MECHANICAL AND FRACTURE PROPERTIES OF REINFORCED CONCRETE USING STEEL INDUSTRIAL SLAG AND GGBS AS PARTIAL REPLACEMENT OF CEMENT

By

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Declaration

I hereby declare that the research work reported in this thesis titled "**Mechanical and fracture properties of reinforced concrete using steel industrial slag and GGBS as partial replacement of cement"** has been performed by the author under supervision of Dr. Nusrat Hoque, Professor, Department of Civil Engineering, Chittagong University of Engineering and Technology, Chattogram. Neither this thesis nor any part of it has been submitted elsewhere for any other purposes.

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Dedication

This thesis is devotedly dedicated to my beloved mother, **Ferdous Ara Begum**, whose unwavering support, encouragement, and prayers have been my guiding light throughout this journey. Her strength and dedication have always inspired me to strive for excellence. I also dedicate this work to all my family members, mentors, and friends who have believed in me and provided their invaluable support during this endeavor. Special thanks go to my **better half** for her constant motivation, which has truly made my journey much easier.

Approval/Declaration by the Supervisor

This is to certify that **A.S.M Nazim Uddin** has carried out this research work under my supervision, and that he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following Thesis in the application for the degree of MASTER of ENGINEERING in CIVIL ENGINEERING. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Abstract

Concrete is an essential building material that is always being improved to satisfy the needs of modern infrastructure while increasing environmental sustainability. This study evaluates the mechanical and fracture properties of concrete using the addition of fiber and the partial replacement of cement with industrial by-products such slag and Ground Granulated Blast Furnace Slag (GGBS). Five concrete mix combinations were used according to the mix design by replacing cement content with the ladle slag, GGBS and fiber at various percentages in the concrete mix. The control mix namely Mix-1 was 100% cement content, whereas 10% ladle slag and 30% GGBS has been replaced with cement in the Mix-2 and Mix-3 respectively. Fiber was used in the Mix-4 and Mix-5 with the same ingredients of Mix-3 by 0.05% and 0.10% of concrete volume respectively. It was observed Mix-1 achieved maximum compressive strength whereas a decrease of 4% and 16% in Mix- 2 and 18% and 22% in Mix-3 at 7 and 28 days. The results showed that the GGBS improved the compressive strength compensating for the decrease in cement content to some extent. The results also indicate that the compressive strength of Mix-4 increased by 4% with the addition of 0.05% fiber but decreased by 6% in the Mix-5 when 0.10% fiber was used comparing to the Mix-3. Thereafter the only difference between Mix-3 to Mix-5 is the amount of fiber content used in the mix, which implies that, the addition of fiber improved the strength but for the uses of excessive amount of fiber does not improve strength rather decreases the strength. Ladle slag, GGBS, and fiber improved flexural strength (MOR), and MOR increases by as high as 48% for Mix-5 over the control Mix-1. The fracture energy G_f which represents the amount of energy needed for the formation of cracks in the concrete surface. In addition of 0.05% and 0.10% fiber in the Mix-4 and Mix-5 enhancing the G_f values by 6% and 45% respectively but reduction of cement content by 40% in the Mix-

3, it's G_f value decreases by 54%. Which implies that fibers significantly improved the G_f capacity and on the other hand, reduction of cement content decreased the fracture energy values. The fracture energy G_f values has been obtained in the range of 80-175 N/m from the all mix combination where control sample Mix-1 has achieved the highest value. The measure of material's ability to prevent an unstable fracture or crack is called stress intensity factor K_{ic}. In this study highest K_{ic} is obtained at control Mix-1 indicating above mix has maximum ability to resist the growth of the cracks. The K_{ic} values are gradually decreases by 8% and 54% for the reduction of 10% and 40% of cement in the Mix-2 and Mix-3. Addition of fiber in the concrete mix significantly enhanced the fracture toughness K_{ic} value by 39% and 33% in the mix combination Mix-4 and Mix-5. The range of K_{ic} values has been evaluated 0.82-1.78 MPa $m^{0.5}$ in this study.

বিমূর্ত

কংক্রিট একটা অত্যাবশ্যকীয় নির্মাণ সামগ্রী, যা আধুনিক অবকাঠামোর চাহিদা পূরণ করছে এবং পরিবেশগত উন্নয়নেও অবদান রাখছে।এই গবেষণায়,ফাইবারের সংযোজন এবং স্ল্যাগ ও গ্রাউন্ড গ্র্যানুলেটেড ব্লাস্ট ফার্নেস স্ল্যাগ এর মতো শিল্প উপজাত দ্বারা আংশিক সিমেন্ট প্রতিস্থাপনের মাধ্যমে কংক্রিটের শক্তি ও ফাটল তৈরি হওয়ার বৈশিষ্ট্য মূল্যায়ন করা হয়েছে। সিমেন্ট প্রতিস্থাপনের উপর ভিত্তি করে কংক্রিটের পাঁচ রকম মিশ্রণ ব্যবহার করা হয়েছে যাতে মিশ্রণে স্ল্যাগ এবং গ্রাউন্ড গ্র্যানুলেটেড ব্লাস্ট ফার্ণেস স্ল্যাগ সিমেন্টের সাথে আংশিক প্রতিস্থাপন করা হয়েছে এবং কংক্রিট আয়তনের ০. ০৫% ও ০. ১০% ফাইবার অতিরিক্ত সংযোজন করা হয়েছে। আদর্শ মিশ্রণ, মিক্স-১ এ কোন সিমেন্ট প্রতিস্থাপন করা হয়নি। যেখানে মিক্স -২ ও মিক্স-৩ মিশ্রণে সিমেন্টের সাথে ১০% ল্যাডল স্ল্যাগ এবং ৩০% জি জি বি এস প্রতিস্থাপিত হয়েছে। মিক্স-৪ ও মিক্স-৫ এর উপাদান গুলো মিক্স-৩ এর মতই শুধু অতিরিক্তভাবে কংক্রিটের আয়তনের ০. ০৫% ও ০. ১০% ফাইবার ব্যবহার করা হয়েছে। ৭ ও ২৮ দিনে মিক্স-১ সর্বোচ্চ শক্তি অর্জন করেছে যেখানে মিক্স-২ তে ৪% ও ১৬% এবং মিক্স-৩ তে ১৮% ও ২২% শক্তি হ্রাস পেয়েছে। ফলাফল অনুযায়ী দেখা যাচ্ছে, জি জি বি এস কংক্রিট স্ট্রেংথ বৃদ্ধিতে কিছুটা সহায়তা করেছে। ফলাফল অনুযায়ী আরো দেখা যাচ্ছে, মিক্স-৪ এ ৪% স্ট্রেন্থ বৃদ্ধি পেয়েছে ফাইবার সংযোজন এর জন্য কিন্তু আবার ৬% স্ট্রেংথ হ্রাস পেয়েছে দ্বিগুণ ফাইবার সংযোজন বাড়ানোর জন্য। এতে বুঝা যায়, কংক্রিটে অতিরিক্ত ফাইবার ব্যবহার স্ট্রেংথ বাড়াতে সহায়তা করেনি বরং হ্রাস করেছে। ল্যাডল স্লাগ, জি জি বি এস এবং ফাইবার কংক্রিটের ফ্লেক্সারাল স্ট্রেন্থ বৃদ্ধি করেছে। এবং ফলাফল অনুযায়ী দেখা যাচ্ছে, মিক্স-৫ এ ফ্লেক্সারাল স্ট্রেন্থ বৃদ্ধি পেয়েছে সর্বোচ্চ ৪৮%। কংক্রিট পৃষ্ঠে ফাটল গঠনে যে পরিমাণ শক্তি প্রয়োজন হয় সেটাই মূলত ফ্যাকচার এনার্জি নামে পরিচিত। মিশ্রনে ০. ০৫% ও ০. ১০% ফাইবার সংযোজনে ৬% ও ৪৫% ফাটল শক্তি বৃদ্ধি পায় কিন্তু ৪০% সিমেন্ট প্রতিস্থাপনের জন্য ৫৪% শক্তি হ্রাস পায়। ফাইবার সংযোজনে ফাটল শক্তি উল্লেখযোগ্যভাবে বৃদ্ধি পায় এবং পরীক্ষা অনুযায়ী বোঝা যায়, সিমেন্টের পরিমাণ কমলে ফাটল শক্তির মান কমতে থাকে। এ গবেষণায় সকল মিশ্রণ থেকে ফাটল শক্তির মান ৮০-১৭৫ নিউটন/মি: পাওয়া যায় যা সাধারণ কংক্রিট এর জন্য অনুমোদনযোগ্য যেখানে

মিক্স-১ সর্বোচ্চ ফাটল শক্তি অর্জন করেছে। কংক্রিটের ক্র্যাক প্রতিরোধ করার জন্য যে পরিমাণ শক্তি এর প্রয়োজন হয় তা মূলত স্ট্রেথ ইনটেনসিটি ফ্যাক্টর (K_{ic})। এই গবেষণায় মিক্স-১ সর্বোচ্চ স্ট্রেন্থ ইনটেনসিটি মান অর্জন করেছে যেটি ক্র্যাক প্রতিরোধের জন্য সর্বোচ্চ ক্ষমতা নির্দেশ করে। মিক্স-২ ও মিক্স-৩ তে (K_{ic}) মান ৮% ও ৫৪% কমেছে ১০% ও ৪০% সিমেন্ট প্রতিস্থাপন করার জন্য। কংক্রিটে ফাইবার সংযোজনের জন্য ফ্র্যাকচার টাফনেস ৩৯% ও ৩৩% বৃদ্ধি পেয়েছে। এ গবেষণায় সকল মিশ্রণ থেকে স্ট্রেন্থ ইনটেনসিটি ফ্যাক্টর (K_{ic}) মান ০. ৮২-১. ৭৮ এম পি এ এম $^{০. ৫}$ পাওয়া যায় যা সাধারণ কংক্রিট এর জন্য অনুমোদনযোগ্য।

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Nomenclature

SCM = Supplementary cementitious materials

CA = Coarse Aggregates

FA = Fine Aggregates

Sp. Gr. = Specific Gravity

GGBS = Ground Granulated Blast Furnace Slag

IF = Induction Furnace

F.M = Fineness Modulus

MOR = Modulus of Rupture

ASTM = American Society for Testing Materials

CTM = Compression Testing Machine

RILEM = The International Union of Laboratories and Experts in Construction Materials, Systems and Structures

UTM = Universal Testing Machine

CHAPTER 1: INTRODUCTION

1.1 General:

Concrete is an artificial composite stone are made by the Portland cement, water, sand, and aggregates (Badur & Chaudhary, 2008). The role of concrete in modern civil engineering activity is strongly justified by the focus on the improvement of the material's properties in terms of mechanical response and sustainability. But the formulation of more resilient and environmentally friendly concrete leads to the investigation of alternative ingredients which have a potential to enhance the concrete properties, though at the same time to reduce its eco-footprint. However, as the materials are added in the cement concrete mix, there is a preference for industrial by-products such as steel slag. The steel slag from steel making processes contains hidden features that affect the strength and brittleness of concrete. As a substitute for traditional cement, act as a binder, cement sets and hardens and may also bind other materials together, hence increasing strength, durability, and sustainability (Anand & Tharunkumar, 2019). The next part of the introduction focuses on mechanical and brittle features of concrete when iron industrial slags are used as an alternative to cement. The mechanical behaviour of concrete plays a key role in the assessment of the structure's integrity and functionality under various types of loading. The majority of concrete compositions based on traditional Portland cement depicts energy consumption and greenhouse gas emissions as being just one of the main concerns. This way the durability of the concrete can be maintained or even increased. In addition, fracture mechanics is an vital factor for the determining the life span and durability of concrete elements, especially when they are subjected to the shock loads and extreme environmental conditions. For instance, introducing steel slag into the concrete mixture will allow the adjustability of its fracture characteristics will improve and service life of concrete will be affected.

1.2 Background of the problem:

Concrete is the most used building material which is characterized by the combination of cement, water, aggregates (sand, gravel or crushed stones) and optionally admixtures (Shoukry et al., 2005). These materials are mixed, and they are being allowed to cure. Finally, they become a hard and rugged solid material that is used for different construction activities. Concrete is a well-known multifunctional and utmost used building or construction material due to its properties (Manasseh, 2010). The understanding of these characteristics is the most crucial point for engineers and construction workers to be able to guarantee that the concrete buildings meet in accordance with the required performance. Some primary characteristics of concrete involve compressive strength, tensile strength, durability, workability, setting time, shrinkage and creep, density, and thermal properties. The most important attributes which should be incorporated within the design and for construction of a safe, lasting and cost-efficient building are the ones that meet the performance requirements for a certain application and climate. The uses of steel industrial slags in concrete as a partial replacement for cement is discussed in this study along with its current advancements and reactions. Huge amounts of carbon dioxide are emitting into the environments due to the production of cement. On the other hands, cement is mostly used construction materials by the human beings and it is also second largest used material after water used by the peoples (Anand & Tharunkumar, 2019). Uses of partial substitution of cement can be beneficial and it can reduce the uses of cement in the construction. The goal of the extensive analytical and experimental research is to determine the mechanical response and fracture characteristics of the proposed concrete mix. The research that explains the impact of steel slag on concrete properties contributes to the ongoing efforts to develop eco-friendly and resilient construction materials. Consequently, this work that includes the research of mechanical and fracture properties of concrete with steel industrial byproducts such as furnace slag, ground granulated blast furnace slag, (GGBS) is considered to be of great importance for the development of ecological construction materials. It's aimed to adopt and apply steel slag/ GGBS unique properties into concrete mixes that meet the structural requirements, environmental compliancy, and resource efficiency principles. Mechanical and fracture properties of concrete define its compliance under stress as well as different environmental conditions. Such skills are essential in maintaining the stability, safety, and longevity of concrete structures as well as for the engineers and construction professional. Some important mechanical and fracture properties of concrete investigated by carrying out their relevant test procedures have been dealt in this thesis.

1.3 Statement of the problem:

Most of the study on concrete was done in primarily based on determining the compressive strength of concrete means mechanical properties but only a few studies were found about the fracture properties. Hence, this study is done for both mechanical & fracture properties together to relate with each other. The mechanical properties like compressive, flexure strength is determined as per standard of ASTM methods & fracture properties is evaluated by RILEM method. Tests had been conducted at seven (07) and twenty (28) days of concrete ages. This study could lead to a reduction of cement quantity in concrete to some extent and the environmental impacts due to the deposition of waste slag in landfills and carbon emission for the producing of cement. So, the main goal of this investigation is to know the concrete's fracture properties in parallel with its mechanical properties.

1.4 Objectives:

- To assess the mechanical properties of concrete by partially replacing cement with steel slag, GGBS and using fibre at various percentages on cube and beam samples at different ages.

- To determine the fracture properties of concrete for the same concrete using standard beam samples recommended by RILEM for fracture test.
- To recommend the optimum level of cement replacement that can be permitted in actual practice based on the mechanical properties and fracture properties.

1.5 Scope of the study:

The current study examines the compressive strength, flexural strength as a mechanical property of concrete for the selected 5 types of mix combination of concrete ingredients with industrial by products like steel industrial slags, GGBS and fibers. Total, 30nos (150mm X 150mm X 150mm, sizes) cubes were cast for compressive strength test and another 20nos beams were cast for flexure and fracture properties test. Compressive strength test is conducted after 7 and 28 days of curing where flexure and fracture test are performed after 28 days of curing. After the necessary testing of the samples, the test results are discussed both graphically and tabularly. After subsequent analysis and findings, certain conclusions have been made.

CHAPTER 2: LITERATURE REVIEW

2.1 General:

Given the concerns of resource depletion and climate change, partial substitution of cement in concrete has become increasingly necessary in the modern day. The construction industry is so much depended on cement for its operations in the improvement of the buildings and other infrastructural facilities (Gwarah et al., 2019). Cement is one of the important ingredients in concrete therefore the production of cement uses various natural resources. Besides, the production of cement contributes a lot to greenhouse gas emissions. As a result, admixtures containing fly ash which is supplementary cementitious materials (SCM), slag and silica fume have gained the status of the everyday tool for reduction of environmental impact. This is the method through which we can produce concrete at less cost, and at the same time can conserve the resources. And also, this is the way through which carbon emissions can be reduced. Alongside lowering cement content, partial cement substitution also offers better structural durability, toughness, and rigidity which directly affects strength of the concrete. Now a days implementing partial cement substitution in concrete production is extremely vital since it gives development to the structures that not only are durable but also are eco-friendly.

2.2 Concrete:

Concrete is a man-made composite substance comprised mainly of cement, water, aggregates (e.g., sand and stone chips), and if necessary, more additives or admixtures. It has now turn out a potentially high-tech material susceptible of very high strength, high durability, excellent outer form and of being easy to pump and even self-compacting (Larrard, 2014). It is among the strongest and reliable construction materials because of its fewer demands and greater adaptability. Hence, it is the most used material. Indeed, the purpose of a binder is to affix the particles so they can be held together to form up the whole mass. Water is responsible for the hydration process to start setting time to harden the concrete. while the solid materials contribute to the mix's volume and strength. Admixtures and additives can change or improve the workability, strength, and durability of concrete.

Concrete is usually produced by mixing with exact amounts of cement, aggregates, water, and additives on construction sites or in batching plants. After mixing, the concrete is poured into formwork or moulds, where it is left to cure and solidify into a mass as per shape. In order to obtain the appropriate cement hydration and the requisite strength and durability, the curing process entails maintaining the concrete at the suitable temperature and moisture content. It is utilized in many different construction applications, such as sidewalks, roads, bridges, dams, structural components, and building foundations etc.

2.3 Concrete mix design:

Mix design of concrete is the process to select suitable ingredients for concrete and determination of their relative proportions to make concrete with the desired properties, such as strength, workability, durability, and economy. Estimation of ingredients of aggregate mixes is a vital part of concrete mix design. (Shakhmenko & Birsh, 1998)

2.4 The main factors which are affected by the mix design of concrete:

Concrete mix design is the procedure of finding the amount of each element (cement, water, aggregates, and admixtures) that should be mixed to produce concrete with the properties that will be required for construction. The mix design is one of the most important factors in the construction of concrete because it is the thing that determines the concrete's performance, durability, and economy. This is to pick the most appropriate ratio of its components.

2.4.1 Required strength:

The compressive strength that the concrete must have in order to pass the test is the result of its structural design and the estimated loads. The minimum strength requirements are described by the factors such as the structural type, the service conditions and the building criteria.

2.4.2 Workability:

Workability is the term that refers to the ease of mixing, transporting, laying, and compacting of concrete. The level of workability that is determined is the consequence of the criteria such as the installation method, the sizes and shape of the structurals element and the site conditions.

2.4.3 Durability requirements:

The necessity of the durability is defined as the ability to withstand the environmental factors such as the freeze-thaw cycles, chemical attack, abrasion, and corrosion. The mix should be made up of the components and proportions which will increase the durability of the concrete over the lifespan of the stated structure.

2.4.4 Aggregates properties:

The aggregates Properties are the most crucial component of the volume in concrete; thus, they have a significant effect on the mix design. The aggregate size, shape, gradation, and moisture content are all the factors that influence the workability, strength, and durability of the concrete.

2.4.5 Cementitious materials:

The kind and the quality of cementitious materials, such as Portland cement, supplementary cementite materials (such as fly ash, slag, or silica fume), and chemical admixtures are very important in the mix formulation. These substances are the ones that give the strength, the setting time and the durability of the concrete.

2.4.6 Water-Cement ratio (W/C):

The water-cement ratio is the most vital component of the mix design of concrete because it is the one that determines the strength, workability, and durability of the concrete. The lower water-cement ratio usually gives more strength and durability, but it also affects the workability and the placement qualities.

2.4.7 Chemical admixtures:

Chemical admixtures are used to modify the properties of fresh and hardened concrete which includes, the improvement of workability, the reduction of water requirement, the control of the setting time, the increase of durability, and the decrease of the impact of the harsh environmental conditions.

2.4.8 Curing conditions:

The purpose of the cure is to achieve the optimal strength and durability of concrete. The curing and the time of the mixture should be included in the mix design so that the maximum hydration of the cementitious components and the strength development over time can be achieved. Environmental Conditions: The factors that affect concrete performance are the temperature, humidity, exposure conditions, and the service environment. These points must be considered while the mix design process is going on so that the concrete performs well during its useful life.

2.4.9 Quality control and testing:

The design of concrete mix is based on the quality control and testing processes because they are the factors that check the properties of fresh and hardened concrete and also ensure that the project specifications and industry standards are met.

2.5 Methods of mix design:

There are several ways of designing concrete mixes, each with its own advantages, restrictions, and suitability for the different kinds of construction. These are-

2.5.1 The American Concrete Institute (ACI) method:

The ACI method is the usual one in North America, and it is based on the statistical analysis of the experimental data. It means the choice of initial mix proportion is based on previous experience or guidelines and then the change of these proportions in trial batches to obtain the desired qualities.

2.5.2 British technique (DOE method):

The DOE method, also known as the British method, is particularly popular in those countries that adopted British standards. The selection of mix proportions based on the specified strength, graded aggregate, and the aggregate-cement ratio is a part of it.

2.5.3 IS (Indian Standard) method:

In this mix method, which is based on IS 10262:2019 and IS 456:2000, provides an organised method to mix concrete materials for the required workability, strength, and durability. Target mean strength, cement content, water-to-cement ratio, and fine and coarse aggregate adjustments based on grading and environmental conditions are all part of the process. This technique ensures concrete that is cost-effective, durable, and high-performing. it is frequently used in construction projects in India.

2.5.4 ACI 211. 1 method:

The ACI 211.1 method is a largely used procedure for designing concrete mixes. It provides a step-by-step procedure to determine the appropriate proportions of cement, water, aggregates, and admixtures to achieve a desired concrete mix with specific properties. The method considers lots of factors such as slump value of concrete, maximum coarse aggregate size, water-cement ratio, and air content in the aggregates to ensure the concrete meets the required strength, durability, and workability criteria.

2.5.5 Absolute volume method:

The absolute volume method is a concrete mix design process used to determine the correct proportions of ingredients for achieving a desired strength and workability. Considering the material's specific gravity and moisture content, it involves calculating the absolute volume of each component occupies within a unit volume of concrete. The total concrete mix volume is then determined by summing these individual absolute volumes. This method helps to ensure the mix meets the specifications and minimizes material waste.

2.5.6 Trial mix method:

The trial mix method is the production of test batches of concrete with different quantities of materials to get the results of their performance and after this modify the mix proportions as well. This cyclical process enables adjusting the concrete blend to the needed characteristics.

2.5.7 Optimization method:

The mathematical methods and the computer software are applied to choose the most suitable mix ratios which contain the bottlenecks and goals as objectives, such as, the least cost, the maximum strength or the desired workability. These approaches are not only efficient but are also well structured to deal with the complex interactive issues involved in mix design.

2.6 Partial replacement of cement in the concrete:

Ongoing production of wastes arising from industrial by-products and agricultural surplus, create acute environmental problems both in terms of their treatment and disposal (Raheem et al., 2012). Partial replacement of cement is a process that comprise alternating an amount of cement with the byproducts like fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, or rice husk. Cement manufacturing is a major source of CO_2 emissions into the environments. Cement industry is one of the largest carbons emitting industrial sectors (Mikulčić et al., 2013). During the production of cement, almost 90% of CO_2 is emitted directly and 10% is occurred from the convey of raw materials and causing some other from the production processes (Gao et al., 2015). Nearly 1 ton of CO_2 emits for the production of 1 ton of cement which is threaten for the environment. Nowadays, one of the principal goals of the universal environmental agenda is to reduce emissions so as to protect global climate (Gao et al., 2015) .That's why, now it is big concern to stop the carbon emission at the atmosphere. This method can reduce the carbon emission by reducing the cement consumption in the construction. Moreover, it can improve the workability of fresh concrete, making it easier to mix, place, and finish. By incorporating waste materials and industrial by-products into concrete, partial replacement also promotes sustainability, helping to recycle materials that would otherwise end up in landfills. Overall, partial replacement of cement plays a crucial role in creating more sustainable, cost-effective, and durable construction materials, which is essential for modern-day infrastructure.

2.7 Mechanical properties of the concrete:

The concrete mechanical properties, such as flexural strength, tensile strength, compressive strength and modulus of elasticity, are the crucial for ensuring the durability, stability, and safety of the structures. These properties determine the load-bearing capacity of concrete, its resistance to cracking, and its ability to withstand different types of stresses. Compressive strength is the most significant property, as it directly influences the structural integrity of buildings, bridges, and other infrastructures. As it is also measuring its ability to resist crushing forces and is a key factor in structural design. Since concrete is very weak in tension, its tensile strength is significantly lower than compressive strength, so reinforcement has to be provided in the concrete's tension zone for enduring the tensile stresses. Flexural strength represents its resistance to bending. Tensile and flexural strengths are also vital in preventing failure due to bending and cracking, especially in reinforced concrete elements. These mechanical properties are required to design the members of the concrete structures. Exact calculations of the concrete's mechanical properties has been a concern as these features are mostly needed to do design and analysis of the structures (Ben Chaabene et al., 2020).

2.8 Types of mechanical properties of concrete:

2.8.1 Compressive strength:

The Compressive strength is the most commonly performed mechanical property test of concretes. It shows the axial load resistance or the pressures that the concrete is capable to bear. The concrete load-bearing members such as columns, beams, and foundations are decided by their compressive strength.

2.8.2 Tensile strength:

The tensile strength is the property of concrete to endure the stretching or pulling forces. Concrete is very strong in compression, but it is very weak to take tension. Due to the insufficient tensile strength capacity of concrete, it is required to put some reinforcement in the tension zone of concrete. So that it can be able to take any other external forces, bending stress and any types of loads.

2.8.3 Flexural strength:

The flexural strength, or the modulus of rupture MOR, is the capacity of concrete to resist the bending forces. The design of the members which are subjected to bending loads, for example, beams and slabs, is very significant. The flexural strength is determined by the factors such as the concrete mix design, curing conditions, and reinforcing.

2.9 Fracture properties of concrete:

Concrete's fracture properties explain how it behaves under cracking and tensile stress. It is a heterogeneous material, where its fracture behaviour is complicated and the quantification of fracture parameters becomes difficult (Shah & Kishen, 2011). Concrete has low tensile strength and breaks easily under extreme stress, in comparison to ductile materials. Its fracture process impacted by the microcracks which is develop due to shrinkage, thermal effects and imposed loading on the structures. Key parameters of the fracture properties are, fracture energy is the energy which is required to propagate a crack on the structural surface and the fracture toughness known to resist the growth of cracks on the structures. And another key parameter is modulus of elasticity of concrete while the modulus of elasticity defines its stiffness and ability to deform under load.

2.10 Types of fracture properties of concrete:

2.10.1 Modulus of elasticity:

The modulus of elasticity, which is also called Young's modulus, is a measure of the stiffness of concrete. It elaborates on the link in-between the stresses and strains in the elastic deformation spectrum. The modulus of elasticity is the most vital factor in the study of the behaviour of concrete under different loading conditions and in the determination of the deflections and deformations of the structural parts.

2.10.2 Fracture toughness:

Fracture toughness is the capacity of concrete to tolerate the process of crack propagation and arrestment. It is a vital part for the assessment of the concrete's capacity to withstand the fracture under dynamic loading, impact, or environmental conditions. High fracture toughness is responsible for the decrease of the enhancement of cracks & increase of the durability of concrete structures.

2.11 Byproducts from steels melting plant:

Steel factories offer a wide range of opportunities from the byproducts produced with their main finished product. The use of waste produced by steel plants has become a critical issue due to increasingly extreme environmental restrictions. These regulations imposed on steel producers have improved the situation for reducing the waste produced by steel mills. The steel industry generates about 500 kg of waste materials for every tonne of crude steel (SK et al., 2018). One of the main byproducts in the steel melting plant are called steel melting slag which is also familiar as induction furnace slag. Above slags are containing calcium, silicon, and aluminium oxides. Slag is produced in ample amounts and can be processed to serve as an alternative to cement at a fraction of the cost while it improves the execution of infrastructure materials such as concrete and asphalt through a reduction in production costs.

The Ground Granulated Blast Furnace Slag (GGBS), is a by-product that is produced abundantly from blast furnaces used in the steel and iron making processes. When iron ore, limestone, and coke are placed under extremely hot temperatures in a blast furnace, the molten iron is extracted to manufacture steel, with the non-metallic materials, i.e., slag, remain in a liquid phase. This slag is sprayed with hot water to instantaneously harden to a glassy granulated material known as GGBS subsequent to granulating slag into grains, they are dried, ground and pulverized to produce GGBS. GGBS is generally used as an SCM (supplementary cementitious materials), alternative to cement making concrete. GGBS is used to make durable concrete structures in the combination with ordinary Portland cement. Typically, the chemical composition of GGBS is Calcium oxide (CaO) is 40%, silica (SiO_2) which is 35%, alumina (Al_2O_3) and magnesia (Mg) are respectively 13% and 8%. Typically, the physical properties of GGBS is, in colour: off white, specific gravity (sp gr.): 2.91, bulk density: 200 kg/m^3, fineness : 350 m^2/kg (Suresh & Nagaraju, 2015). It may be used in concrete as one of its components, leading to an alternative that has a higher resistance to damage, a consumption of chemicals is lessened, and it is also less porous. Another byproduct of the process is milling scale which is a flaking surface layer that is formed on the hot steel can be recycled in the production of iron-rich sinter or resulting as a raw material for cement production.

The dust and sludge, iron oxides and other metals-rich, from the steel plants can be recovered and reused in the steelmaking process or for other industrial application, hence, only little waste is produced and the resources that are available take a minimal fraction in generating processes. In addition, the steelmaking results in emission of gases such as carbon monoxide, carbon dioxide, and hydrogen; these can instead be recovered, and exploited as alternative to fossil fuels in electricity production. In addition to this, desulfurization slag, the byproduct of desulfurization process, can serve as an additive when blending it in soil amendment and fertilizer production because of its high calcium content. Moreover, the long list of other byproducts such as refractories and spent pickle liquor which people have not necessarily heard of can be recycled and reused in the steel industry too. These rejects are dealt with by adopting the comprehensive management strategy and by carrying out innovative utilization of the byproducts. In this way, not only the economic resource use in steel plants is reused but also the principles of sustainable development and environmental stewardship are followed, minimizing waste and promoting resource conservation in industries.

2.12 Research on this field:

Author	Work done	Findings
(Ahmad et al., 2022)	The paper reviews the use of ground granulated blast furnace Slag (GGBS) as a sustainable alternative to Ordinary Portland Cement (OPC) in concrete	The study highlights GGBS potential to reduce carbon dioxide emissions in concrete production by up to 70%. Split

	production, highlighting its mechanical properties, durability, and environmental benefits. It discusses the manufacturing, chemical composition, and hydration reactions of GGBS, emphasizing its pozzolanic activity that enhances concrete density and resistance to chloride attacks. The paper also identifies the optimum percentage of GGBS for improved performance, generally suggested to be around 20%. It concludes that GGBS contributes to sustainable construction by reducing waste and carbon emissions while improving concrete durability.	tensile strength improves with up to 20% GGBS substitution but decreases beyond that. It enhances concrete's mechanical properties, durability, and flowability, particularly at optimal replacement levels. It also can replace up to 80% of cement, significantly benefiting sustainable construction practices. The findings indicate that curing conditions affect GGBS performance in concrete.
(Rashad, 2018)	The paper reviews the influence of High-Volume Slag (HVS) as a cement replacement on the properties of pastes, mortars, and concretes. It highlights improvements in durability, workability, and reduced permeability, porosity, and water absorption with HVS incorporation. The review indicates a reduction in drying shrinkage, which can mitigate cracking in large concrete elements.	The study focused, High-volume slag (HVS) enhances workability, setting time, fracture energy, and toughness in concrete mixtures. It reduces mechanical strength, especially at early ages, and decreases carbonation resistance. It also lowers permeability, water absorption, chloride ion penetration, and pH value. HVS improves corrosion

	However, it notes a lack of literature on the effects of HVS on autogenous shrinkage, suggesting the need for further research. Overall, HVS enhances the mechanical strength and durability of concrete, making it a beneficial alternative in construction.	resistance, chemical resistance, and electrical resistivity. Studies indicate that using HVS can mitigate drying shrinkage in large concrete elements. The literature lacks extensive research on the effects of high slag substitution levels (>60%).
(Zhuo et al., 2022)	The paper studies the impact of steel-slag powder as a cement replacement on concrete's fracture performance. A three-point bending test was conducted on concrete with varying steel-slag powder replacement ratios. Results indicate that appropriate steel-slag powder enhances fracture energy and toughness, peaking at a 5% replacement ratio. The study highlights the potential of steel-slag powder in improving concrete's mechanical properties and environmental sustainability.	The study found that, steel-slag powder improves the fracture performance of concrete, particularly at a 5% replacement ratio. Fracture toughness increased by 53.22% for SPC5 compared to normal concrete, while higher replacement ratios led to decreased toughness. The incorporation of steel-slag powder enhances bond performance between aggregate and matrix due to its hydration activity substances. Appropriate steel-slag powder levels improve compressive strength and energy-dissipation capacity, especially

		in normal-strength concrete. The research indicates that steel-slag concrete exhibits durability comparable to sea-sand concrete in various environmental conditions.
(García-Cuadrado et al., 2017)	The paper investigates the effects of substituting cement aggregate with EAF (black) and LF (white) slags in lime-cement mortars. Response Surface Methodology (RSM) and Central Composite Design (CCD) were utilized to analyse fracture energy. Mortars with black slag exhibit higher mechanical strengths compared to those with natural aggregates. The study highlights the influence of slag content and curing age on fracture properties.	This paper showed, the development of tenacity in mortars varied with lime substitution and aggregate type used. Mortars with siliceous sands showed increased tenacity with more cement, unlike those with white slag. Black slag mortars exhibited better fracture behaviour compared to white slag and sand mortars. White-slag mortars executed better than sand mortars with higher lime content, but showed lower strengths with large cement amounts. The study utilized of the response surface methodology to analyze the effects of slag content on fracture energy.

(Ding et al., 2018)	The research investigates the fracture properties of alkali-activated slag (AAS) concrete compared to ordinary Portland cement (OPC) concrete using three-point bending tests. AAS concrete exhibits higher fracture energy than OPC concrete at the same compressive strength due to denser interfacial transition zones (ITZs). However, AAS mortar shows lower fracture energy than OPC mortar at higher compressive strengths due to the formation of initial micro-cracks. The study also highlights that AAS concrete and mortar have lower elastic modulus values than their OPC counterparts. Overall, AAS cement is presented as much environmentally friendly variant to OPC.	This study found, Alkali-activated slag concrete exhibits higher fracture energy than OPC concrete at the same strength due to denser ITZs. It's mortar shows lower fracture energy compared to OPC mortar. The elastic modulus of AAS concrete and mortar is lower than that of their OPC counterparts. The splitting tensile strength of AAS concrete is similar to that of OPC concrete at the same compressive strength. AAS concrete is more brittle than OPC concrete, especially as compressive strength increases.
(Jaya Prithika & Sekar, 2016)	The paper discussed, eco-friendly concrete using manufactured sand (Msand), ground granulated blast furnace slag and coconut shell. Self-cured concrete coconut shell can be produced without external curing by the water. A compressive strength of 27.4 MPa was achieved for conceal cured coconut shell concrete at 28 days.	This paper concluded, the compressive strength of conceal cured coconut shell concrete reached 27.4 MPa at 28 days, outperforming water and steam cured concrete. Compressive strength decreased by 8% to 26% with 25% and 50% GGBFS

	The MOR for coconut shell concrete ranges from 4.92 to 6.52 MPa. The study emphasizes the importance of using waste materials for sustainable construction.	replacement, respectively. Steam curing negatively impacted compressive strength due to retardants from coconut shell. The static modulus of elasticity for the concrete coconut shell ranged from 6.29 to 8.00 GPa. The Poisson's ratio varied from 0.15 to 0.30, with steam cured concrete showing higher values. Msand is a viable alternative to river sand, providing better bonding and cost efficiency.
(Gencel et al., 2021)	The paper reviews the applications of steel slag in the cement and concrete industry, highlighting its chemical composition and durability properties. It discusses the use of steel slag as fine aggregates and the coarse aggregates in concrete, emphasizing its impact on compressive strength and overall concrete quality. The environmental effects of steel slag usage and its potential for sustainable development are examined, noting the low recycling rates in developing countries compared to	This paper showed, Steel slag can be effectively used as aggregate in concrete, improving compressive and flexural strength in various grades. The addition of steel slag enhances the stability and bonding characteristics of asphalt mixtures compared to traditional aggregates. Steel slag's porous and rough surface improves adhesion with bitumen, leading to higher quality asphalt

	Europe. Recommendations for future studies on steel slag applications in various sectors are provided, aiming to enhance economic and ecological balance.	production. Using steel slag as a supplementary cementitious material reduces environmental impacts and energy consumption in concrete production. The research highlights the need for further studies on the various applications of steel slag in sustainable construction.
(Fazlur et al., 2013)	The paper investigates the effects of substituting of coarse aggregate with blast furnace slag and cement with metakaolin to make concrete. It aims to evaluate the compressive and tensile strength of concrete with varying percentages of these replacements (0%, 10%, 20%, 30%, 40%). The findings indicate that up to 30% replacement of coarse aggregate with blast furnace slag enhances concrete strength, while higher percentages lead to a decrease due to increased air voids. Metakaolin improves strength by converting calcium hydroxide into cementitious compounds, making the concrete more durable and cost-effective.	The research concluded, that replacing coarse aggregates with the blast furnace slag and 10% of cement with metakaolin enhances the compressive and tensile strength of concrete, particularly up to a 30% replacement of slag. Beyond 30% replacement, the strength begins to decrease due to increased air voids. The use of these materials not only improves strength and durability but also reduces construction costs by utilizing industrial waste. The study confirms that metakaolin acts as a mineral admixture,

		converting calcium hydroxide into beneficial cementitious compounds.
(Desta & Jun, 2018)	The paper reviews the use of GGBS as a partial pozzolanic replacement for cement in concrete. GGBS enhances concrete properties at later ages, reducing environmental impact. The study highlights GGBS's cost-effectiveness and lower heat of hydration compared to OPC. Alkali Silica Reaction (ASR) is addressed, emphasizing the importance of mineral admixtures. The research indicates that GGBS improves resistance to chloride and sulfate.	This study showed that, GGBS cement reduces heat of hydration, lowering shrinkage cracking risk in high-temperature construction areas. Increased GGBS percentage enhances concrete's chloride and sulfate resistance. Compressive strength decreases initially with GGBS but increases at later ages. Workability improves with higher GGBS replacement levels, allowing lower water/binder ratios. GGBS significantly reduces concrete permeability compared to control mixes. Replacing cement with GGBS lowers construction costs due to its lower price. The use of GGBS contributes to environmental protection by reducing CO_2 emissions. The paper emphasizes GGBS's

		effectiveness as a supplementary pozzolanic material in concrete.
(Uday, 2017)	The paper investigates size-independent fracture energy (G_f) of concrete using experimental methods. A comparative analysis of three point bending test for measuring G_f is conducted, showing reasonable agreement in results. The study emphasizes the nonlinear behaviour of concrete through load vs deflection line responses across various notch to depth ratios. The research determines the G_f value of concrete and enhance to understand of concrete's failure mechanisms and load-bearing capacity.	The study showed the brittleness of concrete, as G_c and G_f values are not equal. The range of G_c is determined to be between 8 to 10 N/m. Also, the research investigates size-independent fracture energy (G_f) of concrete using experimental method of three-point bending of beams. G_f values are estimated through a developed relationship of the release rate of fracture energy. The load vs. displacement curve indicates strain hardening and softening, showing concrete's quasi-brittle nature. Again, the study provides insights into the mechanisms of failure and load-bearing ability of the concrete structures. RILEM fracture energy and stress intensity factor values are experimentally determined.

(Subathra Devi & Gnanavel, 2014)	The paper investigates the effect of steel slag as a substitute materials for aggregates in concrete's strength and durability properties. It finds that replacing aggregates with steel slag improves compressive, tensile, and flexural strength. The study also evaluates acid resistance, showing low mass loss in cubes after immersion in acids. Workability decreases as the percentage of steel slag replacement increases, determined through slump tests. The research highlights the viability of using steel slag in reinforced cement concrete applications.	The study found that partial replacement of aggregates with steel slag improves compressive, tensile, and flexural strength of concrete. Deflection in RCC beams increases with load, indicating enhanced resistance with steel slag replacement. Chloride ion penetration is low for conventional concrete and 40% fine aggregate replacement, indicating better durability. The mass loss in cubes after acid immersion was minimal, showing good acid resistance. Overall, the research confirms the durability of using steel industrial slag in concrete to improve strength and durability properties.
(Kaushal & Wani, 2022)	The paper addresses the increasing demand for sustainable development in the cement industry by reducing Portland cement usage. It emphasizes using blended cement and recyclable materials to lower construction costs and pollution. An experimental	The study found, cement concrete with good strength and workability using rice husk ash and steel fibers as partial replacements. Compressive strength, split tensile strength, and flexural

	program was conducted with various mixes of steel fibers and rice husk ash to evaluate physical properties. The study highlights the importance of alternative materials for enhancing concrete performance and sustainability.	strength were tested after 7 and 28 days. Sixteen concrete mixes were prepared with varying percentages of rice husk ash and steel fibers. The research aimed to enhance mechanical properties while reducing reliance on Portland cement. The findings support sustainable development by utilizing industrial by-products in concrete.
(Harsha, 2020)	The study investigates the effects of GGBS, silica fume, and steel slag on concrete strength and durability. It aims to enhance concrete properties while reducing cement usage and associated CO2 emissions. The research evaluates concrete characteristics with varying percentages of GGBS, silica fume, and steel slag replacements. The findings contribute to sustainable construction practices by utilizing waste materials in concrete production.	The study found that partial replacement of cement with Metakaolin improves concrete's pore structure and resistance to harmful solutions. GGBS, silica fume, and steel slag positively impact concrete strength, including compressive, tensile, and flexural strength. The research demonstrated that Metakaolin enhances early strength without compromising long-term strength. The investigation confirmed that curing specimens in acid tanks

		assesses concrete durability effectively. The study emphasizes the importance of using waste materials to reduce greenhouse gas emissions from cement production.
(Dineshkumar & Suchithra, 2018)	This study investigates, Steel slag, a by-product of steel manufacturing can replace fine aggregate in concrete, reducing the need for natural resources. The study found that steel slag can effectively replace up to 50% of fine aggregate without compromising concrete strength. Using steel slag in concrete enhances sustainability by minimizing environmental degradation and waste management issues. The maximum flexural strength increased by 4.65% and 2.8% at 7 and 28 days with 40% steel slag replacement. The split tensile strength also improved by 6.3% and 4.9% at 7 and 28 days with 40% steel slag replacement.	The study concluded, The durability of concrete remains similar when steel slag replaces fine aggregate. Addition of steel slag reduces construction costs compared to conventional concrete. Using steel slag mitigates production waste handling risks in industries. The optimal replacement percentage of steel slag is determined through strength tests. Maximum flexural strength at 40% steel slag replacement was 4.65% and 2.8% higher than conventional results. Maximum split tensile strength at 40% replacement was 6.3% and 4.9% higher than conventional results. Steel slag effectively replaces river sand,

		aiding in natural resource conservation.
(Coppola et al., 2016)	The paper discusses eco-sustainable concrete using EAF granulated slag as a partial replacement for natural aggregates at 15%. It highlights improved rheological, physical, and mechanical properties of concrete with slag aggregates. The study emphasizes the need for recycling industrial by-products for economic and environmental benefits. Limitations include higher density and sensitivity to cracks when using EAF granulated slag. The research suggests that slag aggregates can enhance low-cost bituminous mixes for roads.	The study found that EAF granulated slag can replace up to 15% of natural aggregates in concrete without compromising workability. Higher percentages of granulated slag improve density, elastic modulus, and compressive strength of concrete. However, increased slag content leads to higher dry shrinkage in concrete. The use of EAF granulated slag is limited by its higher density and sensitivity to cracking compared to natural aggregates. The research supports the eco-sustainable use of EAF granulated slag in concrete production, enhancing physical and mechanical properties.
(Rooholamini et al., 2019)	The paper investigates the use of steel slag in concrete, highlighting its mechanical properties and effects on strength. Different types of steel slag	The study found that incorporating coarse EAF slag enhances mechanical and fracture properties of concrete

	are identified based on cooling methods and production processes. Incorporating steel slag improves compressive strength and density of concrete mixtures. The study emphasizes the importance of aggregate properties on concrete workability and performance. Results indicate that coarse EAF slag enhances mechanical and fracture properties in Roller-Compacted Concrete.	mixtures. Higher content of coarse steel slag increases compressive strength, while fine slag reduces it. The rough texture of EAF slag improves interlocking and shear resistance in concrete. Concrete with steel slag showed higher compressive strength and slightly lower tensile strength compared to reference concrete. The workability of concrete mixtures was not adversely affected by the rough surface texture of EAF slag. Increased slag content led to decreased absorption and porosity, while ultrasound pulse velocity improved.
(Rubio-Cintas et al., 2019)	The paper evaluates the efficiency of waste treatment through leachate tests and chemical analysis. It discusses the advantages of using stabilization techniques for hazardous waste, particularly with metals. The introduction of Electric Arc Furnace (EAF) dust in concrete enhances compressive strength and maintains	This paper concluded, the introduction of EAF dust in concrete enhances compressive strength compared to traditional concrete mixtures. Ferritic fume dust can be used as a micro-filler in high-performance concrete. Concrete with ferritic fume

	leaching performance similar to traditional concrete. The study highlights the stabilization of contaminants like chromium in the cement matrix. Overall, the research emphasizes sustainable waste management practices in civil engineering applications.	dust shows superior mechanical resistance compared to conventional concrete. The leaching of heavy metals from concrete with ferritic fume dust is comparable to traditional concrete. Some contaminants, like chromium, are stabilized in the cement matrix. The study followed the UNE-EN 12920 standard for leaching tests. Recovery rates of metals from steel manufacturing waste are around 2%.
(Li et al., 2021)	The study evaluates the effects of steel fibers on the mechanical properties of geopolymer concrete. Geopolymer concrete is an innovative, sustainable alternative to ordinary cement concrete. Steel fibers enhance compressive, tensile, and flexural strengths of geopolymer concrete. Optimal steel fiber content is 2%, improving mechanical properties significantly. The research highlights the environmental benefits of using	The study found that, steel fibers significantly improved the mechanical properties of geopolymer concrete, including compressive, splitting tensile, and flexural strength. The optimal steel fiber content was determined to be 2.5%, yielding maximum splitting tensile strength of 3.69 MPa and flexural strength of 9.80 MPa. Increasing steel fiber content enhanced the

	geopolymer concrete over traditional cement concrete.	compressive elastic modulus, with a 47.7% increase at 2% fiber content. The addition of steel fibers improved fracture toughness, with initial fracture toughness increasing by 27.8% at 2.5% fiber content. The research indicates that steel fiber-reinforced geopolymer concrete outperforms plain geopolymer concrete under various mechanical loads.

2.13 Research gaps in this field:

Most of the papers are dealt with the mechanical properties of concrete such as compressive, split cylinder, tensile & flexural strength, etc. So, the current work will assess both mechanical & fracture properties of concrete for a certain strength of concrete mix combination by partial replacement of cement in the concrete using industrial waste. While steel industrial slag is becoming more popular as a partial cement substitute in concrete, there are still significant research gaps regarding how it affects the material's mechanical and fracture characteristics. Although some researches have shown increases in workability, durability, and compressive strength, nothing is known about the whole impact of steel slag on concrete's tensile, flexural, and fracture toughness.

Furthermore, the inconsistent performance of steel slag in various concrete mixes is a worry due to its variable chemical and mineralogical composition, which varies based on the source and processing techniques. Further investigation is required to gain a deeper understanding of the long-term durability characteristics, including how it affects crack propagation and resistance to environmental conditions such sulphate attack and freeze-thaw cycles.

It has also not been thoroughly examined how steel slag interacts with other common admixtures or other cementitious ingredients. Ultimately, further research is required to assess the economic and environmental sustainability of using steel slag in place of cement, particularly in large-scale applications, in order to determine whether it is a feasible substitute for conventional materials.

Based on the above mentioned gaps in research the objective of this current work has been picked.

CHAPTER 3: MATERIALS

3.1 General:

This chapter provides a detailed statement of the materials used in this investigation. Materials are essential to every engineering project's success. Because they offer the fundamental elements for structural stability, longevity, and functionality, choosing and using them is crucial to the success of a project. In addition to being a technical necessity, material knowledge influences performance, cost, and environmental sustainability as a strategic choice.

In this study, Portland composite cement (CEM II), stone chips, coarse sand, and water has been used as the ingredients of the concrete and industrial ladle slags, GGBS are used as the partial substitution of cement where additionally a percentage of fiber material has also used to enhance the concrete stability against flexural integrity and the resistance of crack propagation.

3.2 Materials used in this investigation:

Cement as a binder material, stone chips used as coarse aggregates, coarse sand used as fine aggregates, water used as a filler material. Industrial furnace ladle slag, GGBS, used as a partial substitute of cement in the concrete mix. Another percentage of fibers has been used to improve concrete’s fracture properties. For selecting the above ingredient’s proportion, coarse aggregate and fine aggregate materials properties is tested in the strength of materials lab of CUET prior to the carried out of concrete mix design.

3.2.1 Cement:

Cement which is generally acts as the binder materials in the mixture of concrete. It binds all the ingredients together after the processing of hardening. It also contribute as filler materials as well to fill the very fine voids in the concrete. Portland Composite Cement (CEM II) type has been used in the study. This CEM II conformed to BDS EN 197-1: 2003, strength class of this cement was used 42.5N.

Cement ingredients were Clinker: (65~79) %, Blast furnace slag, Fly ash, Limestone: (21~35) %, Gypsum: (0~5) %.

Figure 3.1: Physical appearance of CEM II used in the experimental works

3.2.2 Fine aggregates:

The portion of aggregates which are passing through 4.75 mm (No. 4) sieve and typically retained on the 75 μm (No. 200) sieve is called fine aggregate conforming as per ASTM C33. Natural river sand was used as fine aggregates and it was sourcing from the Sylhet. Unit weight, Absorption capacity, Moisture content, Specific gravity, Fineness modulus tests is conducted to determine its properties for doing mix design for the investigation. The physical properties of fine aggregates used in this experiment are given in Table 3.1. Figure 3.2 shows the fine aggregates used in this study.

Figure 3.2: Physical appearance of fine aggregates used in the experimental works

Table 3.1: Physical properties of fine aggregates

SL	Name of the Properties	Values	Units
1	Fineness Modulus	2.51	-
2	Unit Weight	1659.92	kg/m^3
3	Absorption Capacity	2.04	%
4	Moisture Content	2.66	%
5	Specific Gravity	2.60	-

3.2.3 Coarse aggregate:

Coarse aggregates are a major component in concrete compositions. They are big particles that typically measure more than 4.75 mm and maximum 25 mm conforming as per ASTM C33.These aggregates are typically formed of crushing stone, gravels, or recycled concrete. Coarse aggregates provide strength and stability to the concrete mixture by dispersing the weight and increasing durability. In concrete mixes, coarse aggregates are mixed with fine aggregates such as sand, cement, and water to create a cohesive material that may be shaped and hardened into a variety of buildings. The percentage of coarse particles in a concrete mix influences its strength, workability, and other characteristics. Various types and sizes of coarse aggregates can be employed based on the requirements. In this study, crushed stone chips typically named “stone chips” is used which was sourcing also from the Sylhet. The sizes of coarse aggregates were used 10mm,12.5mm and 20mm down for making well or dense graded concrete. Unit weight, Absorption capacity, Moisture content, Specific gravity tests is conducted to determine its properties for doing mix design for the investigation. The physical properties of coarse aggregates used in this experiment are given in Table 3.2. Figure 3.3 shows the coarse aggregate used in this study.

20 mm 12.5 mm 10 mm

Figure 3.3: Various sizes of coarse aggregates were used in this study

Table 3.2: Physical properties of coarse aggregates

SL	Name of Properties	Values	Units
1	Unit Weight	1618.15	kg/m^3
2	Absorption Capacity	0.89	%
3	Moisture Content	0.88	%
4	Specific Gravity	2.77	-

3.2.4 Ground Granulated Blast Furnace Slag (GGBS)

It is a byproduct of the iron-making industry that results from fast quenching molten blast furnace slag with water, drying, and grinding it into a fine powder. GGBS is widely utilized as a supplemental cementitious ingredient in concrete manufacturing. When used with Portland or blended cement, GGBS can improve workability, durability and of course the strength of concrete while lowering its environmental effect. The use of GGBS in high-performance concrete improves durability but have the challenges due to its excessive fineness and high water demand when mixed with Ordinary Portland Cement (Balakumari & Sumangala, 2023). It is widely utilized in applications that require great performance and sustainability, in the modern-day constructions. In this study, Fine powder GGBS is used as a partial replacement of cement in the concrete mix. Above materials is collected from CUET lab. Figure 3.4 shows the GGBS.

Figure 3.4: Fine power of GGBS were used in this study

3.2.5 Steel slag:

Steel industrial slag, which is solid waste from the steel production classified by steel type into stainless steel slag, carbon steel slag and by process into ladle refining slag (LFS), pretreatment slag, basic oxygen furnace slag (BOFS), electric arc furnace slag (EAFS), and casting residue (Yi et al., 2012). Again, Industrial induction furnace slag is a byproduct produced in induction furnaces while producing metals, most commonly steel. Induction furnaces are widely used in the metallurgical industry to melt and refine metals. It is often contains of oxides such as magnesium oxide (MgO), calcium oxide (CaO), silica (SiO_2), alumina (Al_2O_3) and other compounds, depending on the raw materials and additives employed in the melting process. This slag can be recycled and used in the different applications, including construction materials, road foundation aggregate, and cement manufacturing, helping to save resources and reduce waste in the metallurgical industry. In this study, Fine powder of industrial furnace slag is used as a partial replacement of cement in the concrete mix. Above materials is collected from a steel plant owned by a local company named "Bangladesh Steel Re-Rolling Mills (BSRM)", Mirsharai Unit. Figure 3.5 shows the fine power of steel ladle slag were used in this study.

Figure 3.5: Fine power of steel ladle slag was used in this study

3.2.6 Fiber:

Polypropylene Fiber Reinforced Concrete is a fundamental construction material which can be said as a concrete which having high mechanical strength, stiffness and durability (Madhavi et al., 2014). The use of fibers helps to prevent cracking, reduce plastic shrinkage, boost impact resistance, and improve the concrete's mechanical property. Fibers used in concrete to compounds that improve its durability, hardness, crack resistance, and other qualities. These fibers are commonly formed of synthetic polymers, steel, glass, natural fibers, or a mix of these components. In this study, Polypropylene fibers are used. This fibers, also called polypropene or PP, is a lightweight synthetic fiber that was used as an additive for reinforcing and crack resisting. According to manufacturers, the materials can improve mechanical strength, resistant to high temperature and corrosion, and easy to use. It can be directly added to the dry materials and mixed thoroughly for a while before the addition of water. In this study, polypropylene fiber of various percentages (0.05%, 0.10%) was added in concrete in terms of it's volume. Figure 3.6 shows polypropylene fiber used in this study. Properties of the fiber are given in Table 3.3. It is purchased from the local market.

Figure 3.6: Physical appearance of polypropylene fiber

Table 3.3: Typical properties of the PP fibers used in this study (CONMIX, 2020)

Colour	White
Formation/Structures	Polyester
Lengths (mm)	12.0
Diameters (μm)	20.0 ± 5.0
Aspects ratio (l/d)	300.0
Density (g/cm3)	1.360–1.380
Specific Gravity (gr.)	0.920 ± 0.020
Elongation at break (%)	25.0
Tensile strength (MPa)	650.0
Types of the fiber	Monofilament
Recommended adding amount quantities	0.20–0.30% of mixes

3.2.7 Water:

The quality of water is very essential in the mixture of concrete, as impurities can deal with cement setting and reduce strength and quality of concrete. Chemical constituents in water may interact with cement, affecting the parameter of concrete like, the setting time, hardening, and strength of concrete (Kucche et al., 2015). Also, too less or too much quantity of water can adversely affect the mix. Using of too less water can make the honeycomb into the concrete by creating voids among the concrete ingredients. On the other hands, though too much water can increase workability but it is responsible to reduce concrete strength as well. Therefore, it is necessary to use optimum amount of water in the concrete mix in terms of all considerations. In this study, potable water was used for mixing and curing. It was free from the suspended solids and organic materials, which might have affected the fresh and hardened concrete properties. The value of P^H of used water was about 6.5 to 7.5. Figure 3.7 shows the physical appearance of potable water used in this study.

Figure 3.7: Physical appearance of potable water used in this study

CHAPTER 4: EXPERIMENTAL INVESTIGATIONS

4.1 General:

This chapter outlines the major components of experimental research in the specimen taken, emphasizing the significance of good experimental design, specimen preparation, testing techniques, and data analysis. Explained the standard experimental techniques such compressive strength testing, flexural testing and fracture analysis methods. All the experimental data has been analyzed carefully and subsequent comparison has been made with theoretical and experimental results.

4.2 Research outline:

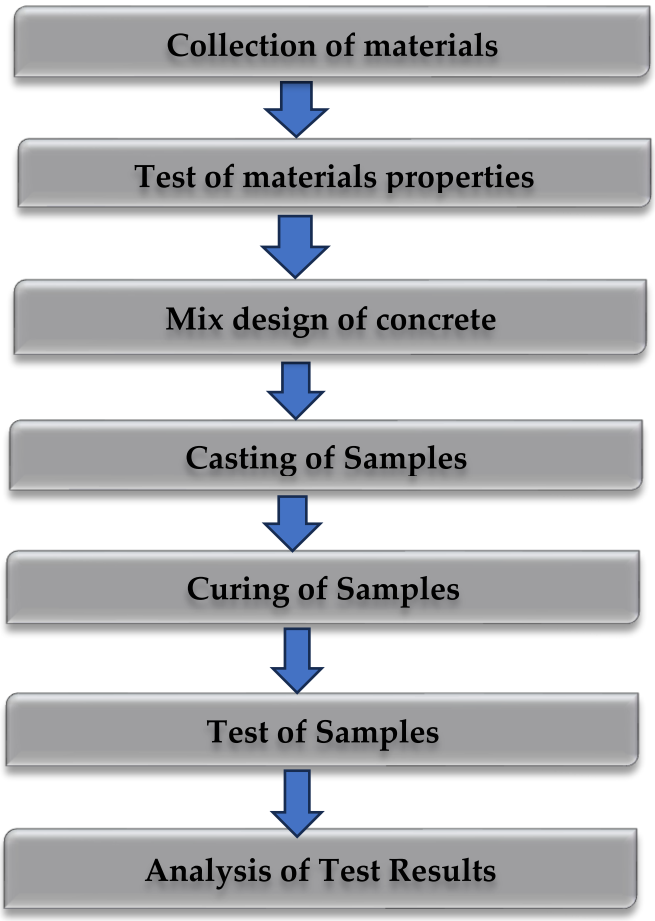

Figure 4.1: Flowchart of the research

4.3 ACI 211. 1 mix design of concrete:

The mix design of concrete is a globally standardized practice that has produced significantly in the recent years. More than that, traditional concrete improvements have led to self-compacting concrete, high-performance concrete, and reactive powder concrete. (Chandrakar & Mishra, 2012). ACI 211. 1 is a systemic approach to preparing a concrete mixture and, as a result, it assures the quality of concrete and consistency from one batch to another. It is founded on a great deal of research and factual data, and therefore, it can dependably forecast the performance of the concrete mixes under different conditions and uses. Hence, it is possible to change the proportions of the mix according to the specific requirements such as strength, durability, workability, and other performance parameters. It can also be modified to different materials, construction techniques and project specifications, therefore, it is suitable for a variety of applications and conditions. These are the reasons that this mix design was chosen for this study.

At first it is required to determine of the material properties like, the fineness modulus of coarse sand, dry rodded unit weight of coarse aggregates, specific gravity of coarse & fine aggregates, absorption & free moisture content of coarse & fine aggregates, specific gravity of cement and maximum size of coarse aggregates etc. Then need to set the target strength of concrete and the slump value of fresh concrete. Once the target strength is set, it is also required to determine of the target mean strength by the formula provided by ACI. From the slump value water-cement ratio can be determined as later on it is also can be calculated the cement content. After that, volume of coarse aggregate is determined. From above, can be identified the density of fresh concrete. And from density of fresh concrete, volume of fine aggregates can be estimated initially. Using absolute volume method quantity of aggregates can be calculated. Then need to require the adjustment in the fields condition by the moisture content of the saturated surface dry (SSD) condition. After that, final ingredients of the concrete can be found. And finally based on concrete ingredients total density of fresh concrete can also be determined.

4.4 Concrete mix design for this study:

A concrete mix design is done to attain concrete compressive strength. From all the mix design methods, ACI 211.1 mix design is followed in this study.

Design Data,
Target strength of Concrete (f'_c) = 30 MPa at 28 days
Specific gravity of coarse aggregates = 2.77
Specific gravity of fine aggregates = 2.60
Unit weight of coarse aggregates = 1688.15 kg/m^3
Unit weight of fine aggregates = 1659.92 kg/m^3
Max. size of coarse aggregates =20mm
Slump Values = 50mm
Absorption capacity of coarse aggregates =0.89
Absorption capacity of fine aggregates = 2.04
Moisture content of coarse aggregates = 0.88
Moisture content of fine aggregates = 2.66
Fineness modulus of fine aggregates =2.51

Step-1 : Determination of target mean strength,

(Specified design strength, f'c=30MPa,
KS value is taken =8.5 as per ACI)

$$f_m = f'_c + KS$$
$$= 30+8.5$$
$$= 38.5 \text{ MPa}$$

Step-2 : Determination of water-cement(w/c) ratio,

(Specified design strength, f'c=30MPa,
W/C ratio is taken =0.40 as per ACI,
Non-air entrained concrete)

w/c = 0.40

Step-3 : Determination of cement content ,

(For the slump value 30-50mm, and Avg. Aggregates sizes, =20mm, Water content is taken=185 kg as per ACI)

$$\text{Cement} = \frac{Water}{W/C}$$

$= \frac{185}{0.40} = 462.5$ Kg,

Step-4 : Determination of volume of coarse aggregates,

(Max. Aggregates sizes=20mm, F.M=2.51, Interpolation value of Coarse Aggregates is taken=0.65 as per ACI)

Volume of coarse aggregates = 0.65
Weight of coarse aggregates = 0.65*1688.15= 1097.30 kg/m^3

Step-5 : Determination of density of fresh concrete,

(Max. Aggregates sizes=20mm, and Non-Air entrained concrete, Volume of first estimated density of fresh concrete is taken=2355 kg/m^3 as per ACI)

Hence, Max size of coarse aggregates=20mm, So density of fresh concrete =2355 kg/m^3

Step-6 : Determination of fine aggregates (Primarily),

Cement=462.5 kg/m^3

Water= 185 kg/m^3

Coarse Aggregates= 1097.30 kg/m^3

Hence, fine aggregates = 2355- (Cement + Water+ Coarse Aggregates)

= 2355- (462.5+185+1097.30)

= 610.20 kg/m^3

Step-7 : Determination of ingredients by absolute volume method,

(For the slump value 30-50mm, water content=185 kg/m^3, entrapped air=2% as per ACI)

Table 4.1: Concrete ingredients by absolute volume method

Ingredients	**Absolute Volume**
Cement	$\frac{462.5}{3.15*100}$=0.147 m^3
Coarse Aggregates	$\frac{1097.30}{2.77*1000}$=0.396 m^3
Water	$\frac{185}{1.00*1000}$=0.1850 m^3
entrapped air (2%)	$\frac{2}{100}$=0.0200 m^3

So, Absolute volume of the fine aggregates =1-(0.147+0.185+0.396+0.02)=0.252 m^3

Hence, the weight of fine aggregates = 0.252*2.60*1000=655.20 kg/m^3

Step-8 : Adjustment in field condition (The mix properties)

2.66 % moisture content found in fine aggregates (free moisture),

So, fine aggregates = $\frac{2.66}{100}$*655.20 = 17.43 Kg/m^3

Hence, Total weight of fine aggregates after adjustment = 655.20 + 17.43 = 672.63 kg/m^3

0.89% of water absorption by coarse aggregates = $\frac{0.89}{100}$ *1097.30 = 9.77 kg/m^3

Hence, weight of coarse aggregates after adjustment = (1097.30 - 9.77) = 1087.53 kg/m^3

Again, We see water contributed by aggregates =(17.43-9.77) = 7.66 kg/m^3

So, Total weight of water after adjustment = (185-7.66) = 177.34 kg/m^3

Step-9 : Final ingredients of concrete :

a) Cement = 462.5 Kg/m^3 , Say 463 kg/m^3
b) Coarse aggregates = 1087.53 kg/m^3
c) Fine aggregates = 672.63 kg/m^3
d) Water = 177.34 kg/m^3

Step-10 : Total density of fresh concrete :

Table 4.2: Total density of fresh concrete

Ingredients	**Quantity (kg/m^3)**
Cement	463
Coarse Aggregates	1087.53
Fine Aggregates	672.63
Water	177.34
Total	**2400**

Step-11: Final selected ingredients for the concrete mix:

Table 4.3: Final selected ingredients for the concrete mix

Ingredients	Quantity (kg/m^3)
Cement	470
Coarse Aggregates as Stone Chips	1085
Fine Aggregates as Sylhet Sand	675
Water	177.34

4.5 Methodology:

4.5.1 Detailing of concrete samples:

Samples of cubes and beams are used to evaluate the flexural, fracture and the compressive strengths of concrete. Beam samples are two types, one is plain and another is notch which is provided in the centre to carried out three point bending test for the analysis of flexure and fracture properties of concrete. Compressive strength test is carried out on cube samples to determine the concrete's capacity to support axial loads. In this study, two types of concrete samples are taken such as beam and cube as standard followed by ASTM. The sizes of beam and cube samples are respectively 500mmX100mmX100mm and 150mmX150mmX150mm. Beam samples are taken as per RILEM standard for the fracture and flexure analysis. Total 30nos cube samples are taken to carried out compressive strength test at the age of seven and twenty days from each mix combination respectively. On the other hand, 10nos notch beam (sign of pre-crack) samples are taken to perform three point bending test for fracture analysis at the age of twenty eight days from each mix combination respectively. Notch is provided at the centre of beams with 40mm depth and 5mm thick. Hence, two samples are taken from each mix combination for the fracture analysis. Again, more 5nos plain beam samples are taken to carried out three point bending test for the flexure analysis. Single sample is taken from each mix combination for the flexure test respectively.

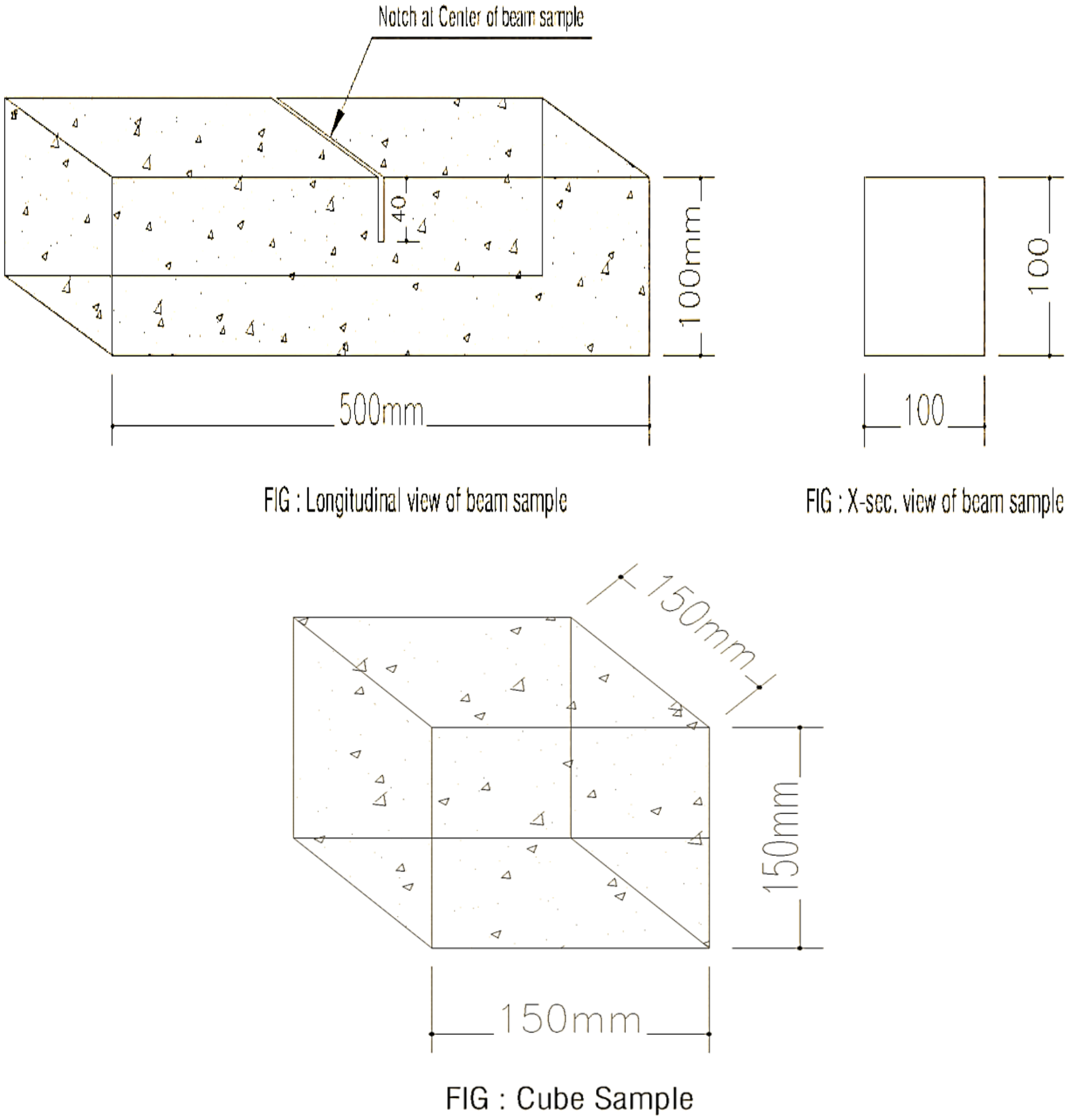

Figure 4.2: Isometric views of the samples using in the investigation

4.5.2 Samples preparation:

After completing of mix design, investigation samples are to be made. Selected five mixing combinations has been made according to the percentage of concrete ingredients used in the mix as per partial replacement of cement. Percentage of concrete ingredients has been given in details in the below table for all the mix combination.

Table 4.4: Proportion of mix combination

SL	Name of Mix	Cement %	Ladle slag %	GGBS %	Fiber %	Remarks
1	M-1	100	0	0	0	
2	M-2	90	10	0	0	
3	M-3	60	10	30	0	
4	M-4	60	10	30	0.05	Fiber quantity is used % of concrete volume.
5	M-5	60	10	30	0.10	Fiber quantity is used % of concrete volume.

4.5.3 Sample casting:

After being made all preparation, the above-mentioned samples are cast as shown in figure 4.1 and 4.2 in the laboratory. Before sample casting all beam and cube molds has been prepared. Firstly, ensured all the moulds are clean such as free from dust, debris, or old concrete residues. After that has checked for cracks, deformations, or loose fittings in the concrete moulds. Then, release agent has been applied in to the inside of the moulds to prevent sticking. Shutter oil has been used as release agent. Again, aligned and fasten mould sides properly before assemble mould components tightly for accurate dimensions and securing tightening of the screws/clamps to prevent leakage as well. Therefore, all the mould’s dimensions have checked to secure the sizes of the samples. Hence, needed to place the moulds on a stable, level, vibration-resistant surface before starting of sample casting.

At first, as per mix design all the ingredients have been measured individually and kept in a place. Before adding water on it, it is thoroughly mixed up so that all the ingredients are uniformly mixed with each other. Then optimum amount of water has been added according to the water cement ratio in the mix. After mixing all the ingredients, slump value has been measured for the fresh concrete. Fresh concrete has been placed into the sampling moulds which is prepared previously for the sample casting. Necessary blows have been given in layer by layer during sample casting to ensure empty voids into the samples. Once concrete placing has been done into the specific moulds then it is kept for 24 hours for the hardened in a shape. Moulds has been removed once concrete samples gets hardened and submerged into the tank for the curing.

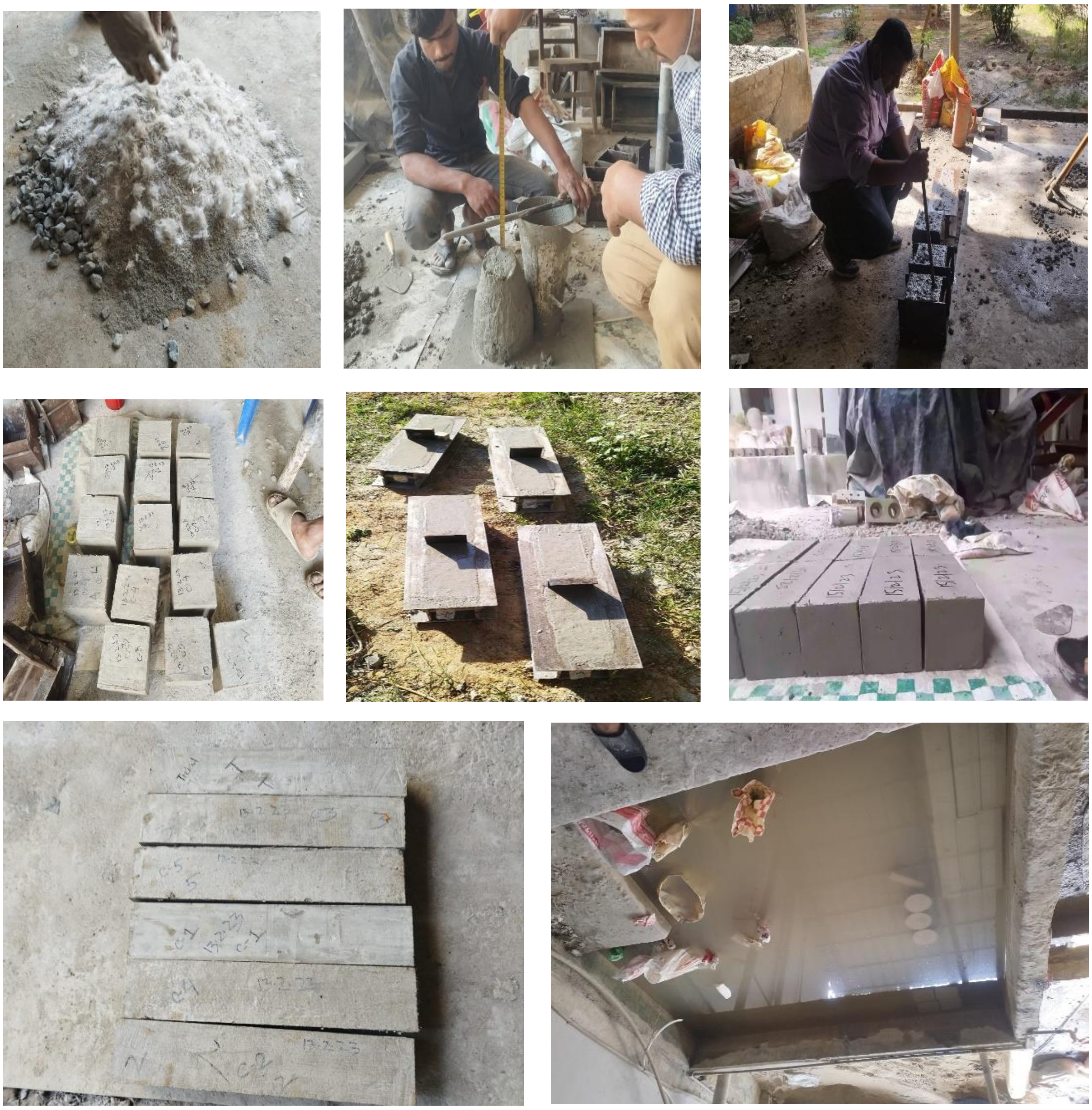

Figure 4.3: Pictorial views of the sample casting and curing works

4.6 Compressive strength of concrete:

The compressive strength test is the most common concrete test due to its simplicity and cost-effectiveness in the world. (del Viso et al., 2008). It has the characteristic of being able to bear the axial loads or pressures that lead to its compression. It is one of the major components of concrete and the standard testing methods are used to determine its value. It is a vital element in the process of the establishment of the structure's strength and the load-bearing ability of concrete constructions. It assures that concrete can withstand the loads and stresses that are applied to it during service conditions without failing or collapsing. Compressive strength testing is the quality control for concrete manufacturing and construction, and it is a must. Engineers can check that concrete has attained the design requirements and the technical specifications by assessing its compressive strength. Compressive strength data is used to confirm the good fit of concrete mix designs and to alter the proportions of the constituents such as cement, aggregates, water, and admixtures. It assists engineers to discover the proper mix proportions thus to achieve the required strength and performance goals. The relationship between the durability of the concrete and the resistance of the environment to the factors of freeze-thaw cycles, chemical attack, and abrasion is what it is. Compressive strength leads to the durability. The compressive strength of concrete is the main factor which determines whether the structures and the people are safe or not. It helps in the prevention of the structural failures and the dangers that might be caused by the not enough strength. The compressive strength of concrete in general is a factor that affects the design, construction, and performance of concrete structures. Engineers can ensure that the concrete infrastructure is safe, durable, and reliable by exactly measuring and controlling the compressive strength. The compressive strength of concrete is determined by the compressive strength test which is a particular testing procedure that is standardized.

The test that measures the compressive strength in this way is the one that was carried out in this program.

4.6.1 Specimen preparation:

The rounded or cubed concrete specimens are made from a sample of the concrete that is under the test and that is a good representative. The samples are produced in moulds in accordance with the dimensions mentioned in the standards (for instance, ASTM or BS). The samples are tapped properly to get rid of the air pockets and to maintain the same density.

4.6.2 Curing:

On completion of the moulding, the samples are put under controlled state to facilitate the hydration and creation of the strength. Moisture curing, which is done by immersion in water or wrapping with wet burlap, and steam curing are the two most frequent curing processes, which are used according to the testing requirements and the regulations.

4.6.3 Testing setup:

After the curing stage, the specimens are put on the platen of the testing machine to make sure the alignment and the even loading are done. The loading surfaces are normally designed to have a strong contact and to prevent the sliding during the testing.

4.6.4 Loading application:

The increasing axial compressive load is applied to the specimen in a gradual manner at a certain rate, which is usually the same as the testing standard. The force is exerted on the specimen until the moment it breaks which usually takes place by crushing or fracture.

4.6.5 Load and deformation measurements:

In the test, the load and deformation of the specimen are always monitored and the recording of the load cells and the displacement measuring instruments is done. Hence, the researcher can watch the specimen behaviours while the load is being increased.

4.6.6 Failure mode observations:

The test is continued until the specimen gets crushed, and the kind of failure (crushing, splitting or shear) is noted and reported. The resulting data can be used in studying the behaviour and performance of the concrete.

4.6.7 Compressive strength calculation:

The compressive strength of the concrete specimen is the highest load for which it can withstand before it breaks, and the cross-sectional area of the sample is the area of the surface of the specimen. Compressive strength is usually presented as the load per unit area. Shown in below at equation (4.1)

Compressive strength, $\sigma = \frac{P}{A}$ ………………………………………………………(4.1)

Where, σ= Compressive strength in MPa (For SI unit)

P= Highest load carrying capacity by the specimen, in Newton

A= In contact average surface area with the machine plunger, in mm^2

4.6.8 Reporting:

The tests of the compressive strength, which are the highest load, the failure mode, and the calculated compressive strength, are done and reported in conformity with the testing standard. Figure 4.4 Showing the compressive strength setup and testing procedure,

Figure 4.4: Compressive strength test setup in the lab

4.7 Flexural strength (modulus of rupture) of concrete:

Flexural strength of concrete, which is also known as the modulus of rupture, is the maximum tensile stress that a reinforced concrete beam or slab can resist before it breaks under bending. It is one of the main features of concrete especially the ones which are to be incorporated in the structural parts and are subjected to bending or flexural loads. It is widely recognized that cement-based materials exhibit higher flexural strength compared to their uniaxial tensile strength. (Maalej & Li, 1994). It is a crucial factor when one is calculating the bending stress on concrete beams, slabs and other structural parts which are subject to bending stresses. Flexural strength tests are done to understand the performance of structural elements under applied loads, without significant deformation or failure. The concrete flexural strength performs the critical function of structural safety and stability against bending. It keeps the structural integrity that can lead to collapse or people safety challenges. Moreover, concretes can impact the serviceability and performance of the components for their entire lifetime. It helps to coordinate the deflections, the cracks and other forms of deformation that may lead to the damage of the structure's functionality and attractiveness. The flexural strength testing remains an integral quality control process in concrete manufacture and construction. This can be understood as a measure to ensure that the concrete is in agreement with the design requirements and the standard by bearing the flexural strength test. The data offered by it is also employed to improve concrete mix designs by the adjustment of the quantities of the main constituents which are the cement, aggregates, water, and admixtures. The possibility of modifying the concrete mix to get the right strength and performance properties is provided. Furthermore, it also connects to the concrete's durability that is the ability of a concrete to withstand cracking and deformation under pressure. It suggests a higher level of resistance to injury and fatigue caused by bending and bending-induced fatigue.

The flexural strength of concrete is usually examined by the standard testing process referred to as the flexural or beam test.
The procedure of the test is as described below:

4.7.1 Specimen preparation:

At the start, the cylindrical or prismatic concrete specimens are made from a typical sample of the concrete that is under test. These samples are beams or prisms of certain dimensions which are provided by the standard (such as ASTM or BS).

4.7.2 Curing:

The specimens are cured in a wet environment with regulated temperature for a given period of time, which ensures the correct hydration and the strength development.

4.7.3 Testing setup:

The specimens are put on supports of a testing machine after the curing. The loading points are usually set at a certain distance apart, and this distance varies with the size of the specimen.

4.7.4 Load application:

An unevenly increasing load is placed at the midspan of the specimen at a specific rate which usually is in accordance with the testing standard. The load is kept on until the specimen breaks, usually by way of cracking or fracture.

4.7.5 Deflection measurements:

In the test, the middle span deflection of the specimen is always measured by the help of the suitable displacement measuring instruments. Therefore, you can observe the specimen's behaviour while the load is rising.

4.7.6 Failure mode observation:

The test is repeated until the specimen breaks, and the kind of the failure (cracking, crushing, or both) is noted and regulated. This data will be a tool to understand the behaviour and the performance of the concrete.

4.7.7 Calculation of flexural strength:

The flexural strength of the concrete specimen is then determined by the maximum load it can carry before it breaks and the dimensions of the specimen. Flexural strength is often defined by the force per unit area, pounds per square inch or megapascal.

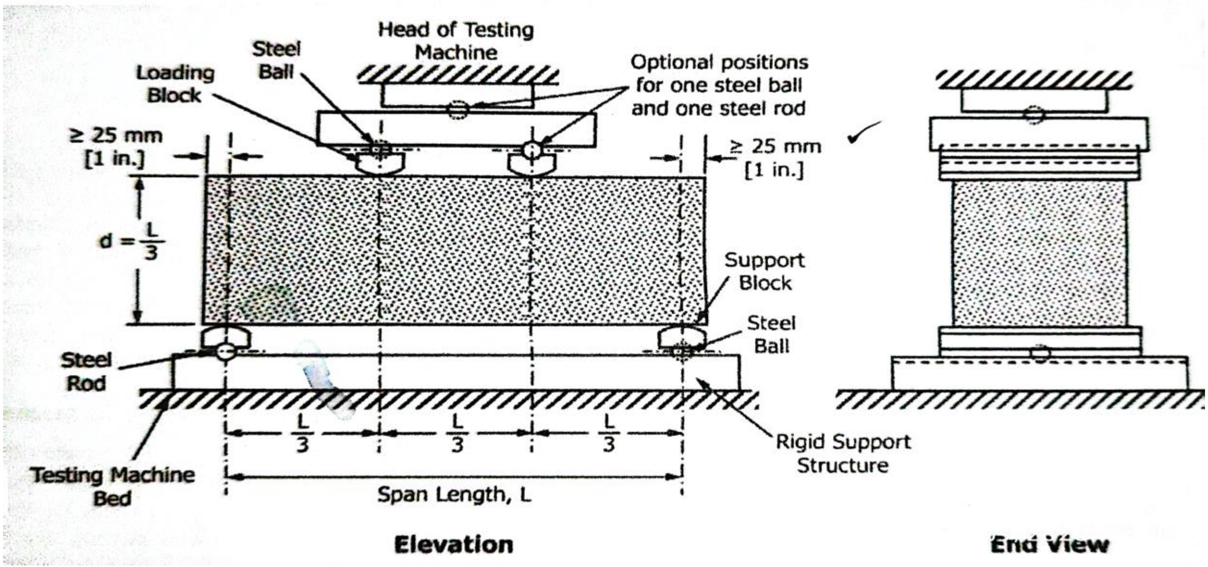

Figure 4.5: Schematic diagram of the three-point bending test for the determination of MOR

In Figure 4.5, a typical testing apparatus is shown for the determination of MOR of concrete. Which is basically known as three-point bending test.

According to **ASTM** if the fracture occurs in the tension surface within the middle third of the span length, then modulus of rupture will be calculated by the following equation at (4.2):

$$R= \frac{PL}{bd^2} \qquad (4.2)$$

Where **"R"** indicates Modulus of rupture, MOR in **MPa** of the concrete. **"P"** is the maximum applied load indicated by the testing machines in **N**. "**L"** is the length of the span in, **mm.** **"b"** is the average width of the specimen in, **mm** at the fracture area. And **"d"** is the average depth of the specimen in, **mm** at the fracture area also.

Again, if the fracture initiates in the tension surface outside of the middle third of the span length by not more than 5% of the span length, then modulus of rupture will be calculated by the following equation at (4.3):

$$R=\frac{3Pa}{bd^2}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.3)$$

Where, **"a"** is the avg. distance in-between line of fracture and the nearest support measured on the tension surface of the beam, in **mm.** Other factors will be as like as equation in (3.1).

4.7.8 Reporting:

The results of the flexural strength test, for instance, the maximum load, the deflection at failure, and the failure mode are documented and submitted according to the testing standard.

Figure 4.6: Test of Flexural strength of beam in the lab

4.8 Fracture energy of concrete:

Concrete fracture energy is the energy that the material uses when the crack or fracture propagates. It rates the concrete's capability to absorb the energy and to avoid the cracking when it is subjected to the tensile or bending loads. It is one of the most important factors in the testing of the strength and durability of concrete structures. The true specific fracture energy of concrete (G_f) is the most significant material parameter for analyzing cracked concrete structure. (Karihaloo et al., 2003). A higher fracture energy means that the material is more able to stand against the cracking and can endure dynamic loading, impact, and other types of mechanical stress without dropping catastrophically. Concrete is a material that is brittle in nature with no foreseeing when a tensile force is applied that is bigger than its limit. Despite this, the fracture energy measurement allows one to find out the material's resistance to crack initiation and thus to determine its suitability. The RILEM method is a method that tests the fracture energy of concrete, the energy that is needed to make a crack or a fracture in the concrete specimen. Fracture energy is the primary parameter for the calculation of the ductility and toughness of the concrete, more specifically under the tensile or bending forces.

4.8.1 Specimen preparation:

The practical specimens in prisms or beams should be made according to the standard of measurement and dimensions.

4.8.2 Notch creation:

Need to create a crack or a notch at the centre of the specimen to initiate the crack propagation during the test. A saw or related tool is generally used to make the notch.

4.8.3 Testing setup:

The specimen has to be placed inside a load-controlled testing instrument to measure the crack mouth opening displacement (CMOD). The various parts of the test equipment which consist of loading fixtures, displacement sensors, and a loading frame are usually the test equipment components.

4.8.4 Loading:

Gradually, increase the specimen's load to produce the crack initiation from the notch. The force can be given in the ways of tension, compression, or bending.

4.8.5 Record load displacement data:

The records of the load displacement data collected through the test are registered. This data is employed to make load-displacement curves that are the indication of the connection between the applied loading and the crack opening displacement.

4.8.6 Calculation of fracture energy:

The method of numerical integration is employed to determine the fracture energy of the concrete specimen by the area under the load-displacement curve. The energy absorbed by the concrete in the crack propagation is the fracture energy which is usually expressed in units of energy per unit.

4.8.7 Reporting:

The fracture energy test results, for example, the estimated value, testing parameters, specimen data and any major findings should be demonstrated. It can look at the toughness, durability, and fracture behaviours of concrete using the RILEM method, which is vital for the evaluation of its use in structural applications that are subject to tensile or bending stresses.

Figure 4.7: Test of fracture energy by Digital UTM

4.9 Necessary equations or empirical formula to calculate Fracture energy (G_f) , Fracture toughness (k_{ic}).

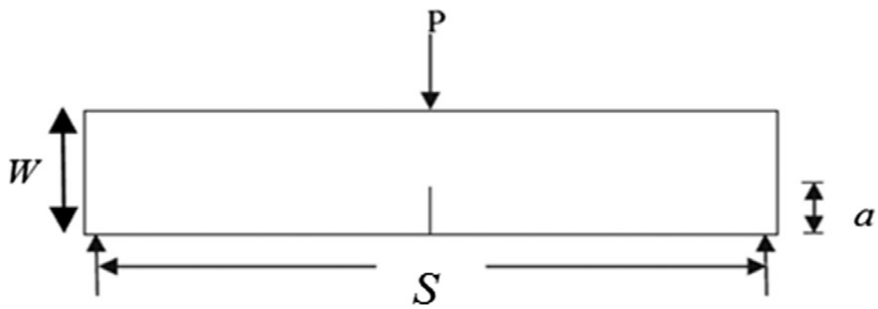

Figure 4.8: Schematic diagram of the three-point bending test

As per RILEM recommendations, fracture energy is calculated by dividing the total applied energy by the projected ligament area.

Here, **"S"** is the length of span and "**W"** is the depth of specimen. "**P"** is the applied load where "**a"** is denoted depth of notch which is centre of the specimen. **In figure 4.8,** here is shown the schematic diagram of a three-point bending test which is performed during fracture toughness test of concrete by the notch-beam samples.

So, from the definition, Fracture energy can be defined as below equation at (4.4),

$Gf\,(\alpha, W) = \frac{1}{(W-a)*B} \int P\, d\partial$…………………………………………………...(4.4)

Where, $\boldsymbol{\alpha}$ is the ratio of notch & specimen ratio's that is $\frac{\boldsymbol{a}}{\boldsymbol{W}}$

Fracture energy can be estimated in various way such as can be used like equation (1) in above, Again From the byzant model, it can be also derived as below equation at (4.5),

$Gf = 2.5\, \alpha_0 \left(\frac{f_c}{0.058}\right)^{0.40} \left(1 + \frac{D_{max}}{1.94}\right)^{0.43} \left(\frac{W}{C}\right)^{-0.18}$……………………………………(4.5)

Where, $\boldsymbol{\alpha_0}$ is the aggregate shape factor, $\boldsymbol{fc}$ denoted concrete compressive strength in 28 days, with α_0 =1 for rounded shape aggregate and α_0 =1.12 for angular shape aggregates. Dmax representing that the max. aggregate size. And $(\frac{W}{C})$ is the water-cement ratio of concrete. Fracture toughness is a measure of a materials ability to resist an unstable fracture or crack. There are different methods and standards to estimate the fracture toughness,

From Srawley and Gross, at the below equation (4.6),

$$\mathbf{K}_{IC} = \frac{PL\sqrt{a}}{BW^2}\frac{3}{2(1-\frac{a}{W})^{1.5}}Y \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.6)$$

Where, $Y = 1.989 - 1.33\frac{a}{W} - \frac{\left[3.49 - .0.68\frac{a}{W} + 1.35\frac{a}{W}^2\right]\frac{a}{W}(1-\frac{a}{W})}{(1+\frac{a}{W})^2}$

Where, $\mathbf{K}_{IC}$ (MPa . $\sqrt{m}$) is the fracture toughness, "**P**" is the maximum load in, (N). **"L"** is the length of the span of beam in, mm. And "B**"** is the width of the beam in, mm, **"a"** is the depth of notch in, mm, "**W"** is the depth of the beam in, mm also.

In conclusion, this chapter summarizes the testing methods used for this study and the various numerical approaches for determining different quantities to define properties. The results help to understand how materials behave under certain conditions. These findings are important for further study and practical use supporting the goals of the research.

CHAPTER 5: RESULT AND DISCUSSIONS

5.1 General:

The research results obtained through experiments, surveys, data analysis, and other research methods are presented in this chapter. This also includes tables, figures, charts, graphs, and analyses of the data that was collected. After the results are presented, the chapter provides a detailed interpretation and analysis of the findings, discussing any patterns or trends that were observed, explaining the significance of the results, and offering insights into the implications of the findings for the research topic or field of study. The chapter also discusses the limitations of the study, including any restrictions, prejudices, or uncertainties that might have affected the findings. The chapter shows the compressive strength, flexural strength results for the different mix combination of concrete at different ages with corresponding graphs and charts. The chapter also shows the fracture test results of concrete with load vs displacement curve for obtaining fracture toughness, Stress intensity factor, and energy release rate for crack propagation in the concrete. Experimental and empirical comparison of the test results has also been made.

5.2 Compressive strength:

Figure 5.1 represents the compressive strength of all five mixes for the age of 7 days and 28 days. It is seen from the figure that; concrete strength is gradually decreasing with the change of mixing combination. The highest strength is achieved for the mix ID M-1 with 100% of cement content. However, the goal of this work is to find the best quality with replacement.

it is seen that; concrete strength decreases with the change of mixing combination. Though all the concrete mixes achieved its target strength, but the highest strength is found for the mix combination of M-1 where 100% cement quantity is used. From the compressive strength analysis, it is found that for a

10% cement replaced with ladle slag, the strength decreases to 4 % and 16% respectively for 7 days and 28 days. As the cement content decreases more 30% and replaced with GGBS, the compressive strength is decreased by around 18% and 22% & for 7 days and 28 days respectively. It implies that the decrease in cement is slightly compensated by replacing it with GGBS. In comparison between sample M-2 and M-3, though the total cement content is decreased by 30 % the strength decrease is only 16% and 9% than M-2 for 7 days and 28 days respectively. So, it is obvious that the GGBS helps improving the strength. For sample M-4 which is similar to M-3 with only difference being the addition of 0.05% fibre the strength is not increased for 7 days however the 28 days strength is higher than M-3. That means fibre also improves the strength. But in case of M-5, where fibre percentage is 0.10% both 7 days strength and 28 days strength are lower than M-4. It implies that higher percentage of fibre does not improve strength rather it decreases strength. The black dotted line in **figure 5.1** shows the design target strength of the concrete. And from this visual observation it can be said that all the concrete reaches the design target strength.

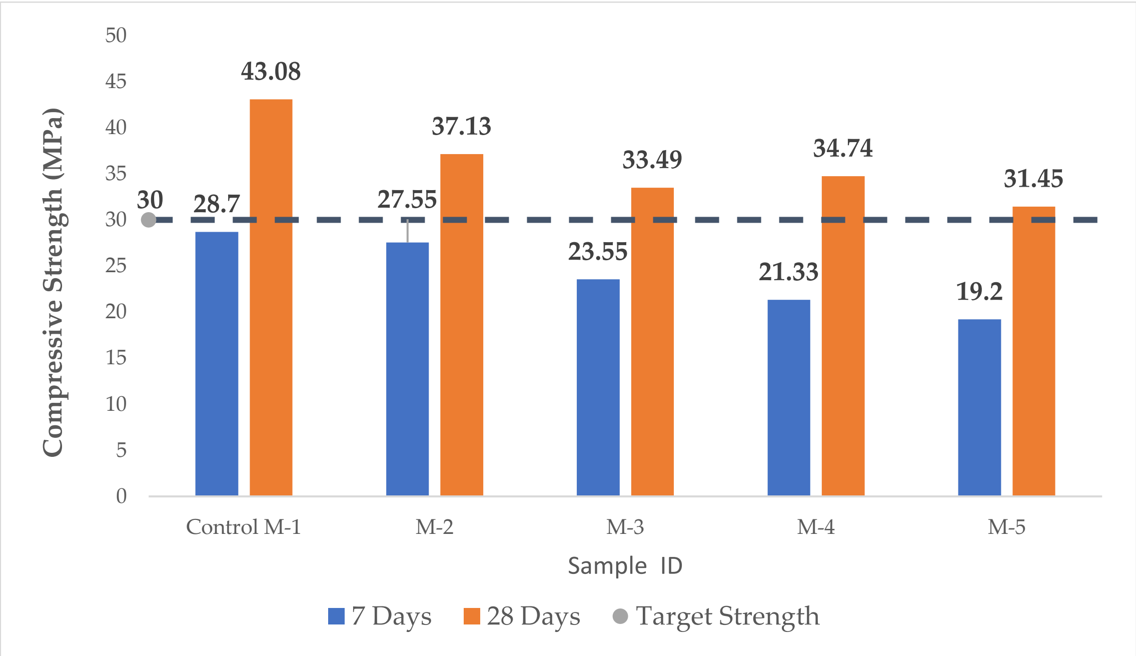

Figure 5.1: Compressive strength Vs Concrete Mix Combination in 28 days.

Figure 5.2 represents the comparison of elastic modulus of various mix using empirical relationships provided by ACI as in equation 5.1.

$E_c = 4700\sqrt{f_c'}$ $MPa\ in\ SI\ units$ .... (5.1)

Where E_c is the modulus of elasticity and f_c' is the specified compressive strength of concrete.

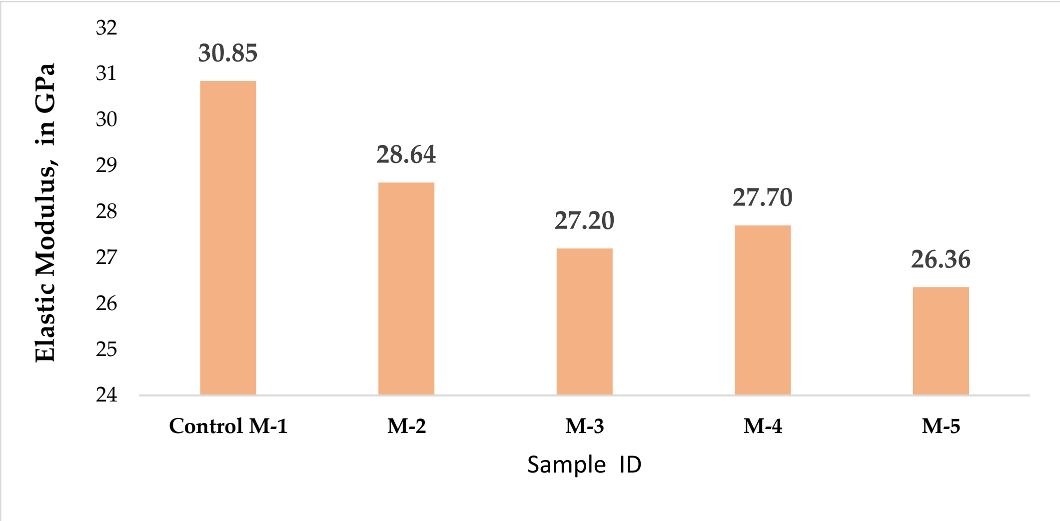

Figure 5.2: Elastic modulus of Concrete for all mixes using empirical relationships.

5.3 Modulus of rupture:

The graph in **figure 5.3** represents the Flexural strength i.e. modulus of rupture of concrete of all five mixes at the age of 28 days. The modulus of rupture indicates the maximum tensile stress a material can endure without breaking. It also represents the ability of a material to resists bending or flexing before it fractures. From the graph, it is seen that Mix-5 concrete has the highest modulus of rupture at 2.58 MPa, followed closely by Mix-2 concrete at 2.55 MPa, indicating that these concrete mixes have the highest resistance to bending or flexure before breaking. Concrete mixes of M-1, M-3 and M-4 have the lower modulus of rupture values indicating slightly lower flexural strength compared to M-5 and M-2 concrete mixes. So, the test results indicate that replacing cement by 10% with ladle slag in sample M-2 increases the flexural capacity by 46%. For sample

M-3 whereas cement is replaced more by 30 % GGBS the strength is still higher than the control sample by around 14% though it is lower than the sample M-2. This is an interesting observation which implies that though compressive strength decreases for M-2 and M-3, flexural strength increases. The trend of modulus of rupture from sample M-3 to M-5 indicates that this value is directly proportional to the amount of fibre content. For M-4 by adding 0.05% fibre the MOR value increases by 13% and when the fibre percentages are increased by 0.1% this value is increased by 34% which is quite impressive. The higher value of MOR for M-2 than control sample implies that the reduction of cement by only 10% and adding ladle slag is beneficial in increasing MOR. On the contrary for sample M-3 a lower value is obtained for MOR which implies that reducing cement percentages by more 30% decreases the MOR value.

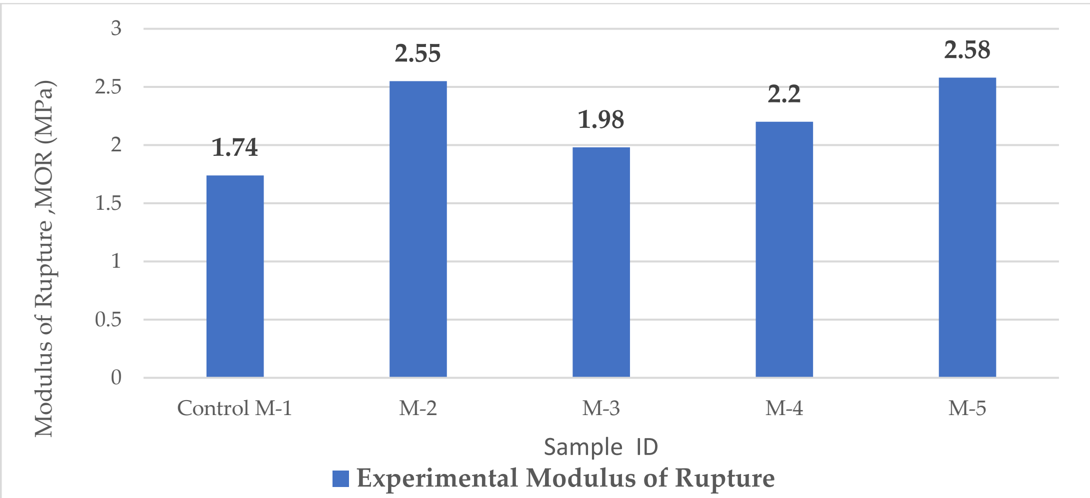

Figure 5.3: Modulus of rupture vs concrete mix combination in 28 days

The graph in figure 5.4 shows the graphical comparison between the experimental modulus of rupture and the empirical relationship provided by ACI in equation 5.2 and it shows that the empirical equation overestimated the modulus of rupture hugely and the scatter for the experimental value is high in case where the compressive strength is high.

$$f_r = 0.62\sqrt{f_c'} \quad MPa\ in\ SI\ unit \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5.2)$$

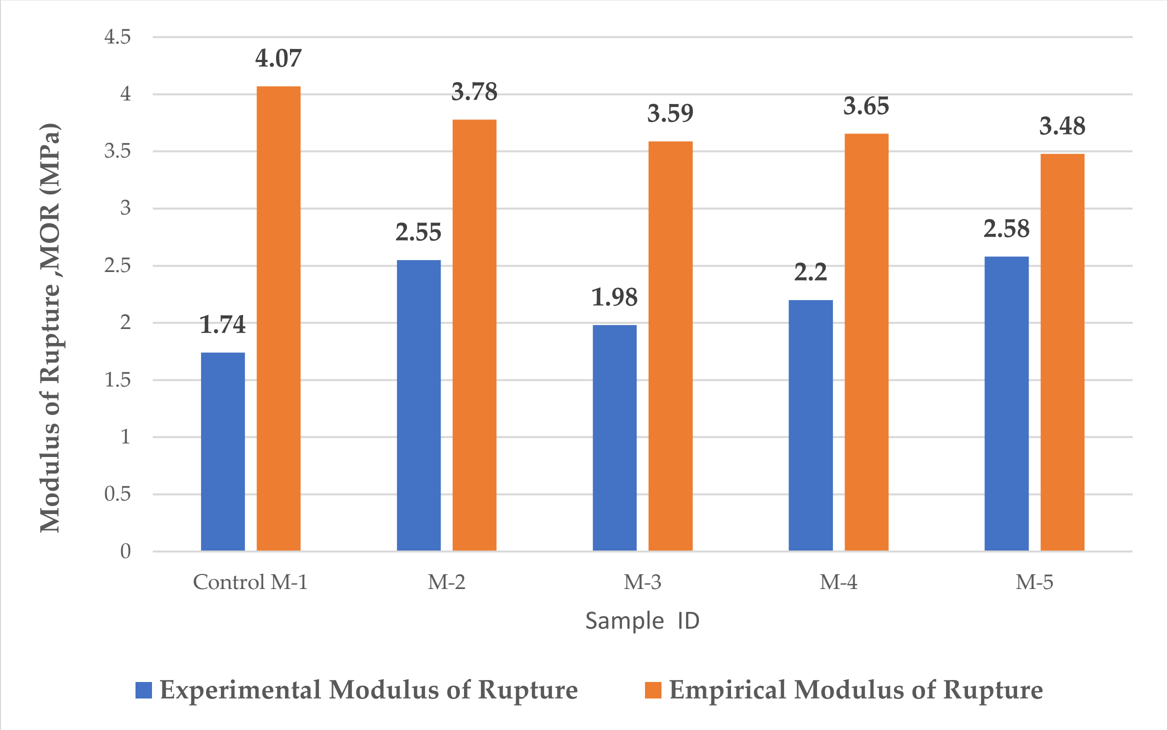

Figure 5.4: Modulus of rupture vs concrete mix combination in 28 days.

figure 5.5 shows the comparison of square root of compressive strength and modulus of rupture. From the plot a relationship among this can be established with a R^2 value of 0.96 as shown in plot as well as in equation 5.3.

$f_r = 0.37\sqrt{f_c'} \quad MPa\ in\ SI\ units$ … ..(5.3)

Comparing these two equations in 5.2 and 5.3 it can be said that actual multiplying factor among these two values is around half the empirical value.

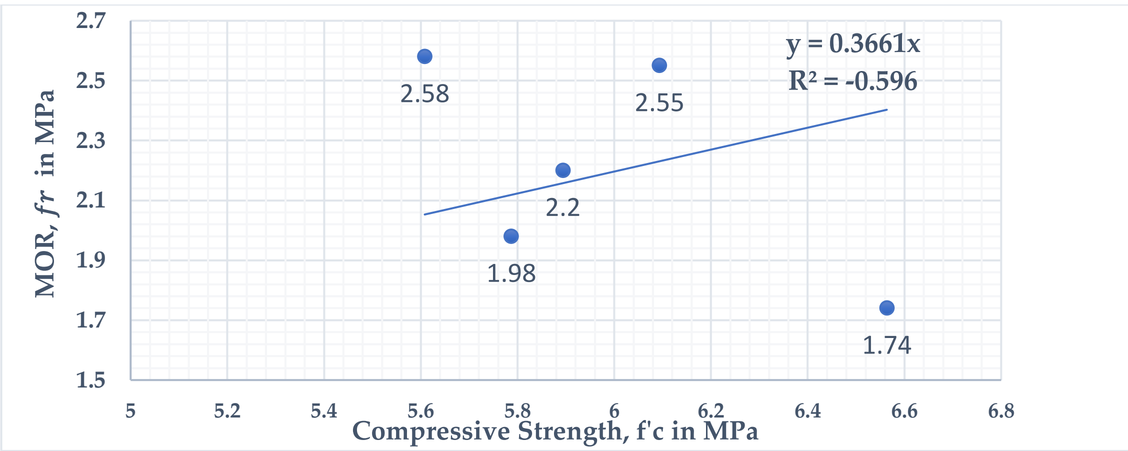

Figure 5.5: Plotting experimental compressive strength vs modulus of rupture.

5.4 Load displacement curve from the fracture test:

The graph in figure 5.6 represents the load vs displacement curve of the Mix-1 samples. It is observed that the curve remains straight line before it reaches to maximum load & gets downward for the decreases of load, but displacement is still increasing up to the ultimate breaking. For sample-1 of that mix; maximum load is taken 8.02 kN where corresponded displacement is found 0.970 mm. On the other hand, for the sample-2 of that mix; maximum load is taken 7.36 kN where corresponded displacement is found 0.850 mm.

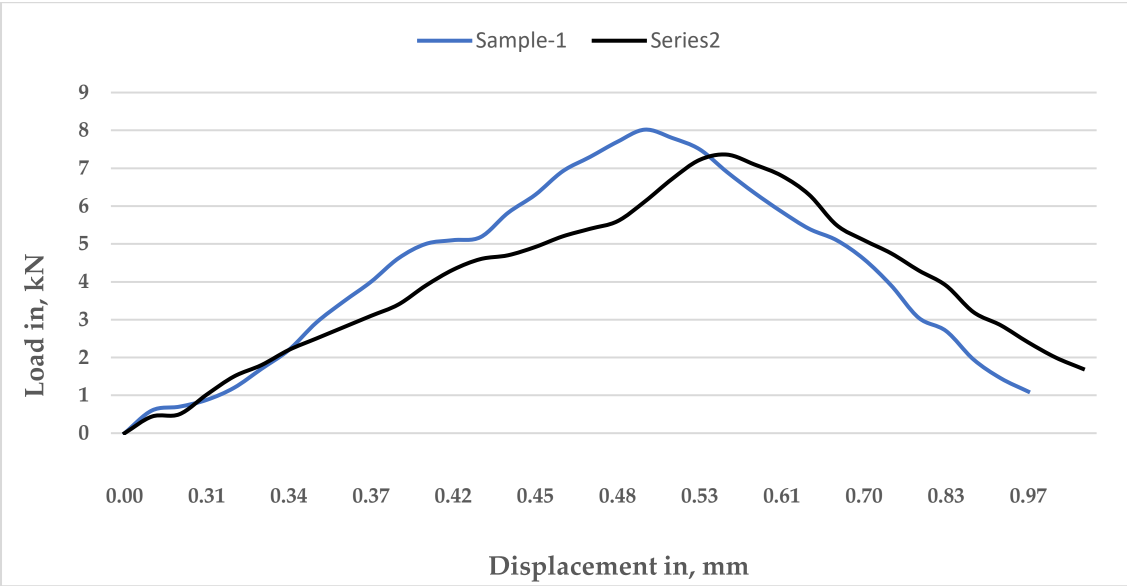

Figure 5.6: Load vs displacement for Mix-1 in 28 days.

The graph in figure 5.7 represents the Load vs displacement curve of the Mix-2 samples. It is observed that the curve remains straight line before it reaches to maximum load & gets downward for the decreases of load, but displacement is still increasing up to the ultimate breaking. For sample-1 of that mix; maximum load is taken 7.46 kN where corresponded displacement is found 0.930mm. On the other hand, for the sample-2 of that mix; maximum load is taken 6.74 kN where corresponded displacement is found 0.80 mm.

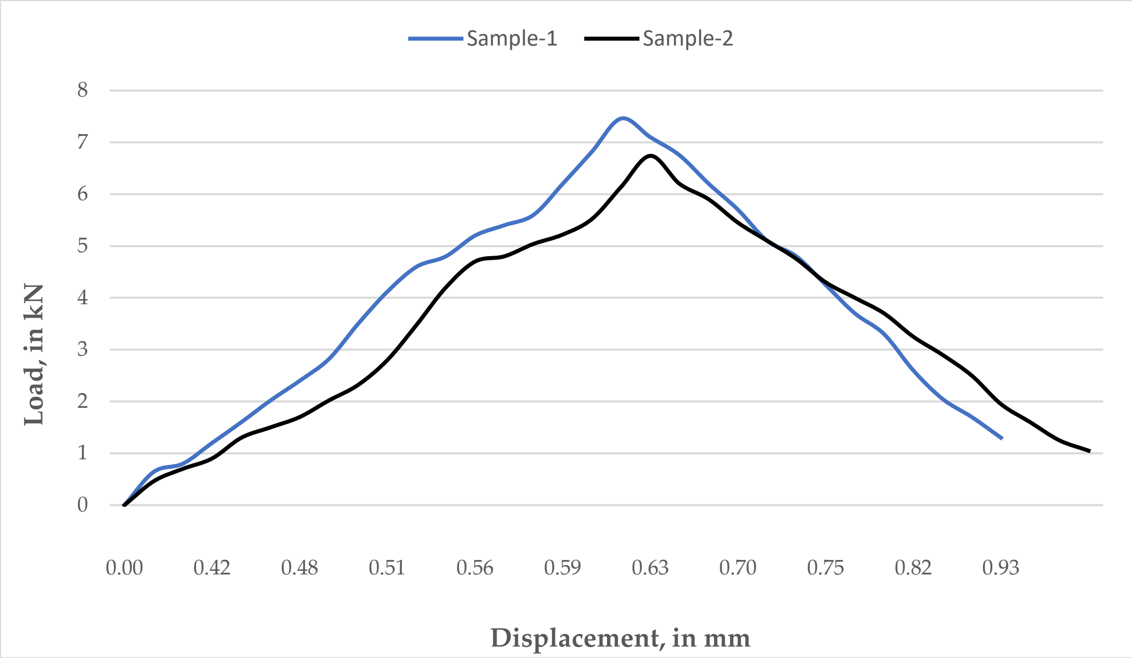

Figure 5.7: Load vs displacement for Mix-2 in 28 days

The graph in figure 5.8, represents the Load vs displacement curve of the Mix-3 samples. It is observed that the curve remains straight line before it reaches to maximum load & gets downward for the decreases of load, but displacement is still increasing up to the ultimate breaking. For sample-1 of that mix; maximum load is taken 3.36 kN where corresponded displacement is found 0.320 mm. On the other hand, for the sample-2 of that mix; maximum load is taken 3.70 kN where corresponded displacement is found 0.311 mm.

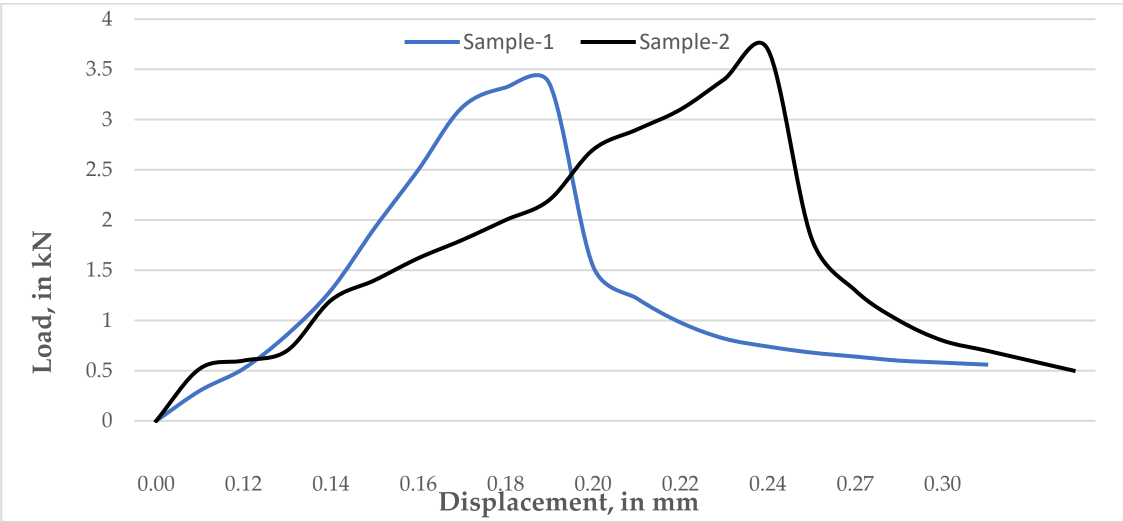

Figure 5.8: Load vs displacement for Mix-3 in 28 days

The graph in figure 5.9 represents the Load vs displacement curve of the Mix-4 samples. It is observed that the curve remains straight line before it reaches to maximum load & gets downward for the decreases of load, but displacement is still increasing up to the ultimate breaking. For sample-1 of that mix; maximum load is taken 4.98 kN where corresponded displacement is found 0.550 mm. On the other hand, for the sample-2 of that mix; maximum load is taken 4.86 kN where corresponded displacement is found 0.490 mm.

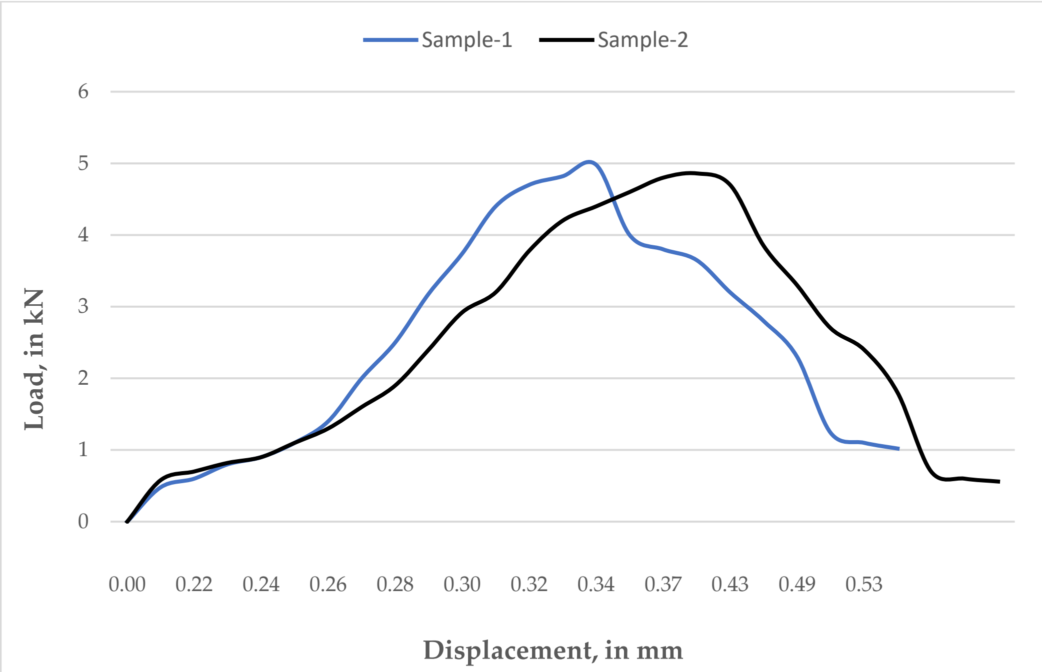

Figure 5.9: Load vs displacement for Mix-4 in 28 day

The graph in figure 5.10 represents the Load vs displacement curve of the Mix-5 samples. It is observed that the curve remains straight line before it reaches to maximum load & gets downward for the decreases of load, but displacement is still increasing up to the ultimate breaking. For sample-1 of that mix; maximum load is taken 4.64 kN where corresponded displacement is found 0.790 mm. On the other hand, for the sample-2 of that mix; maximum load is taken 4.70 kN where corresponded displacement is found 0.810 mm.

By observing the load-deflection curve above, it is viewed that maximum load & failure load for all types of beams differ from each other. Thus, Mix-1 beam samples take more load than other beams samples. Displacement observed at maximum load for this mix does not have much difference in compared to maximum displacement for other types of samples. From, load vs displacement curve, Mix-1 samples are more ductile than other four types of samples. It also observed that, ductility decreases at the change of mix ratio of concrete (partial replacement of cement in the concrete mix).

Almost all the samples show brittle type failure at ultimate load and then snapped into two pieces instantly which is demonstrated by the sudden drop in the load. These samples retain no strength after reaching ultimate load. A striking difference is being observed in the flexure failure characteristics of Mix-4 where 40% of cement is replaced by ladle slag and GGBS and adding 0.05% fibre. For sample Mix-4 failure is not as brittle as other samples, rather the sample shows a slightly ductile behaviour as seen from the load deflection curve **at the graph in figure 5.9**.

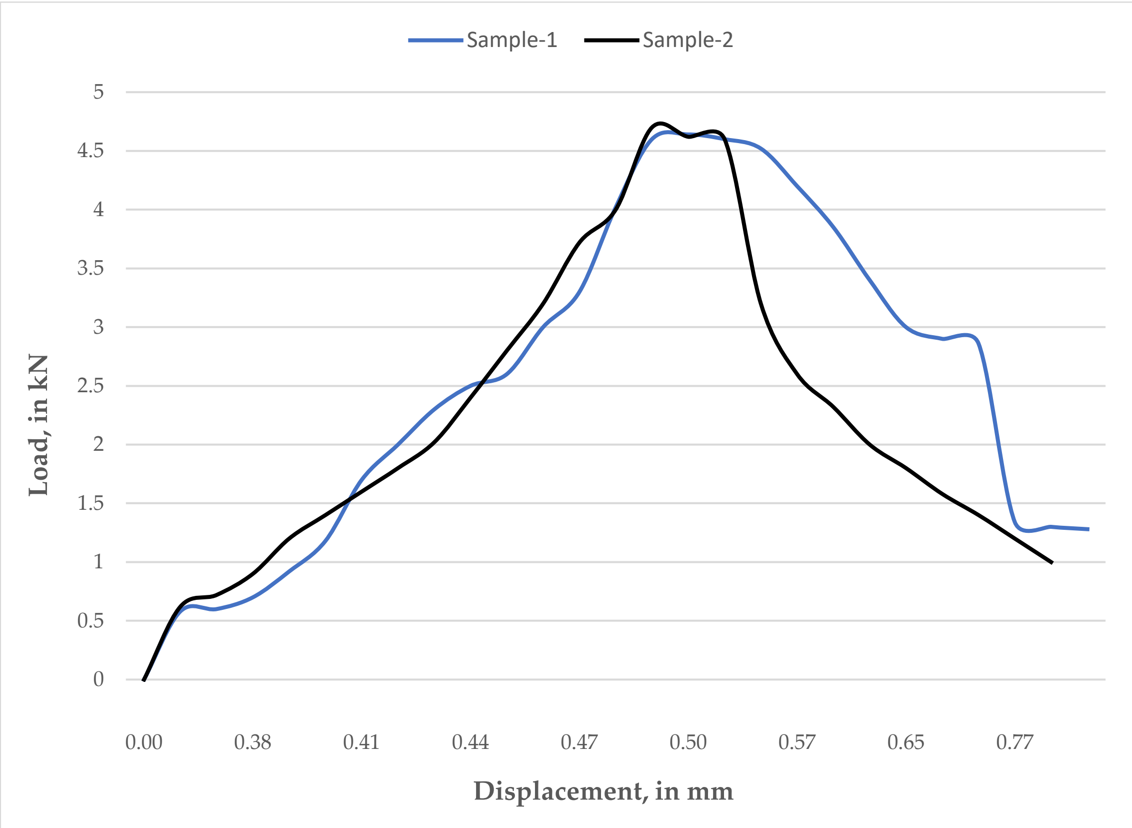

Figure 5.10: Load vs displacement for Mix-5 in 28 days.

The graph in figure 5.11 represents that the maximum load carrying capacity of the beam samples of different mixes. And **in the figure 5.12,** By comparing the maximum deflection of all samples, it is evident that control sample can sustain midspan deflection of 0.91 mm whereas the lowest deflection was observed for Mix-5 with 0.1% fibre and this lowest deflection may be attributed to the fibre content added to this mix. Mix-3 with 30% GGBS and 10% ladle slag also showed lower displacement. The displacement for Mix-4 is slightly higher than Mix-5 but much lower than Control sample Mix-1, and for Mix-2 also.

It is observed from the figure that that Mix-1 samples carrying maximum loads where Mix-3 samples are carrying minimum loads. which implies that reducing cement percentages by 40 % reduces the maximum load by 54%. On the hand adding fibre in the concrete in sample Mix-4 and Mix-5 increases the maximum load from Mix-3 by 40% and 32% respectively. If sample Mix-1 and Mix-4 are compared it shows that the maximum load is decreased by 36% by replacing 40% cement with ladle slag, GGBS and 0.05% fibre. Another interesting observation is that decreasing cement by 10% in sample Mix-2, reduces the maximum load by 7.5%, however the maximum deflection rises by almost 5% with the reduction of cement by 10% only. On the other hand, deflection increases by 65% and 42% than Mix-1 for mix Mix-3 and Mix-4. But for sample Mix-5 the deflection is remarkably reduced than Mix-3 and Mix-4 and increase by 12% only than Mix-1. This observation implies that adding more fibre might be helpful in reducing deflection.

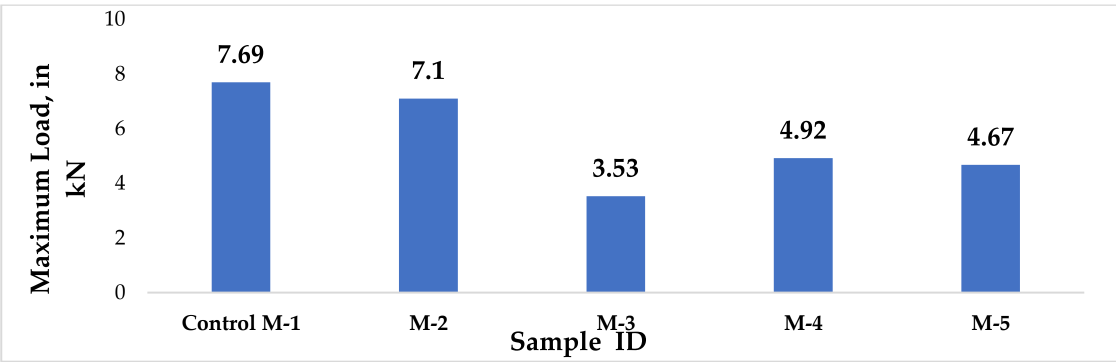

Figure 5.11: Comparison of maximum load for all samples

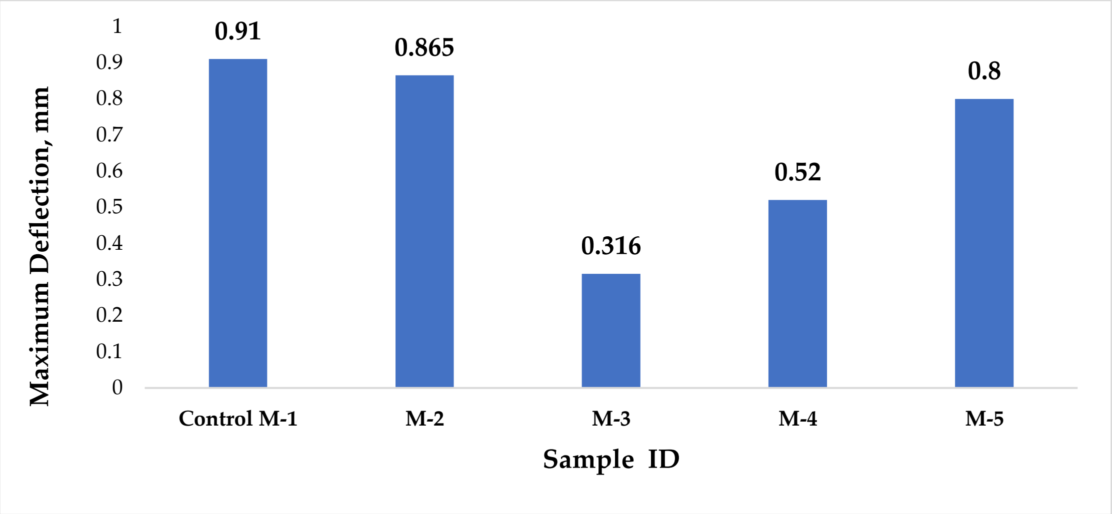

Figure 5.12: Comparison of maximum deflection for all samples.

In figure 5.13 it shows that, the crack propagation from the notch towards the top of the specimen and the sample was not split into the two pieces for the ultimate load indicating by the characteristics of ductile failure mode.

Figure 5.13: Failure profile of sample Mix-3

In figure 5.14, shows that, the crack propagation occurred along the notch in the specimen and the specimen instantly split into two pieces due the ultimate load which is the mode of brittle type failure. Almost all the samples like M-1, M-2, M-4, and M-5 showed this character.

Figure 5.14: Failure profile of Sample Mix-1, Mix-2, Mix-4, and Mix-5

5.5 Fracture parameters:

To characterize the fracture properties of the concrete tested in this work, parameters such as K_{IC}, G_f, were used. **Table 4** Appendix-A report the mean values of fracture energy, stress intensity factor calculated from the load displacement curve. As already mentioned earlier, if a sharp crack can occur in concrete the minimum value of K_{IC} can be empirically determined, which is the critical value of stress intensity for the propagation of the crack.

The graph in figure 5.15 shows, Fracture energy or fracture toughness G_f is calculated for all types of beam samples & the value was obtained in between the range of 80-175 N/m. For typical concrete it is well known that the fracture energy value is 75-100 N/m depending on the concrete grade (Lee & Lopez, 2014) .On the other hand, some researchers obtained a fracture energy value in between the range of 185-189 N/m using crack mouth opening displacement method and stroke control (Asiva Noor Rachmayani, 2015) .So, from the previous studies it can be said that the fracture energy values obtained in this work is within acceptable range. However, the difference due to various parameter in this work effect the G_f value. It can be incurred from the G_f value that it is highest for the control sample. However, for 10% decrease in cement this value is reduced by

17% and for 40% decrease in cement and replaced by ladle slag and GGBS this fracture energy value is decreased by 53%.

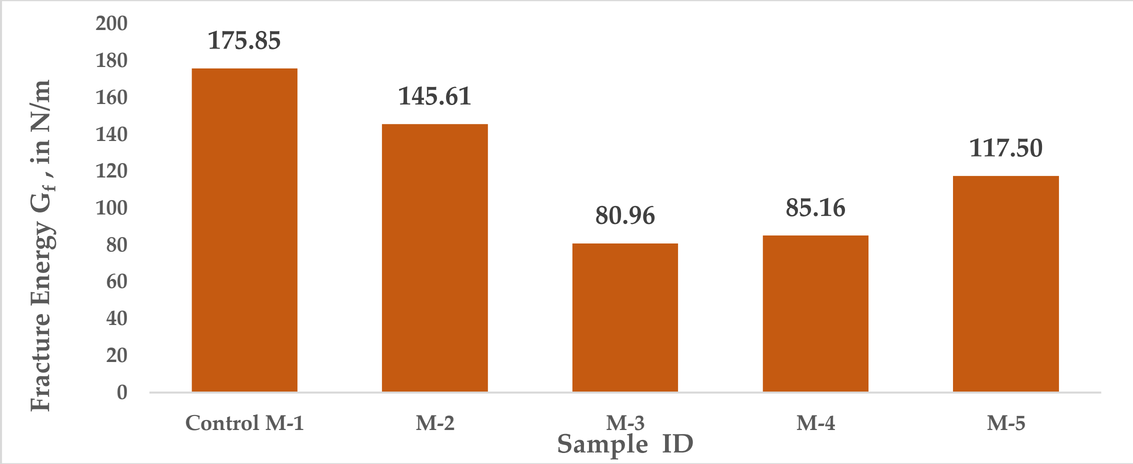

Figure 5.15: Average fracture energy value obtained from the experiment

With the addition of fibre in sample Mix-4, the decrease is 51.5%, that means fibre increases the fracture energy by 5% and 45% for samples Mix-4 with 0.05% fibre and Mix-5 with 0.1% fibre respectively with respect to sample Mix-3 where no fibre is added. As we know, fracture energy is the amount of energy to create new crack surface and hence higher the energy higher the time to develop failure. So, from the test result analysis, it can surely be said that a sample with no other waste material will require more time to create a crack surface. However, replacing 40% cement with ladle slag and GGBS with added fibre by 0.10% can compensate that loss in fracture energy extensively. **Figure 5.16** shows that with the decrease in cement percentages the fracture energy decreases almost linearly. On the other hand, in the **figure 5.17** shows, with the addition of fibre percentages, there is an increase in fracture energy but not in linear manner.

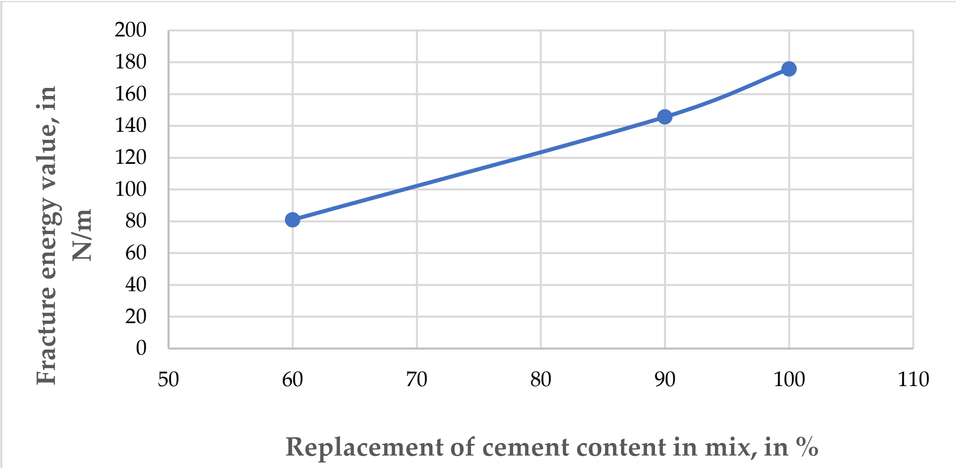

Figure 5.16: Variation of fracture energy with change the cement percentage.

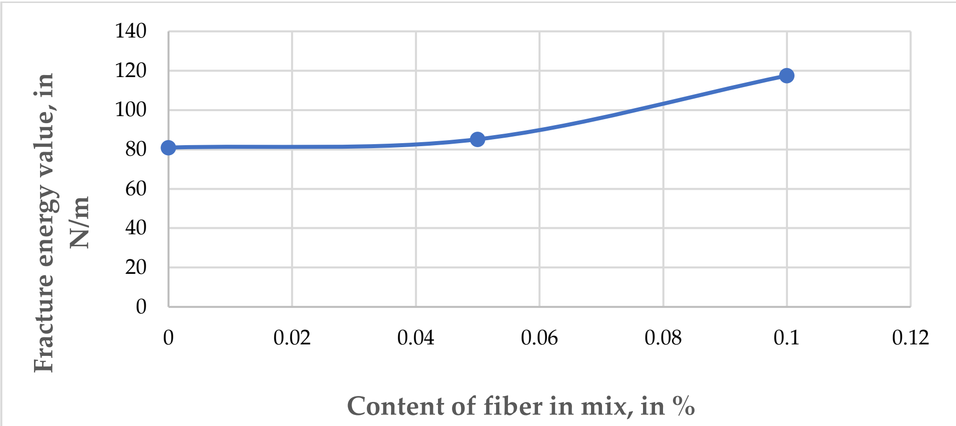

Figure 5.17: Variation of fracture energy with change the fiber percentage.

The graph in figure 5.18, shows the stress intensity factor of the tested concrete mix. Results shows that the highest K_{IC} is found for control mix, which mix it has maximum ability to resist crack growth. This value gradually decreases for mix-2 and mix-3 by 8% and 54%, which was expected since the cement content decreases by 10% & 40%. On the other hand, adding fibre increases the K_{IC} value for mix-4 by 39% and mix-5 by 33%. This reduction may be due to the smaller particle size of GGBS and ladle slag which makes the mix brittle and decreases the fracture load.

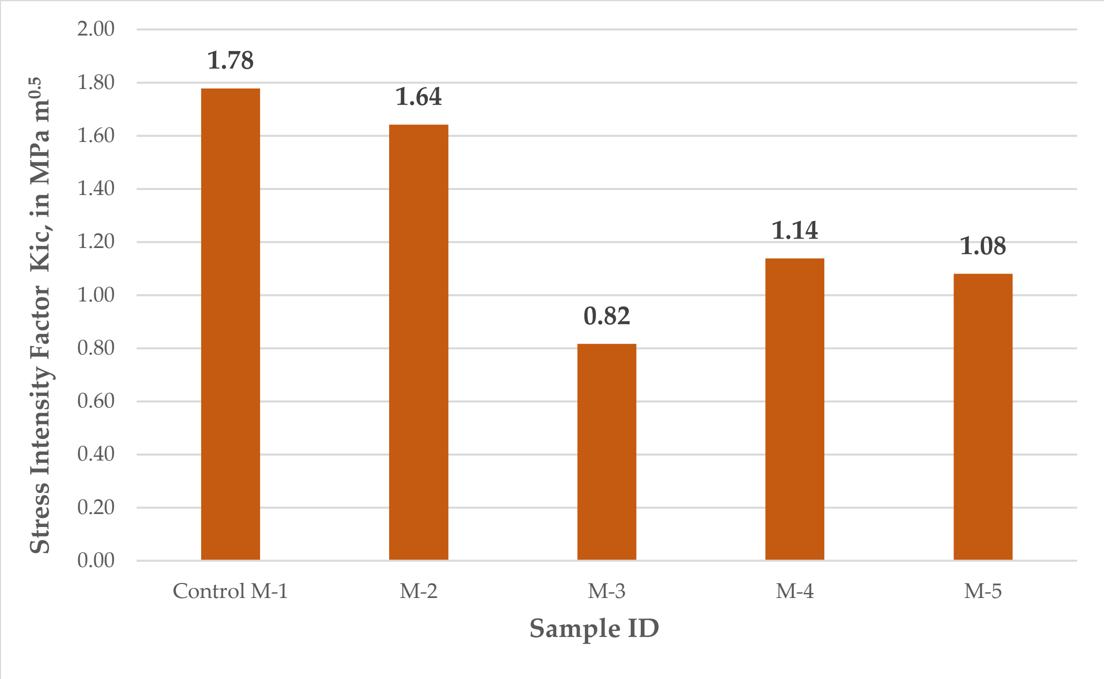

Figure 5.18: Stress Intensity factor of the samples.

The measure of a material's ability to prevent an unstable fracture or crack is called the stress intensity factor or fracture toughness. Various standards and methods are available to predict the fracture toughness of concrete materials.

Stress Intensity factor i.e. fracture toughness "K_{IC}" is also calculated by using the relationship provided by (Srawley et al.,1975). Fracture energy "G_f" & Toughness "K_{IC}" represent the same quantity in energy and stress. They imply the propagation of cracks in energy & stress terms respectively. Hence, the range is found 0.82-1.78 MPa $m^{0.5}$ which is close to the stress intensity factor value of 1.19 reported by (Park et al., 2011). **The graph in figure 5.19,** shows the comparison of the experimental fracture energy value and the value obtained by the formula proposed by Bazant considering the compressive strength, size of aggregate, and the water-cement ratio. The comparison shows that the model is quite conservative and underestimated the fracture energy value.

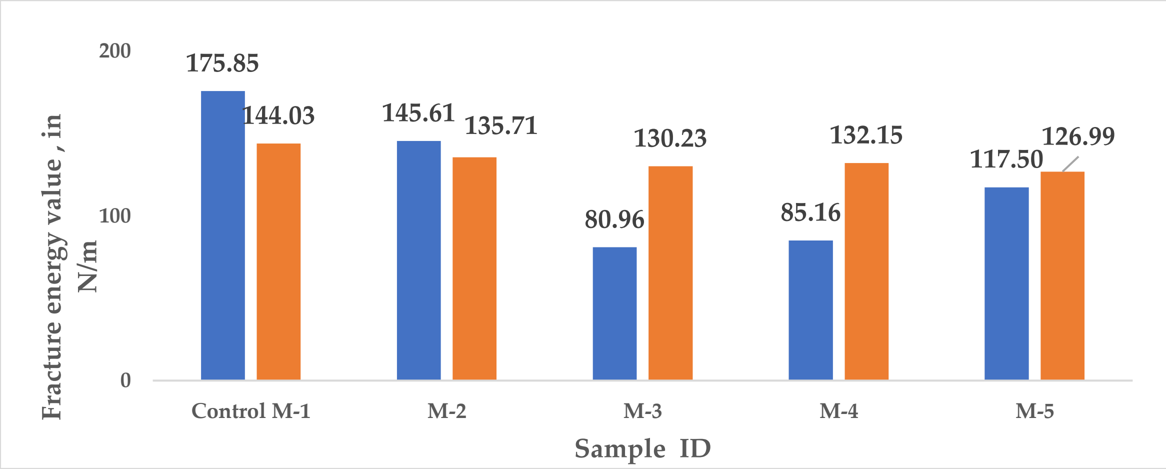

Figure 5.19: Comparison of experimental fracture energy value and empirical value using Bazant formula.

The graph in figure 5.20, shows the compressive strength vs fracture energy and confirms that fracture energy is directly proportional to compressive strength and an empirical relationship has been provided from data regression with a R^2 value of 0.96 as shown in the plot. The higher value of R^2 denotes better predictability of the relationship developed (Bažant & Becq-Giraudon, 2002).

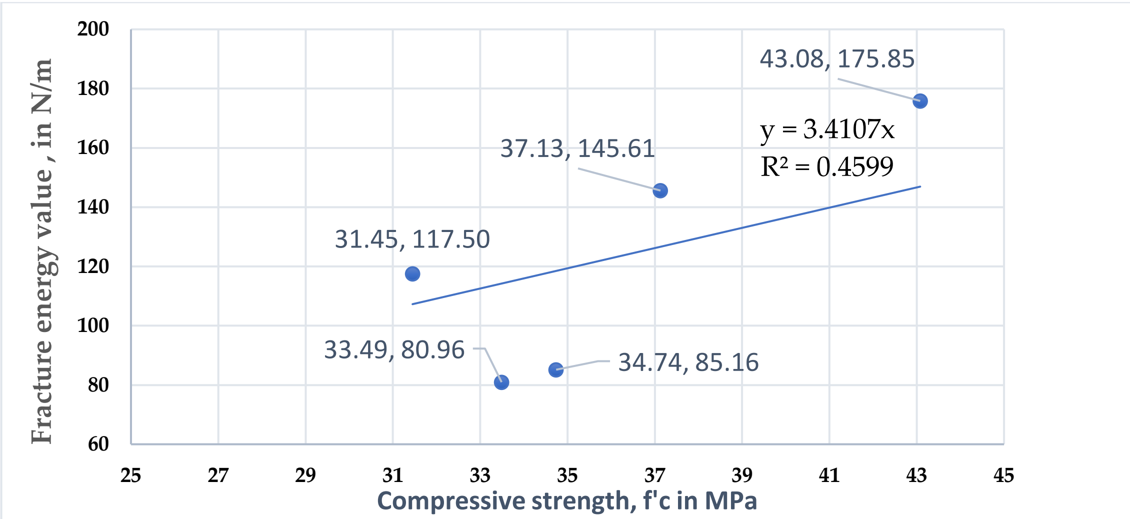

Figure 5.20: Variation of fracture energy with compressive strength

CHAPTER 6: CONCLUSIONS

6.1 Introduction:

In this study, concrete's mechanical & fracture properties such as compressive strength(f'_C), Elastic modulus (E_C), Flexural strength (Modulus of rupture, MOR), fracture energy or fracture toughness (G_f), and stress intensity factor (K_{ic}), has been explored for cube and beam samples at the different ages for a design strength of 30 MPa. After conducting all the tests and based on tests results, the following conclusion can be made,

According to this study, the compressive strength in concrete decreases over the time at both 7 and 28 days for the reducing of cement content in the concrete mix as low as 22% for a maximum reduction of 30% cement content is replaced with GGBS in the concrete mixture. For the reduction of 30% cement with GGBS in the Mix-3 as compressive strength has only marginally reduced than the Mix-2 with no GGBS showing the positive impact of GGBS in that mix. Addition of fibres has improved the strength of concrete in Mix-4. But in Mix-5 where the fibre amount is doubled than Mix-4 shows decreases the strength is by 9%. From that, it has been concluded that, higher percentages of fibre content do not improve higher strength in the concrete mix rather can be decreased.

However, the inclusion of fibre improved the modulus of rupture (MOR) of the concrete. Flexural capacity is greatly increased by 46% when 10% of cement is substituted with ladle slag in Mix-2, and MOR is improved by 14% when 30% of cement is substituted with GGBS in Mix-3. As seen in Mix-4 and Mix-5, there is a direct correlation between the MOR values and the fibre content. As the increment of fibre content, the MOR values also increases.

Again, for fracture properties of concrete, At the ultimate load, the fracture toughness tests on beam samples Mix-1, Mix-2, Mix-3, and Mix-5 showed mostly brittle failure. On the other hand, Mix-4, which is substituted by ladle slag, GGBS, and 0.05% fibre for 40% of the cement, showed slightly ductile behaviour in the load-deflection curve.

According to the fracture energy, G_f analysis, shows G_f values decreases by 17% for the reduction of 10% of cement and for more 30% reduction, the G_f values decrease more by 54% in the concrete Mix-3. The addition of 0.05% and 0.10% fibre in the concrete Mix-4 and Mix-5 has increased fracture energy values by 5% and 45% respectively. It can imply that, adding more fibre positively impacts to increase G_f values. The values are obtained in the range of 80-175 N/m. The values of fracture toughness (K_{IC}) varied between 1.78 and 0.82 MPa $m^{0.5}$ in this study and Mix-1 has the best resistance to crack propagation due to its maximum cement content used in the concrete mix. In Mix-4 and Mix-5, fibre addition increased the K_{IC} values by 39% and 33%, respectively, indicating that, it is beneficial in increasing toughness even when cement is reduced.

In a nutshell, from all the conclusions summarized above, it can be concluded that sample with ladles slag and GGBS as partial replacement of cement can gain desired strength and fracture toughness value though lower than control sample, still acceptable for practical usage. In some cases, it shows better strength and toughness by adding fibre. In terms of modulus of rupture, which is the maximum stress before yielding, surprisingly increased value was observed with reduced cement content. Therefore, in short, this cement replacement with ladles slag and GGBS and also some fibre can be a sustainable solution to reduce the consumption of cement and at the same time converting waste into a resource.

6.2 Recommendation:

There is a lot more room for this experiment in future research: -

- ❖ More mixing combination(ratio) of concrete can be checked.
- ❖ Can check the effect of admixtures in the concrete mix.

- ❖ Different "notch to depth" ratio ($\frac{a}{w}$) in the beam samples can be tested.
- ❖ "Finite Element Model" could be used to compare experimental & numerical work for fracture toughness test.
- ❖ Different beam samples having constant span to depth ratio can be tested for both flexural strength & fracture toughness test.

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Appendices

Table 1: Appendix A: Values of properties obtained associated to fracture parameter.

Mix ID	Notch to depth ratio $(\frac{a}{w})$	Notch depth "a" (m)	Max Load "P" kN	Area Under Curve "A" kN-m	Bending Moment "BM" kN-m	G_f (N/m)	K_{IC} $MPam^{0.5}$	G_f (N/m) By Bazant formula
M-1	0.4	0.04	8.02	1.097	0.814	182.85	1.85	
	0.4	0.04	7.36	1.013	0.748	168.85	1.70	144.03
M-2	0.4	0.04	7.46	1.056	0.758	176.04	1.72	
	0.4	0.04	6.74	0.691	0.686	115.18	1.56	135.71
M-3	0.4	0.04	3.36	0.574	0.348	95.70	0.78	
	0.4	0.04	3.70	0.397	0.382	66.22	0.86	130.23
M-4	0.4	0.04	4.98	0.456	0.510	76.03	1.15	
	0.4	0.04	4.86	0.566	0.498	94.29	1.12	132.15
M-5	0.4	0.04	4.64	0.660	0.476	110.01	1.07	
	0.4	0.04	4.70	0.750	0.482	125.00	1.09	126.99

Table 2: Appendix B : "K" Harmsworth constants value factor

"K" Harmsworth constants value factor	
Allowed the min. percentage of results to fall below	"K" Values
0.100	3.090
0.600	2.500
1.000	2.330
2.500	1.960
6.600	1.500
16.000	1.000
From Interpolation 5.00	1.64

Table 3: Appendix C : Coarse aggregate volume (dry bulk volume) of per unit volume of concrete as per ACI 211.1-91

Coarse aggregate volume (dry bulk volume) of per unit volume of concrete as per ACI 211.1-91				
Max. size of aggregates (mm)	Dry rodded coarse aggregate volume (bulk volume) of per unit volume of concrete for sand's fineness modulus			
	F.M			
-	2.400	2.600	2.800	3.000
10.00	0.500	0.480	0.460	0.440
12.50	0.590	0.570	0.550	0.530
20.00	0.660	0.640	0.620	0.600
25.00	0.710	0.690	0.670	0.650
40.00	0.750	0.730	0.710	0.690
50.00	0.780	0.760	0.740	0.720
70.00	0.820	0.800	0.780	0.760
150.00	0.870	0.850	0.830	0.810

Table 4: Appendix D : Relation of average compressive strength and concrete's Water/Cement ratio as per ACI 211.1-91

Relation of compressive strength (Avg.) and concrete's Water/Cement ratio guided by ACI 211.1-91		
Concrete Compressive Strength at the age of 28 days (Avg.)	Water/cement ratio (by mass)	
(MPa)	concrete as (Non-air entrained)	concrete as (Air entrained)
45.00	0.380	-
40.00	0.430	-
35.00	0.480	0.400
30.00	0.550	0.460
25.00	0.620	0.530
20.00	0.700	0.610
15.00	0.800	0.710

Table 5: Appendix E : Special exposure conditions for W/C ratio and strength required as per ACI 318-89

Special exposure conditions for W/C ratio and strength required as per ACI 318-89		
Condition of exposure	Max. water-cement ratio (W/C), aggregate concrete with normal density	Min. design strength, aggregate concrete low density
i. Watertight concrete to be intended		(MPa)
(a) Fresh water to be exposed	0.500	25.00
(b) Brackish or sea water to be exposed.	0.450	30.00
ii. Freezing and thawing to be exposed of concrete		
(a) Thin sections, Guard rails, Gutters, and Kerbs	0.450	30.00
(b) Elements of others	0.500	25.00
© in presence of de-icing chemicals	0.450	30.00
iii. For the reinforced concrete protecting from corrosion and exposing to de-icing of sea water or spray, brackish water, and salts from these sources.	0.400	33.00

Table 6: Appendix F : Specified slump values for the different types of construction as guided by ACI 211.1-91

Specified slump values for the different types of construction as guided by ACI 211.1-91	
Types of structural members / Construction types	Slump ranges (mm)
RCC foundation walls and footings	20.00-80.00
Substructure walls, Caissons, and Plain footings,	20.00-80.00
RCC Walls and beams	20.00-100.00
Vertical members/ Columns of building	20.00-100.00
RCC Slabs and Pavements	20.00-80.00
Mass footing or Mass Concrete	20.00-80.00

Table 7: Appendix G : Air-Content and mix of water for the various workability and max. nominal size of aggregates approximately guided by the ACI 211.1-91

Air-Content and mix of water for the various workability and max. nominal size of aggregates approximately guided by the ACI 211.1-91								
Content Or Workability	indicating max. aggregates size (mm) for the concrete of kg/m3, Water content							
(mm)	10.0	12.50	20.0	25.0	40.0	50.0	70.0	150.0
Value of slump (mm)	concrete (non-air entrained)							
30.0-50.0	205.0	200.0	185.0	180.0	160.0	155.0	145.0	125.0
80.0-100.0	225.0	215.0	200.0	195.0	175.0	170.0	160.0	140.0
150.0-180.0	240.0	230.0	210.0	205.0	185.0	180.0	170.0	-
% of entrapped air content approximately	3.0	2.50	2.0	1.50	1.0	0.50	0.30	0.20
	Concrete (Air entrained)							
30.0-50.0	180.0	175.0	165.0	160.0	145.0	140.0	135.0	120.0
80.0-100.0	200.0	190.0	180.0	175.0	160.0	155.0	150.0	135.0
150.0-180.0	215.0	205.0	190.0	185.0	170.0	165.0	160.0	-
Total avg. air content % Recommended And mild exposure condition	4.500	4.000	3.500	3.000	2.500	2.000	1.500	1.000
Exposure in moderate condition	6.000	5.500	5.000	4.500	4.500	4.000	3.500	3.000
Exposure in extreme condition	7.500	7.000	6.000	6.000	5.500	5.000	4.500	4.000

Table 8: Appendix H: Fresh concrete density (unit weight) estimation guided by the ACI 211.1-91

Fresh concrete density (unit weight) estimation guided by the ACI 211.1-91		
Max. sizes of Coarse aggregates (mm)	Density (unit weight) of fresh concrete estimation	
	Concrete (non-air entrained) kg/m^3	Concrete (air-entrained) kg/m^3
10.0	2285.00	2190.00
12.50	2315.00	2235.00
20.0	2355.00	2280.00
25.0	2375.00	2315.00
40.0	2420.00	2355.00
50.0	2445.00	2375.00
70.0	2465.00	2400.00
150.0	2505.00	2435.00

Table 9: Appendix I : Improvement in mean strength required for the specified designed strength (specified characteristic of strength) when available of no test data guided by the ACI 318-89

Improvement in mean strength required for the specified designed strength (specified characteristic of strength) when available of no test data guided by the ACI 318-89	
designed strength (Specified), MPa	Increase in Strength (Required), MPa
Less than 21.00	7.000
21.0 to 35.0	8.500
35.0 or Above	10.000

Table 10: Appendix J : Determination of specific gravity, water absorption, moisture content of stone chips

Description	Value	Unit	Remarks
SSD Wt. of Agg. in Air(A)	2380	Gm	
Wt in water (B)	1529	Gm	
Loss of wt in water ©	851	Gm	
After Oven dry, dry sample wt (D)	2359	Gm	
Water Content€	21	Gm	
Specific gravity	2.77		$\frac{Dry\ sample\ wt(D)}{Loss\ of\ water\ in\ water(C)}$
Water Absorption Capacity (%)	0.89		$\frac{100x\ (A-D)}{(D)}$
Moisture content of stone (%)	0.88		$\frac{Water\ content\ X\ 100}{Sample\ wt\ in\ SSD\ condition)}$

Table 11: Appendix K : Determination of moisture content of coarse sand

Description	Value	Unit	Remarks
Sample weight (X)	200	gm	
After oven dry, Dry Sample weight (Y)	194.68	gm	
Water Content	5.32	gm	
Moisture Content (%)	**2.66**		$\frac{5.32\ X\ 100}{200}$

Table 12: Appendix L: Determination of unit weight of sand

Description	Value	Unit	Remarks
Volume of mould (X)	0.002834	m^3	Mould volume $\frac{1}{10}$ cft
Weight of Sample (Y)	4.705	kg	
Unit Weight	**1659.92**	**kg/m^3**	$\frac{4.705}{0.002834}$

Table 13: Appendix M : Determination of absorption capacity of sand

Description	Weight	Unit	Remarks
SSD Sample weight (X)	500	gm	
Oven dry Sample weight (Y)	490	gm	
Absorption capacity (%)	0.02		$\frac{500-490}{490}$
Absorption capacity	**2.04**		

Table 14: Appendix N : Determination of unit weight of stone chips

Description	Value	Unit	Remarks
Volume of mould (X)	0.014172	m^3	Mould volume $\frac{1}{2}$ cft
Weight of Sample (Y)	23.925	Kg	
Unit Weight	**1688.15**	**Kg/m^3**	$\frac{23.925}{0.014172}$

Table 15: Appendix O : Specific gravity of coarse sand

Description	Weight	Unit	Remarks
Sample weight (X)	150	gm	
Pycnometer weight (Y)	99.88	gm	
Pycnometer weight (Y)+Sample weight (X)	249.88	gm	
[Pycnometer weight (Y)+Water weight +Sample weight (X)] (M)	438.97	gm	
[Pycnometer weight (Y)+Water (wt)] (N)	346.56	gm	
Specific Gravity	**2.60**		$\frac{X}{X+N-M}$

Table 16: Appendix P : Sieve analysis of fine aggregates (Coarse Sand)

# **Sample taken 500gm**							
Sieve No	Sieve Size (mm)	Mass Ret.(gm)	% Ret	Cumulative % Ret.	% Finer	F.M	Remarks
#4	4.75	0	0	0	100	**2.51**	$\frac{\sum Cumulative\ \%\ Ret.}{100}$ $= \frac{251.47.}{100}$
#8	2.36	22.35	4.48	4.48	95.52		
#16	1.18	83.25	16.68	21.16	78.84		
#30	0.60	131.80	26.41	47.56	52.44		
#50	0.30	174.11	34.88	82.44	17.56		
#100	0.150	66.82	13.39	95.83	4.17		
Pan	-	20.81	4.17	100.00	0.00		
Total		499.14		251.47			