, PG13, and PG31 mix respectively by different ratios.

The torsional frequency of concrete is used to evaluate the dynamic modulus of rigidity. G_{dyn} is 2.84 GPa for regular concrete cylinders. G_{dyn} is greater for PG mix than it is for PC. The values of G_{dyn} however, it is greater than PC for all PG11, PG21 and PG31 mixes respectively. G_{dyn} of PC for beam-lets is 5.6 GPa. PG, PG11, PG21 and PG31 mixes all have G_{dyn} values that are greater than PC. Table 4.4 illustrates the dynamic poison ratio for cylinders and beamlets.

4.4 Water Absorption

On cylinders of PC and HFRC, a water absorption test is carried out in the lab. Before immersing, these cylinders are weighted, and then remain immersed for 24 hours. After removing the cylinders from the water, the weight of each cylinder is once more measured, and an increase in weight as a percentage is computed as described in table 4.5. P, PG, PG11, PG12, PG13, PG21 and PG31 cylinder weight increases are 0.77%, 1.28%, 2.77%, 3%, 2.33%, 3.56%, and 3.76%, respectively.

(a) Keeping BF length constant and GF length varying:

Comparison of P with PG, PG11, PG12, PG13, PG21 and PG31 mixes which absorbed more water. HFRC has a higher water absorption capacity because fibers have a greater water absorption capacity. Due to the stiffness of concrete and its incapability to replace all voids, water seeps into the spaces left by the fibers in concrete, increasing the water absorption capacity of mixes with more glass fiber.

(b) Keeping BF length varying and GF length constant:

Comparison of PC with PG, PG11, PG21 and PG31 mixes which absorbed more water. HFRC has a higher water absorption capacity because fibers have a greater water absorption capacity. Due to the stiffness and its incapability to replace all voids, water seeps into the spaces left by the fibers in concrete, increasing the water absorption capacity of mixes with more glass fiber.

TABLE 4.5: Water Absorption of PC and HFRC

Index	**W (Kg)**	**W_w (Kg)**	**Water Absorption%**
PC	3.89	3.92	0.77
PG	3.88	3.93	1.28
PG11	3.61	3.71	2.77
PG12	3.66	3.77	3
PG13	3.86	3.95	2.33
PG21	3.65	3.78	3.56
PG31	3.72	3.86	3.76

The water absorption ability of different PC and HFRC combinations is shown in Figure 4.5. Many researchers produced similar work. The results suggested that minimizing the channel permeability and conductivity between the gaps might be achieved by incorporating fibres with a low water absorption capacity [15 and 16].

4.5 Summary

The assessment is made regarding the mechanical, dynamic, and water absorption properties of PC and HFRC with mixed design ratios of 1:2:3 and W/C ratios of 0.6 and 0.75. Slump values and densities of HFRC added and the mixture are less than

PC values. Properties such as compression, split-tensile, and flexural are evaluated and measured against PC. The HFRC has lower compressive strength, split tensile strength test, and flexural strength than the PC. The dynamic properties of PC and HFRC are additionally examined. The comparison of PC with HFRC has a greater damping ratio. For HFRC the dynamic elastic modulus, the dynamic rigidity modulus, and the dynamic poisons ratio all are increased.

Chapter 5

Discussion

5.1 Background

The mechanical properties of PC and HFRC, including as their compressive, split tensile, and flexural properties are studies in chapter 4. Hybrid fibers having varying length along with GGBS are added to the concrete to enhance some of its characteristics. This chapter discusses the empirical equation for water absorption (WA). Using this equation, water absorption values are determined and the outcomes are related with experimental values. Mechanical and dynamic properties have the following impacts: The commercial usage of HFRC is considered and encouraged.

5.2 Optimization of HFRC

Table 5.1 shows the minimum, maximum and recommended value of HFRC for mechanical and dynamic properties. PG13 mix having 7.5cm long glass fiber and 2.5cm long banana fiber gives good properties under compression and dynamic testing ,so the recommended HFRC under compression and considering dynamic properties, for commercial purposes is PG13. The possible reason for this could be the high strength of glass fibers as the strength enhanced with its increased content i.e. 7.cm length. PG11 mix having each fiber of 2.5cm length, gives good

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

Concrete Type	**Compression**				**Splitting Tensile**			
	P_{max} (kN)	**$\epsilon\circ$ (mm)**	**CE (MJ/m^3)**	**CTI**	**P_{max} (kN)**	**δ (mm)**	**SE (MJ/m^3)**	**STI**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
PC	105.49±38.67	0.017±0.00	0.113±0.012	1.08±0.03	57.23±3.88	0.68±0.16	17.03±1.64	1±0.00
HFRC with minimum value	43.28±4.41 (PG11)	0.035±0.003 (PG31)	0.138±0.010 (PG31)	2.10±0.27 (PG31)	47.38±2.24 (PG12)	1.0±0.11 (PG11)	21.23±0.13 (PG11)	1.08±0.03 (PG11)
HFRC with maximum value	92.33±8.65 (PG13)	0.082±0.037 (PG11)	0.211±0.024 (PG13)	3.27±0.49 (PG13)	73.60±1.36 (PG11)	1.41±0.22 (PG31)	34.92±3.58 (PG21)	1.82±0.37 (PG13)
Recommended HFRC	(PG13) (Compression)							(PG11) (Split Tensile)
Flexural				**Dynamic Properties**				
P_{max} (kN)	**△ (mm)**	**FE (MJ/m^3)**	**FTI**	**ζ**	**RFI (Hz)**	**Poisons Ratio**	**E_{dyn} (Gpa)**	**G_{dyn} (Gpa)**
7.51±1.28	1.30±0.18	4.66±1.31	1±0.00	2.01±0.20	5615±22	0.65±0.01	2.20±1.33	1.22±0.15
7.45±1.02	1.20±0.29	4.83±0.07	1.12±0.02	2.26±0.3	1375.5±44	0.56±0.06	1.38±0.4	0.90±0.12
(PG31)	(PG31)	(PG21)	(PG21)	(PG21)	(PG21)	(PG31)	(PG31)	(PG31)
8.65±0.28	1.51±0.15	5.57±0.30	1.24±0.11	3.2±1.3	3306±435	0.94±0.13	6.54±4.2	6.24±4.08
(PG11)	(PG11)	(PG11)	(PG13)	(PG31)	(PG13)	(PG13)	(PG12)	(PG13)
	PG11					PG13		
	(Flexural)					(Dynamic)		

strength under flexural and split tensile test. So for commercial purposes, PG11 is recommended in case of flexural and split tensile strength. The PG11 mix having 2.5cm long GF and BF each can be concluded the optimum combination under flexural and split tensile properties.

The samples were inspected visually after testing and the pullout was observed. The pullout of the fibers has been observed to be affected by the length of the fibers in the concrete sample. The pullout of fibers in PG13 is more as compared to PG31 because GF fiber have bridged crack in PG13 due to larger length of GF and fibers are broken in PG31 due to larger length of BF having relatively less tensile strength. The possible reason for this could be the high strength of GF as compared to BF.

5.3 Use of Research Result in Real Life Applications

Mixing concrete using fibers and an additive is economical and environmentally friendly. Previous chapters have established that HFRC has outstanding mechanical and dynamic properties because the HFRC of compression, split tensile and flexural having higher values of the toughness index, damping ratio, dynamic elastic modulus, and dynamic rigidity modulus as discussed in result chapter. Hybrid fibers provide outstanding properties having a strong bond between the concrete mix and fiber, utilizing banana and glass fiber enhances the damage bearing capacity of concrete. Concrete cracking and spalling may be minimized and prevented with proper fiber concrete bonding. The flexural resistance under impact loading is higher because HFRC with GGBS has a larger moment capacity.

The brittle nature of ordinary concrete make it more prone to cracking because of the different movement of concrete structures, bending loads develop and differential settlement-related cracking is prevented by enhancing the flexural strength of concrete. For this reason, it is necessary to increase the energy absorption capacity and toughness of concrete by transforming the brittle character of concrete to the tough nature of FRC. The brittle nature of concrete is also responsible for breaking in various concrete structures. The experimental performance of PC and HFRC for minimizing concrete cracking and spalling is examined in the current research. The addition of GGBS to concrete increases its flexural strength and the limited replacement of cement with GGBS reduces differential settling of concrete because the temperature of concrete rise and helps to avoid early-age thermal cracking. The concern of cracking in rigid pavements may be resolved by HFRC which has a higher toughness index value and a lower water absorption value. Mix PG11 and PG21 works well under compression loading and splitting loading containing combination of varying lengths of 2.5cm, 5cm long and 5% fiber content. Utilizing PG21 mix in columns enhances the column's properties under compression loading as the column serves as the compression member. Similar to this, foundations, slabs and bridge decks where flexural loading is absolutely critical utilize the PG, PG12, PG13, PG31 mix having different combinations of varying lengths 2.5cm, 5cm, 7.5cm for each fiber i.e. banana fiber and glass fiber along with 5% fiber content. The PG31 mix can be used to prevent concrete from cracking and spalling.

5.4 Summary

The relationship between PC and HFRC water absorption is developed by analyzing CS, STS, FS and an empirical equation is produced. An excellent association between water absorption, experimental and empirical evidence is discussed. The capacity of the specimens to absorb water will decrease while its strength increases. The practical use of recent research and its use in daily life are explored. It performed best in controlling cracking because HFRC has a greater energy absorption capacity than PC. It is suggested for commercial application to utilize HFRC with different fiber mixes after analyzing all of its properties.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Hybrid fibers enhance the performance of concrete because the presence of single fiber increases the properties of the other fiber. Integrating natural and artificial fibers has a significant impact on improving the concrete properties. Experimental research is used in this study to evaluate the mechanical, dynamic, and water absorption characteristics of HFRC. In the 1:2:3 mix design, 5% of the mass of cement with the combinations of different varying lengths of 2.5 cm, 5 cm and 7.5 cm is comprised of banana fiber and glass fiber. GGBS is used as an additive, replacing 8% of the cement. The properties of HFRC and PC are examined. From the research the following results are obtained.

- PG, PG11, PG12, PG13, PG21 and PG31 having compressive strengths that are 9.77 MPa, 5.51 MPa, 9.74 MPa, 11.76 MPa, 11.43 MPa and 10.36 MPa less than PC respectively. The PG, PG11, PG12, PG13, PG21 and PG31 mixes having tensile strengths that are respectively 2.11 MPa, 2.34 MPa, 2.14 MPa, 1.64 MPa, 2.16 MPa and 1.51 MPa less than those of PC. Set PG, PG11, PG12, PG13, PG21 and PG31 mixes having flexural strengths that are 2.87 MPa, 3.89 MPa, 3.37 MPa, 3.44 MPa, 3.40 MPa and 3.35 MPa respectively less than PC.

- The proportion of total compressive energy (CE) that the cylinders in set PG have absorbed ultimately is 0.052 MJ/m^3 less than that of PC. While the compressive energy absorption for PG11, PG12, PG13, PG21 and PG31 is 0.132 MJ/m^3, 0.092 MJ/m^3, 0.146 MJ/m^3, 0.137 MJ/m^3 and 0.072 MJ/m^3 more than that of PC, respectively. As compared to PC the improvement in splitting tensile energy absorption for PG11, PG12, PG13, PG21 and PG31 is 1.62 MJ/m^3, 9.10 MJ/m^3, 15.65 MJ/m^3, 15.05 MJ/m^3 and 8.16 MJ/m^3. Total flexural energy values for beamlets of the set PG11, PG12, PG13, PG21 and PG31 are 5.57 MJ/m^3, 4.87 MJ/m^3, 5.01 MJ/m^3, 4.83 MJ/m^3 and 5.18 MJ/m^3 respectively higher than PC.

- P, PG, PG11, PG12, PG13, PG21 and PG31 having corresponding compressive toughness index (CTI) of 1.08, 1.78, 2.97, 2.23, 3.27, 3.02 and 2.10. CTI for combination of PG13 have toughness index better compared to PC however it is 5.51 MPa, 9.74 MPa, 11.76 MPa, 11.43 MPa and 10.36 MPa is greater for PG11, PG12, PG13, PG21 and PG31 mixes, respectively. For the P, PG, PG11, PG12, PG13, PG21 and PG31 correspondingly, the splitting tensile toughness index is 1, 1, 1.08, 1.57, 1.82, 1.76 and 1.56. In the case of HFRC mixtures, an enhancement in splitting toughness index is shown. Mixtures P, PG, PG11, PG12, PG13, PG21 and PG31 having flexural toughness index (FTI) of 1, 1, 1.15, 1.19, 1.24, 1.12 and 1.17, respectively.

- For cylinders, the damping ratios for combination PG, PG11, PG12, PG13, PG21 and PG31 mixes are greater than those used for the PC. The damping ratio for ordinary concrete beam-lets is 2.64, but it is greater for PG11, PG12, PG13, PG21 and PG31.

- Comparing to PC, E_{dyn} of PG11, PG12, PG13, PG21 and PG31 contains cylinders that are more. Edyn is 4.14GPa for ordinary concrete beam-lets. E_{dyn} value in PG is equivalent to that in PC, whereas it is greater in PG11, PG12, PG13, PG21 and PG31 by different percentages, respectively.

- For PC cylinders, the poisons ratio value is 0.65. PG13 mix has a poison ratio of 0.94 which is greater than that of normal concrete while PC beam-lets have a poison ratio of 0.88.

- On overall basis, PG13 is recommended because strength and toughness in all three loadings are reasonable. On the other hand where split tensile and flexural strength and toughness of PG11 is good to be used.
- By analyzing CS, SS, and FS, a relationship between the water absorption of PC and HFRC is developed and an empirical equation is created. A significant relationship between water absorption and experimental and empirical data is explored.

Based on the aforementioned conclusions, it is apparent that HFRC offers outstanding properties and has the ability to reduce cracking and prevent concrete deterioration. Some of the necessary properties of concrete are enhanced when natural and artificial fibers are used.

6.2 Recommendations

Listed below are the recommended actions:

- Research can be carried out by varying the lengths of two fibers and combining them in different percentages or by adding two different admixtures along with hybrid fibers with different percentages.

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