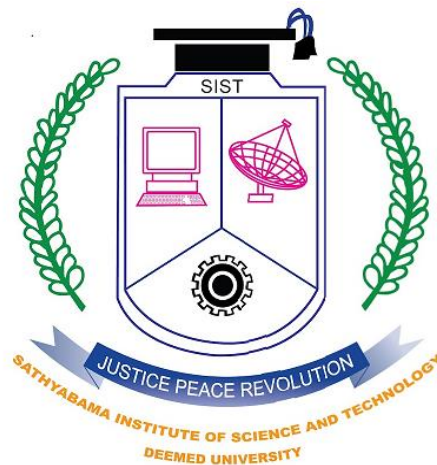


EXPERIMENTAL AND ANALYTICAL STUDIES ON BEHAVIOUR OF BASALT FIBRE REINFORCED CONCRETE BEAM BY PARTIALLY REPLACING CEMENT WITH GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

Submitted in partial fulfilment of the requirements of the award of
Master of Engineering Degree in Structural Engineering

By

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**DEPARTMENT OF CIVIL ENGINEERING
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**INSTITUTE OF SCIENCE AND TECHNOLOGY
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MAY 2023



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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafied work of **MOHAMED ANAS B (41380014)** who carried out the project entitled "**EXPERIMENTAL AND ANALYTICAL STUDIES ON BEHAVIOUR OF BASALT FIBRE REINFORCED CONCRETE BEAM BY PARTIALLY REPLACING CEMENT WITH GROUND GRANULATED BLAST FURNACE SLAG (GGBS)**" under my supervision from December 2022 to May 2023.

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Submitted for the Viva voce Examination held on 05/05/2023

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DECLARATION

I **MOHAMED ANAS B (41380014)** here by declare that the Project Report entitled “**EXPERIMENTAL AND ANALYTICAL STUDIES ON BEHAVIOUR OF BASALT FIBRE REINFORCED CONCRETE BEAM BY PARTIALLY REPLACING CEMENT WITH GROUND GRANULATED BLAST FURNACE SLAG (GGBS)**” done by me under the guidance of **Dr. R. Nirmala** at **SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY** is submitted in partial fulfillment of the requirements for the award of Master of Engineering Degree in Structural Engineering.

DATE: 05-05-2023

PLACE: Chennai

A handwritten signature in blue ink, appearing to read 'B. J. A.', is positioned above the signature line.

SIGNATURE OF THE CANDIDATE

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ABSTRACT

The construction industry has seen a growing demand for cementitious compound, which is a primary building material. Traditionally, cementitious compound has been made using heavy materials, with steel being a popular reinforcement option. However, in recent years, there has been a trend towards reducing the amount of steel used in structures, and instead, Basalt Fibre Reinforced Polymer (BFRP) rods are being utilized. This study aims to investigate the behaviour of reinforced cementitious compound by adding BFRP bars as reinforcement and partially replacing cement with Ground Granulated Blast Furnace Slag (GGBS) in M50 grade cementitious compound. Various ratios of GGBS (0%, 20%, 40%, and 60%) were used to partially replace the cement content, and the compressive resistance, split tensile resistance were tested after 7, 14, and 28 days of curing. The flexural resistance of the beam is also tested using hydraulic jack. The reinforced cementitious compound beam was modelled and analysed using Finite Element Analysis ABAQUS software, and experimental observations were compared with analytical observations. The cementitious compound with a 40% replacement of GGBS demonstrated rised resistance in compression resistance, split tensile resistance, and flexural resistance with less deflection than other types of cementitious compound. Finally, the 0% and 40% samples were analysed through Field Emission Scanning Electron Microscopy (FE-SEM) to identify the hydration process of both cementitious compound samples.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Cementitious compound, a cement-based substance, is widely used in constructing buildings, bridges, tunnels, and roadways due to its advantageous attributes. It can work seamlessly with steel bars, has impressive compressive resistance, and can withstand various environmental conditions, which has made it increasingly popular in the physical structures and infrastructure. Cementitious compound comprises sand (fine aggregate), crushed rock (coarse aggregate), chemical admixtures, and water. When cement and water are mixed, they undergo a process called hydration, observationing in the hardening and solidification of the cementitious compound mixture with fine and coarse aggregates, ultimately forming a composite material. Cementitious compound is a man-made type of stone that can be shaped into various forms.

1.2 BASALT FIBRE REINFORCED CEMENTITIOUS COMPOUND

The production of basalt fibres involves melting basalt rocks and then dividing them into small particles without the need for additional additives. This streamlined process provides a cost advantage and observations in fibres that offer multiple benefits, including greater tensile resistance than E-glass fibres, greater failure strain than carbon fibres, and resistance to chemical attack, impact loads, and fire with less toxic fumes. Consequently, basalt fibres are highly anticipated to be used as a structural resistance material. Research on Basalt Fibre Reinforced Polymer has explored the fundamental attributes of basalt fibre as a replacement for reinforcing steel in cementitious compound structures. An alternative for steel that shows promise is basalt fibre reinforced polymer, especially in environments such as ports, mining areas, and other zones where cementitious compound and steel corrosion must be avoided, due to its high resistance, durability, insulation, non-magnetism, and other factors. Adding fibres to cementitious compound is highly beneficial in enhancing the structure's tensile resistance, toughness, ductility, and load carrying capacity. However, the bond degradation mechanism is complex. Moisture can infiltrate the resin and between the resin and fibre, leading to cracks and voids in the bar material, particularly if the moisture contains chloride ions.

Basalt fibres, which are not completely natural fibres obtained in basalt rocks, possess high tensile resistance, better chemical and heat resistance, and are more environmentally friendly due to their low energy consumption during production. The degradation of FRP material occurs due to a chemical reaction between the fibre and the attacking solution, which can be prevented by providing appropriate resin protection to the fibres. In a study conducted by Davalos et al, surface degradation of GFRP bars embedded in high resistance cementitious compound was reported. Although the melting process of basalt fibres emits some carbon dioxide, it is minimal compared to other fibres such as steel fibres. Basalt fibres are also considered eco-compatible and recyclable green inorganic materials due to their non-flammable and un toxic attributes, production from natural mineral sources. CaCO₃ whisker and basalt fibres have been extensively studied in the literature for improved cracking resistance and mechanical performance in cementitious composites. However, Enhancing the connection between the fibre and matrix interface is critical for the fibre composite material's performance. Ground granulated blast furnace slag, which exhibits high chemical reactivity and a high specific surface area, has been proven to be an economical and effective method for improving the bond performance at the fibre-matrix interface.

The basalt fibre reinforced cementitious compound which contains of BFRP rods at a steady proportion so that resistance and flexural details is to be identified and it acts a good corrosion resistance in which it helps to resistanceen the grade and lifespan of cementitious compound. In order of these materials used it might be necessary to investigate the mechanical and durability issues simultaneously with the addition of GGBS might also observations in resistanceening of reinforced cementitious compound in it.

Basalt, a natural material that observations from molten magma at great depths beneath the Earth's surface and takes the form of a thick, walnut brown to black volcanic igneous rock, can be melted and extruded into fibre-forming material to produce basalt fibres. This process, known as spinning, involves applying lubricants and winding the material into a lengthy thread with a density of around 300 g/cm² and a length-to-diameter ratio ranging from thousands to infinity. Basalt fibres are non-toxic, do not react with water, and do not cause air pollution. They offer excellent attributes, including rigidity, resistance, heat resistance, and other structural

attributes, that make them useful in Basalt Fibre Reinforced Polymer (BFRP). These fibres are resistant to alkaline and acid and offer thermal, electrical, and acoustic insulation, as well as greater tensile resistance and elongation than small carbon fibres. Basalt fibres have been incorporated into randomly dispersed Fibre Reinforced Cementitious compound (FRC) to meet practical engineering needs, providing excellent attributes such as economy, anti-aging, and three-dimensional dispersion. Basalt fibre is a competitive alternative to polypropylene fibres and polyacrylonitrile fibre, as it does not expand in cement and cementitious compound. This material is a typical ceramic fibre that can be easily distributed when mixed with cement cementitious compound.

1.3 GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

The Ground Granulated Blast Furnace Slag (GGBS) as a replacement for cement has been shown to decrease carbon emissions in the atmosphere and its surroundings. However, exposing Fibre Reinforced Polymer (FRP) bars to harsh environments like aqueous solutions or chemical attacks can lead to degradation of their mechanical and physical attributes, outcome in bond deterioration. Hence, investigating the bond between newly created Basalt Fibre Reinforced Polymer (BFRP) bars with cementitious compound is crucial for their acceptance as reinforcing materials. The combining of GGBS to cementitious compound, which has a high specific surface area and exhibits high chemical reactivity, has been demonstrated to be an economical and effective technique for enhancing cementitious compound attributes. The GGBS, a by-product of manufacture process of iron, has excellent stiffness and resistance when included to cementitious compound, and when combined with basalt fibre and polymer rods, it observes its enhanced durability, resistance, and other mechanical attributes. The chemical structure of the GGBS is tabulated in table 1.1

Table1.1 Percentage of Binder for OPC& GGBS

% OF BINDER	OPC	GGBS
SiO ₂	21.29	34.90
Al ₂ O ₃	4.89	14.8
Fe ₂ O ₃	3.42	0.60
Cao	64.16	39.8

MgO	1.41	6.0
SO ₃	2.53	0.07
Na ₂ O	-	0.46
Mn ₂ O ₃	-	0.25
Cl	0.1	0.01
S	-	0.95

1.4 OBJECTIVES OF THE STUDY

The primary goals of the project are

- To ascertain the corporeal attributes of the substances
- To ascertain the mechanistic attributes such as compressive resistance, split tensile resistance, and durability of the cementitious compound beam
- To ascertain the bending conduct of the cementitious compound beam
- To ascertain the formative scrutiny of the cementitious compound beam utilizing SEM (Scanning Electron Microscopy) examination.
- To substantiate the outcomes utilizing FEM software and juxtapose the Analytical outcomes and Empirical Outcomes.

1.5 SCOPE OF THE STUDY

The scope of the project is

- Ascertain the characteristics like compressive resistance, split tensile resistance of basalt fibre reinforced cementitious compound.
- Observe the merits and demerits of usage GGBS in cement in basalt reinforced cementitious compound.
- Study and compare analytical and experimental observations of the modified cementitious compound.

1.6 NEED FOR PROJECT

The need for the project is

- The cementitious compound has become one of the pollution in the environment for that to overcome this the reduction of carbon emission various material are substituted.

- The research is to ascertain the mechanical attributes of the cementitious compound beam.
- The cementitious compound beam consists of GGBS replacement which helps to minimize the emission of CO_2 and to obtain the same or higher resistance as required.
- The beam consists of BFRP bars as reinforcement in case of steel reinforcement present in the conventional cementitious compound.
- Determination of compression test on cementitious compound
- To find the flexural resistance and the split tensile resistance in cementitious compound.
- The determination of morphological study of the casted cementitious compound beam using SEM analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Various literature studies related to replacement of BFRP rebar in the beam and the substitution of a portion of the cement content with ground granulated blast furnace slag are discussed in this chapter.

2.2 LITERATURE STUDY

Douglas Tomlinson And Amir Fam (2014), The objective of this literature review is to showcase the performance of cementitious compound beams reinforced with Basalt Fibre Reinforced Polymer (BFRP) bars and stirrups in flexural and shear tests. The dimensions of the beams were $150 \times 300 \times 3$ and 100mm, respectively, and they were tested under four-point bending with varying flexural reinforcement ratios (ranging from 0.28 to 1.60) and different types of stirrups to evaluate their effects on performance. The study included both BFRP and steel reinforcement without any shear reinforcement, with ultimate and service loads analyzed for all types of shear reinforcement. The cementitious compound used was grade 53 with a nominal resistance of 35 MPa and maximum aggregate size of 19mm. The research examined the resistance of the cementitious compound in each beam and discovered that the relationship between resistance and curvature deviates further from the one predicted based on middle span strain energy when shear-related deformation rises. The study confirms that conventional design provisions predict the capacity of beams that fail due to bending accurately, but the behaviour of beams that fail due to shear is both conservative and non-conservative. Moreover, the modified compression field test gives a reliable estimate of the shear capacity for members with and without stirrups. The research primarily focuses on the impact of BFRP flexural reinforcement ratio and stirrup type on ultimate load and serviceability, as well as failure modes. The findings show that BFRP reinforcement significantly improves the flexural and shear resistances, observationing in a 54% rise in normalized shear resistance. Additionally, the study identifies various potential failure modes, including flexural tension, flexural compression, shear failure without stirrups, and failure by BFRP stirrup rupture, and provides insights

into ultimate capacities, major diagonal shear cracking, and flexural behaviour. Finally, the observations are compared to theoretical predictions.

Andreea Serbescu et al (2014), The focus of this document is on the decay of GFRP bars during the product improvement process as a observation of exposure to harsh environmental conditions. A technique is proposed for the long-term design resistance of BFRP bars by conducting stress tests on samples that are conditioned in solutions with pH values of 9 and 13 at a range of temperatures between 20°C and 60°C. A comprehensive model is suggested for predicting the long-term MP resistance of FRP bars in diverse environments, based on industry Guidelines governing the use of FRP reinforcement in cementitious compound structures and on the observations obtained. The research also looks into how various conditioning environments affect the resistance and elastic modulus of commercial basalt fibre rods. The tensile resistance of the rods varied between 972 MPa to 1481 MPa, while the elastic modulus ranged from 34 GPa to 47 GPa. The study discovered that the bars that were exposed to a pH 9 solution at 60°C had the lowest resistance retention of 69%, and an 8% decrease in resistance occurred as the pH level rose from 7 to 13. Despite some resistance deterioration, the bars' elastic modulus rised by an average of 6.5%, which can be attributed to post-curing of the resin matrix. The study recommends that manufacturers of FRP bars should provide information on the mechanical degradation characteristics of their products, based on tests conducted on samples conditioned in water at 20°C, 40°C, and 60°C, and pH 13 at 20°C and 40°C.

Fareed Elgabbas, (2016), The present paper concerns an experimental investigation aimed at studying the bending behaviour and operational efficacy of cementitious compound beams reinforced with corrugated BFRP bars. The cementitious compound beams measured 3.1 m in length × 0.2 m width × 0.3 m in depth and were subjected to failure testing. The investigation involved testing of The experimental program consisted of testing beams reinforced with ribbed 8 mm, 12 mm, and 16 mm BFRP bars, as well as two control beams reinforced with 10M and 15M steel bars, in accordance with Canadian standards. The beams were subjected to four-point bending over a clear span of 2,700 mm, and their cracking behaviour, deflection, and modes of failure were analyzed. The study yielded an average bond-dependent coefficient to be 0.83, which is below the recommended level of 1 for

FRP ribbed bars as per the standards. Comparison of the two standards revealed that ACI provides deflection and serviceability load values for ribbed FRP bars.

Jason Duic et al (2018), This investigation assesses the efficiency of BFRP and steel reinforced cementitious compound beams withstanding shear and flexural. The findings indicate that BFRP reinforced beams with lower reinforcement ratios exhibit more cracking in flexural and shear compared to their steel reinforced counterparts, but still exhibit acceptable deformation. The cracking moment for BFRP reinforced specimens was discovered to be 30-50% lower than steel reinforced specimens. Additionally, the design of BFRP cementitious compound beam, containing BFRP stirrups should prioritize shear failure since it governs their design. Although BFRP reinforced beams can also fail in flexural tension or compression, pre-manufactured BFRP bent stirrups are required for BFRP reinforced cementitious compound beams containing stirrups. Thus, this investigation emphasizes the necessity for pre-manufactured BFRP stirrups. The BFRP stirrups employed in this research proved effective in delaying shear failure for low reinforcement ratios.

Zhihua Li et al (2022), In this study, the flexural behaviour of cementitious compound-basalt fibre reinforced cementitious compound beams with steel reinforcement was examined both experimentally and theoretically. The study proposed equations for computing the cracking, yielding, and the deflection of RC-BFRC beams, and these equations were validated through experiments. The study also carried out a parametric investigation using the proposed methods to gain a more profound understanding of the flexural performance of the RC-BFRC beam. The findings indicated that yield and ultimate moments rised with an rise in the yield resistance and amount of steel reinforcement, but ultimate curvature decreased in cases of under-reinforced failure. The curvature ductility and energy dissipation of the entire stage decreased with an rise in yield resistance and amount of steel reinforcement in cases of under-reinforced failure, but rised with an rise in cementitious compound. The study also examined the compressive resistance and ultimate compressive strain of the cementitious compound. Parametric analyses demonstrated that the yielding and ultimate moments rised with an rise in yield resistance and amount of steel reinforcement, but ultimate curvature, curvature

ductility, and energy dissipation of the entire stage decreased with an rise in yield resistance and amount of steel reinforcement in cases of under-reinforced failure.

Lina Xu et al (2021), This study investigates the impact of high temperatures on the mechanistic attributes and ultrasonic attributes of Basalt Fibre-Reinforced Cementitious compound with a high content of stone powder. To evaluate the mechanical attributes and ultrasonic attributes of the specimens at various temperatures, compressive resistance and nonlinear ultrasonic tests were conducted. The study found that the compressive resistance of the specimens improved with the addition of basalt fibre, but the resistance did not continuously rise with increasing fibre length and content. The study determined the optimal length and amount of fibres, which observed in the highest unconfined compressive resistance of the specimens followed by a decrease of regression model for the unconfined compressive resistance response of the cementitious compound reinforced with fibres and high stone powder content was established using the Box-Behnken design (BBD) method. The analysis of multifactor interactions revealed that the fibre content, length, and temperature had a significant effect on the observations. Ultrasonic analysis using signals based on the S transform demonstrated that increasing temperature observed in a decrease in the amplitude of the acoustic response signals, frequency spectrum, and time-frequency spectrum. The addition of fibres in the cementitious compound led to delayed crack propagation at high temperatures, observing in fewer cracks generated under the same heating conditions, and more energy was retained when the acoustic signal passed through the specimen

Julio F. Davalos et al (2008), “The objective of this paper is to examine the resilience of the bond between FRP bars and cementitious compound, with a focus on the degradation of the surface of the FRP bars when used with high-resistance cementitious compound. A variety of FRP bars were cast for bond resistance tests, and other specimens were prepared for compressive resistance testing of the cementitious compound, visual inspection of the FRP-cementitious compound interface, and scanning electron microscopy analysis to assess environmental effects. The specimens were exposed to a variety of conditions, including tap water at ambient temperature or 60°C, and thermal cycling air from 20 to 60°C. The deterioration of the FRP bars was identified as the primary cause of bond

degradation, with cementitious compound having a lesser impact. The bond failure mode and degradation mechanism were analyzed in relation to damage to the FRP bars. The bond performance of these bars in cementitious compound was enhanced by the interface bond between sand coating and core-bar. The material attributes and surface characteristics of the FRP bars, such as geometric indentations and coatings, were found to have an impact on their bond resistance, as bond failures were mainly observed on the bar surfaces. These discoveries can be used to establish appropriate local bond slip traction laws for numerical modeling of bond behaviours due to FRP bar material degradation, particularly in the case of high-resistance cementitious compound. GFRP bars primarily experienced pull-out bond failure within the bar surfaces, and in this instance, the bond resistance of FRP bars was not influenced by cementitious compound resistance. However, when cementitious compound resistance is relatively low, bond failure is dependent on cementitious compound compressive resistance and is mostly due to cementitious compound failure.”

Naraindas Bheel (2021), Lately, the utilization of basalt fibres to reinforce the attributes of hardened cementitious compound has gained popularity. Nonetheless, the integration of these fibres has an impact not only on the hardened state of cementitious compound but also on its fresh attributes, specifically its workability. Therefore, comprehending the influence of basalt fibre incorporation on both the Attributes of cementitious compound in its fresh and hardened states is vital. This article provides a comprehensive overview of the attributes of basalt-fibre reinforced cementitious compound (BFRC) regarding its fresh and mechanical attributes, with a particular focus on the effect of basalt fibre length and dosage. As the length and quantity of basalt fibre in cementitious compound rise, the slump of reinforced cementitious compound with basalt fibre decreases due to water absorption by the fibres. Previous research has indicated that the splitting tensile resistance of cementitious compound gradually rises with age and dosage of basalt fibre. Moreover, several researchers have demonstrated that an rise in the quantity of basalt fibre observations in an rise in the flexural resistance of cementitious compound. Additionally, the modulus of elasticity also rises with the rise in both the length and amount of basalt fibre.

Eric Hughes et al (2020), The present study conducts experiments to explore the feasibility of utilizing basalt fibre reinforced polymer fabrics for reinforcing reinforced cementitious compound (RC) structural elements subjected to flexural loads. The main objective of this research is to investigate the practicality of using BFRP fabrics as an in-situ reinforcement method for RC members. BFRP fabrics are a promising option for external resisting of RC members, offering economic and environmental benefits. These fabrics are more economical, durable, and have a higher fracture strain compared to alternative FRP materials. The study reveals that when a beam is over-reinforced with BFRP fabrics, the failure mode may unexpectedly change to brittle shear failure, which suggests that further shear resisting should be considered once the maximum flexural resisting is achieved. The observations demonstrate that externally bonded BFRP is a viable alternative to other FRP fabrics for flexural resisting of RC beams, as the beams resisted with BFRP fabrics showed significantly improved load-carrying capacity at both yield and ultimate load points.

Giri Prasad Goud et al (2021), The corrosion resistance of M30 grade cementitious compound containing basalt fibres was investigated by analysing on the resistance of cementitious compound reinforced with basalt fibres and BFRP bars against corrosion, as measured by its resistivity, potentials, and chloride ion diffusion. The cementitious compound specimens tested were of M30 grade and had basalt fibres and BFRP rebars as reinforcement. The beams with both basalt fibres and BFRP rebars exhibited an extended time of total charge passing at failure, suggesting their ability to resist fissures or micro cracks. Moreover, the measured electrical resistivity values in these beams were high, indicating excellent corrosion inhibition attributes. The study presented a minimal probability (less than 5%) for corrosion at the end of the project.

Qiaoyun Wua et al (2018), When attaching prestressed BFRP (basalt fibre reinforced polymer) rods to reinforce cementitious compound structures, the open-up of prestress may cause interfacial shear stress at the ends of the BFRP, leading to early debonding. To avoid this issue, the interfacial adhesive resistance must not exceed the BFRP-induced shear stress from prestressing. In this investigation, the mechanical attributes of the adhesive interface at the ends of BFRP rods bonded to cementitious compound beams were evaluated using experimental methods such

as double pull-pull and single push-push tests. A modified formula was developed to predict the interfacial shear stresses, BFRP stresses, and maximum scoring prestress level based on previous studies. The experimental observations validated the accuracy and reliability of the proposed theoretical formula. Furthermore, the study suggested a practical approach for reducing interfacial shear stress and preventing premature failure near the BFRP ends due to shear stress concentration.

Yiqing Dai (2016), Basalt fibre reinforced polymer (BFRP) presents a promising alternative to steel, as it offers superior resistance, durability, insulation, non-magnetic attributes, and resistance to corrosion, particularly in challenging environments like ports, mining areas, and high-speed railway structures. In these conditions, continuously reinforced cementitious compound pavement (CRCP) reinforced with BFRPs is gaining popularity due to its exceptional characteristics. To investigate specific mechanical attributes, this study employs ABAQUS to construct a finite element model based on material testing. The analysis explores the impact of variables like crack width, BFRP modulus, reinforcement ratio, and voids under the pavement. The observations demonstrate that replacing steel bars with BFRP bars observations in wider cracks and rised spacing between cracks. Both crack width and voids under the pavement significantly affect the mechanical state and load transfer efficiency. Once the crack width exceeds 1.1 mm, the cementitious compound's ability to transfer loads decreases. BFRP modulus and reinforcement ratio do not have a significant effect on mechanical attributes or load transfer efficiency in a constant state. However, the calculations illustrate their efficiency in controlling crack width. This research provides practical guidelines for designing CRCP reinforced with BFRP.

Md Hasham (2021), This paper investigates the deflection characteristics of M30 grade cementitious compound slabs reinforced with basalt fibre reinforced polymer rebars and compares them to those reinforced with steel rebars. The optimal ratio of basalt fibres is determined to be 0.3% for 50mm length fibres. The addition of basalt fibres leads to high particle packing density, which helps prevent micro cracks and improve fatigue and stress dissipation capacity. Moreover, the basalt fibres enhance energy absorption capacity, toughness, resistance to local damage, and spalling. They also help control crack growth and width. Compared to conventional cementitious compound slabs reinforced with steel rebars, the

deflection at the center of M30 grade cementitious compound slabs reinforced with BFRP rebars is nearly twice. The calculated toughness indices for M30 grade basalt-fibre-reinforced cementitious compound slabs reinforced with BFRP rebars demonstrate that both basalt fibres and BFRP bars boost the energy absorption capacity of the slabs.

Mehran Khan (2022), This paper examines the attributes of mixing of steel & basalt fibre reinforced cementitious compound under various environmental situations. The long-term behaviour of cementitious compound is a critical factor for structural integrity, particularly in situations involving acid or sulfate attack. The study explores the optimization of basalt fibres and a quantitative analysis of the fibre factor for various environmental conditions. The researchers combined basalt fibres and steel fibres with a fly ash- CaCO_3 whisker mixture to create hybrid fibre reinforced cementitious compound (HFRC), which was then subjected to different aggressive environments. A new fibre factor for HFRC is proposed, and empirical models are established for the mechanical attributes. Additionally, scanning electron microscopy (SEM) analysis was performed on the HFRC to evaluate the microstructural damage caused by chemical attacks. The observations show that including steel fibres and basalt fibres significantly improves water absorption, weight loss, and compressive resistance of HFRC when exposed to hazardous environmental conditions compared to plain cementitious compound.

Jongsung Sim (2005), The purpose of this research is to investigate the viability of using basalt fibre as a reinforcement material to enhance the resistance of cementitious compound structures. Various tests were performed to evaluate the mechanical attributes, durability, and ability to resistance flexure. The basalt fibre was sourced from Russia and exhibited a tensile resistance of 1000 MPa, which is 30% of the carbon fibre and 60% of the high-resistance glass (S-glass) fibre. When immersed in an alkali solution, both the basalt and glass fibres experienced volume and resistance losses, and a reaction product formed on their surfaces. However, the carbon fibre did not show any significant reduction in resistance. The observations of an accelerated weathering test revealed that the basalt fibre outperformed the glass fibre in terms of resistance. At a temperature of 600°C for two hours, the basalt fibre retained approximately 90% of its resistance at normal

temperatures, whereas the carbon and glass fibres did not maintain their volumetric integrity.

Zhongyu Lu (2019), The aim of this investigation is to assess the effectiveness of basalt fibre-reinforced polymer (BFRP) bars in resisting cementitious compound structures against marine environments. To accomplish this, 20-mm cementitious compound covers were applied to BFRP bars and then immersed in ocean water or simulated seawater at room temperature ($\sim 23^{\circ}\text{C}$), and the observing thermomechanical attributes were evaluated. Furthermore, a group of uncovered BFRP bars were also submerged in ocean water and laboratory-accelerated simulated seawater (23°C , 40°C , and 60°C) for comparison. After one year, the BFRP bars that were exposed to 60°C simulated seawater without a cover demonstrated the most considerable mechanical degradation, followed by the covered BFRP bars in the laboratory immersion. The deterioration of the resin matrix and sizing exposed the basalt fibres to the alkaline solution, which initiated the alkali-aggregate reaction (AAR).

Ahmad Altalmas (2015), This paper investigated the bond behaviour of basalt and glass fibre reinforced polymer bars to cementitious compound under various test parameters, including conditioning environment, material type, and exposure duration. The study evaluated the adhesion, bond resistance, slip, and failure point of the specimens. BFRP bars showed higher bond resistance and adhesion to cementitious compound than ribbed GFRP bars, regardless of the fibre type or exposure condition. The suction of the bar material and manufacturing quality affected the bond structure of the conditioned specimens. All specimens failed in pull-out mode due to inter-laminar shear. Conditioning reduced the bond resistance of BFRP bars by 14-25% of their initial resistance. However, it should be noted that the specimens were directly exposed to saturated solutions until testing, which may not accurately represent the actual conditions of FRP bars in service. The study concluded that BFRP bars have potential as reinforcing materials, but further research is needed to include other commercially available bars.

John Branston (2016), This research evaluates the efficacy of two basalt fibre types, bundle dispersion fibres and minibars, in enhancing the mechanical characteristics of cementitious compound. The aim of this research was to

investigate the influence of different types and quantities of fibres on the flexural and impact attributes of cementitious compound specimens. Scanning electron microscopy was used to evaluate the interfacial attributes between the fibres and the cementitious compound. The observations indicated that both types of fibres enhanced the pre-cracking resistance of the cementitious compound, but only minibars improved the post-cracking behaviour due to the polymer's protective effect. The study also observed the formation of cement hydration products between individual filaments of the bundles of fibres. After nine months, physical changes were observed on the surface of the fibres, indicating their degradation. The study concludes that the brittle behaviour of the basalt fibre composites could be due to fibre rupture caused by an rise in the fibre-matrix bond resistance and a decrease in the fibre tensile resistance.

Majhi (2018), The aim of this investigation is to devise sustainable cementitious compound by using ground granulated blast furnace slag and reused coarse aggregate (RCA) as replacements for ordinary Portland cement and natural coarse aggregate (NCA), correspondingly. Sixteen cementitious compound mixes were produced by varying the proportions of RCA and GGBFS as replacements for NCA and cement, respectively. The study assessed the attributes of fresh and hardened cementitious compound, including workability, density, compressive resistance, split tensile resistance, flexural resistance, volume of voids, water absorption, and rebound number. The outcomes revealed that incorporating RCA or GGBFS, or both, amplified the workability of the cementitious compound. However, as the percentage of RCA or GGBFS, or both, rised compressive, split tensile, and flexural attributes resistances decreased. According to the study findings, the optimal mix was the one with 50% RCA and 40% GGBS. This mix fulfilled the mix design's target mean resistance while saving 40% of cement and 50% of NCA and utilizing maximum waste products such as GGBS and RCA, promoting sustainability.

Dong (2016), This research paper explores the mechanistic characteristics and microstructure of basalt fibre reinforced recycled aggregate cementitious compound, which encourages the recycling of cementitious compound in the construction industry and caters to the rebuilding necessities of earthquake-prone areas. The study centres around to assess the impact of basalt fibre (BF)

content and the ratio of recycled coarse aggregate substitution on the tensile and compressive resistance, ultimate strain, Poisson's ratio, elastic modulus, and failure mode of BF-reinforced RAC, the study was conducted. The study found that the mechanical characteristics of RAC could be improved by adding BF, and SEM examination suggested that BF could accumulate in the pores and on the surface of attached mortar, enhancing RAC's microstructure and refining the interfacial transition zone, leading to rised ductility and resistance.

Yihong Guo (2019), This study examines the influence of basalt fibre and mineral admixtures, such as fly ash and silica fume, on the resistance to cementitious compound to chloride penetration at various curing ages. To investigate this, fifteen mixtures were created with varying BF volume contents and three types of cementitious compounds, and they were cured for 28 or 56 days. The specimens were tested for compressive resistance, charge passed, apparent density, and chloride diffusion coefficient. The observations indicate that the optimal compressive resistance of basalt fibre reinforced cementitious compound is achieved at a BF content of 0.15%. However, the addition of BF decreases the resistance in cementitious compound to chloride, and as the BF volume rises, the resistance decreases even further. In contrast, the use of mineral admixtures and longer curing periods improves the resistance of BFRC to chloride penetration.

Saikrishna (2021), The purpose of this study is to analyze the moment-curvature behaviour of cementitious compound beams reinforced with basalt fibre reinforced polymer (BFRP) bars, and compare it with conventional steel rebar reinforced beams. The flexural attributes of both types of rebars were examined by casting M30 grade beams with BFRP and steel rebars. The load-deflection plots were used to evaluate flexural characteristics such as load at first crack, ultimate flexural resistance, deflection at the centre, and crack width at failure. Deflections were measured using deflection meters at the central point and under load, and the values of moments and curvatures were obtained. This study demonstrates the significance of moment curvature relationships in assessing the ductility of the structure and the potential redistribution of stresses.

Rami Hawileh (2017), The present investigation analyzes the relationship between the moment and curvature of cementitious compound beams, which are

reinforced in basalt fibre-reinforced polymer (BFRP) bars and compared with typical steel-reinforced beams. The beams of M30 grade were constructed by using both steel and BFRP rebars to analyse the flexural attributes of BFRP bars and basalt fibres. Various flexural attributes such as ultimate flexural resistance, load at first crack, deflection at the center, and crack width at failure were evaluated using load-deflection plots. Deflections were determined at the central point and under load using deflection meters, and the values of moments and curvatures were calculated. The outcomes of the study highlight the importance of moment-curvature relationships in assessing the ductility of the structure and the potential redistribution of stresses.

Fareed Elgabbas (2015), This study reports the observations of the experimental investigation aimed at evaluating the characteristics of physical, mechanical, and durability of basalt fibre-reinforced polymer (BFRP) bars. The investigation assessed the long-term performance and durability of BFRP bars by exposing them to an alkaline solution, which mimics the cementitious compound environment, to ascertain their suitability as internal reinforcement for cementitious compound elements. Three types of BFRP bars were examined to evaluate their physical, mechanical, and durability attributes and compared with their unconditioned (reference) values. The findings revealed that the BFRP bars exhibited satisfactory mechanical performance, comparable to grade II and grade III GFRP bars (based on tensile modulus of elasticity), and a higher tensile resistance than CFRP bars. Nonetheless, the BFRP bars exhibited poor alkali resistance and a significant decline in mechanical attributes due to issues with the resin-fibre interface, which must be addressed to attain the desired durability characteristics.

Chaohua Jiang (2014), In this investigation, the effect of basalt fibre (BF) on the mechanical attributes of fibre-reinforced cementitious compound (FRC) was studied by varying the volume fraction and length of BF. In addition, the microstructure of the BF cementitious compound was analyzed using scanning electron microscopy (SEM) and a mercury intrusion porosimeter (MIP). The observations show that the inclusion of BF in the cementitious compound leads to a notable enhancement in tensile , flexural , and toughness index, but not compression resistance. Furthermore, the length of BF has a significant impact on

the mechanical attributes. The addition of 12 mm BF to the cementitious compound observed in an rise in compressive, split tensile, and flexural resistance by 0.18-4.68%, 14.08-24.34%, and 6.30-9.58%, respectively, when compared to plain cementitious compound.

SUMMARY

The condensed account of the examined literature is as follows:

- From the review of literature, the attributes of basalt fibre reinforced bar and the characteristics of ground granulated blast furnace slag.
- The basalt rod contains high corrosion resistance which inhibits the acceleration of electrons to pass through the rebar and contains rust in the steel and this process is not occurred in this type of bar.
- The GGBS contains certain substances which are useful in reduction of CO₂ emitted from plain cement cementitious compound and helps to rise the resistance of cementitious compound beam than the conventional one.
- The degradation characteristics of the basalt fibre which contains mechanical attributes like compressive, flexural and other like durability, water absorption etc...
- The attributes of the cementitious compound added with basalt fibre and the reinforced bar contains a good resistance and stiffness.

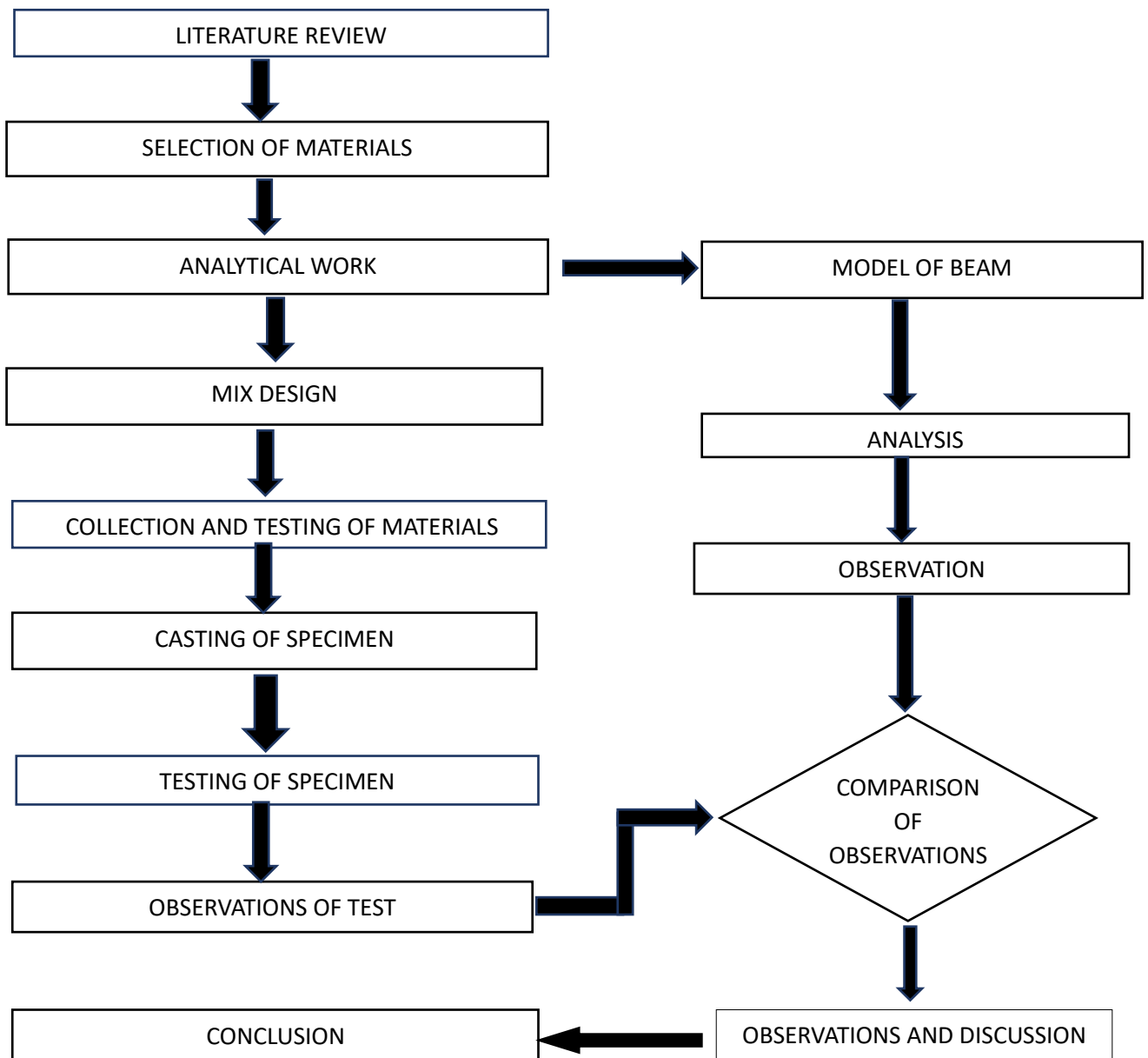
CHAPTER 3

METHODOLOGY

3.1 GENERAL:

The methodology shows the step by step procedure and their detailed explanation about both experimental and analytical process and both the observations should be compared and explained.

3.2 METHODOLOGY:



- At Initial stage, the review of the literature is examined and the materials are selected as per the reference of the paper.

- The model of the beam is worked out in analysis software and examined.
- After successful of the analytical part the materials which are to be used are collected and the initial test are made on it.
- The casting of cube, cylinder and beams are done as per the IS code and the specimens are cured and the tests are made at an interval of 7, 14 and 28 days.
- The testing of specimen contains compression test, split tensile resistance test and flexural resistance test are done and the SEM analysis of the beam are also done.
- The experimental observations are compared with analytical observations obtained in FEM software and the discussion are made and the final conclusion is also done.

CHAPTER 4

MATERIALS AND EXPERIMENTAL INVESTIGATION

4.1 GENERAL

In this research work various materials are used, their description and attributes are explained and this chapter also explains about the experimental test and their observations in it.

4.2 MATERIALS

There are various materials selected and used in this project and they are listed below

- Cement
- Fine Aggregate
- Coarse aggregate
- Water
- GGBS
- BFRP Rebar

4.2.1 Cement

The cement utilized in the study must satisfy all of the IS criteria. Several types of cement are commercially available, with Portland cement being the most common and easily accessible. For this experiment, OPC 53 grade was utilized. The physical attributes of the cement were analysed and found to meet Indian Standards requirements.



Fig 4.1 Cement

Table 4.1 Physical Attributes of Cement:

S.No	Attributes	value
1.	Specific gravity	3.13
2.	Initial setting time	43 min
3.	Final setting time	260 min
4.	Fineness test	6% retained

4.2.2 Fine Aggregate

Aggregate is a granular material utilized in making cementitious compound or mortar. When the granular material's particles pass through a 4.75mm sieve, it is referred to as fine aggregate. Fine aggregate is commonly used in the building industry to higher the volume of cementitious compound, which saves on costs. By selecting the fine aggregate based on criteria such as grading zone, particle shape and surface texture, abrasion and skid resistance, absorption, and surface moisture, the cementitious compound or mortar mixture can become more durable, stronger, and more cost-effective. The specific gravity of fine aggregate is 2.61.

4.2.2.1 Specific Gravity and Water Absorption test on Fine aggregate

The identification of stones can be done through the specific gravity test, which is a helpful method. The resistance of an aggregate can also be determined through the water absorption test. Aggregates with a higher rate of water absorption are usually more holes and may be considered inappropriate unless they pass the necessary tests such as impact resistance, hardness, and resistance. Tests are conducted based on IS 2386 part 3 1963.

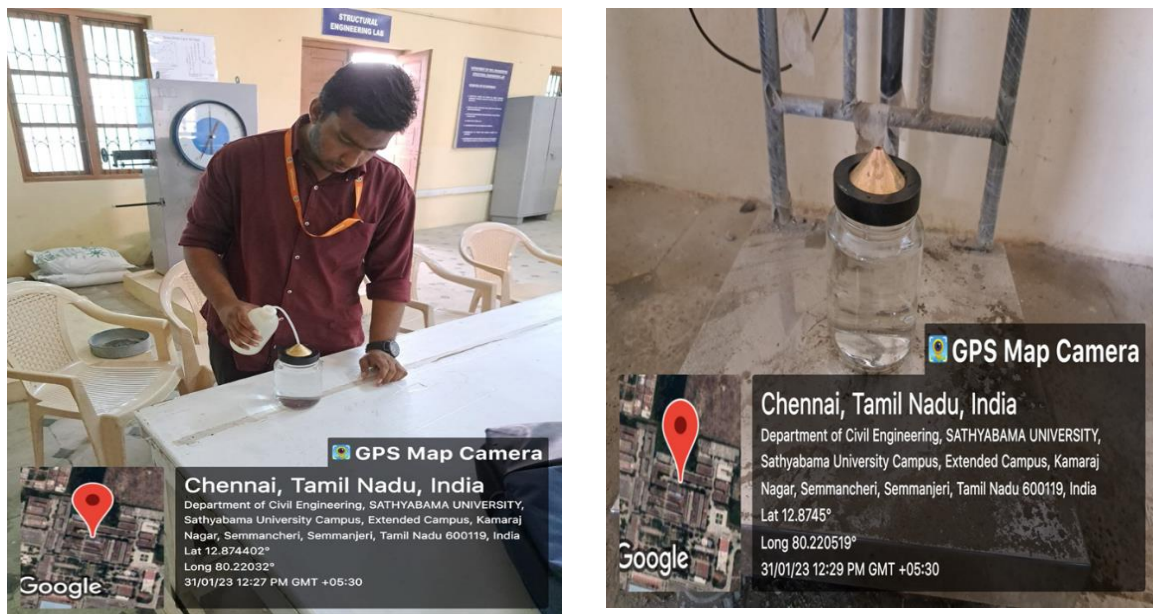


Fig 4.2 Addition of water to the pycnometer

Apparatus required:

- Balance
- Oven
- A wide mouthed vessel
- Hair drier
- Tray
- Airtight container
- Filter paper
- Funnel

Test Procedure

- We dehydrated the test specimen to achieve an air-dry condition before conducting the sieve analysis.
- We accomplished this by either letting it dry naturally at ambient temperature or heating it to 100-110°C.
- Once the sample reached the air-dry state, we weighed it and then sifted it through appropriate sieves, commencing with the largest.
- Before using the sieves, we cleaned them meticulously. We shook each sieve individually over a pristine tray for at least two minutes, using various motions such as backward-forward, left-right, circular clockwise and anticlockwise, and intermittent jolting.
- We ensured that the material kept moving on the sieve surface in different directions. We didn't apply any manual force to push the material through the sieve, but we allowed particles to be placed on sieves coarser than 20 mm.
- We gently broke any lumps of fine material present using our fingers against the sieve side.
- We lightly brushed the sieve underside with a soft brush to clear the openings, and we used a fine camel hair brush to prevent powder aggregation and blocking of the openings of 150-micron and 75-micron IS sieves.
- We avoided using stiff or worn-out brushes, and we didn't apply any pressure to the sieve surface to force particles through the mesh.
- After completing the sieve analysis, we weighed the material remaining on each sieve, as well as any material removed from the mesh.
- Table 4.2 below can be used by us to identify the fine aggregate zone after sieve analysis.

Calculation:

A= 1000g

B=3372g

C=2754g

D=990g

$$\text{Specific gravity} = \frac{D}{A-(B-C)} = \frac{990}{1000-(3372-2754)} = 2.61$$

$$\text{Water Absorption} = \frac{100(A-D)}{D} = \frac{100(1000-990)}{990} = 1.01\%$$

Where,

A = weight in g of saturated surface-dry sample,

B = weight in g of pycnometer or gas jar containing sample and filled with distilled water,

C = weight in g of pycnometer or gas jar filled with distilled water only, and D = weight in g of oven-dried sample.

Observations:

- Specific Gravity of fine aggregate = 2.61
- Water Absorption of Fine Aggregate = 1.01%

4.2.2.2 Sieve Analysis:

The sieve analysis of fine aggregate is a process utilized to determine the distribution of particle sizes present in materials like sand, silt, or clay that are smaller than 4.75mm in size but larger than 75 microns, as they pass through the former sieve and are retained by the latter. This test and observations are conducted based on IS 2386 part1 1963 and IS 383.



Fig 4.2 Fine Aggregate sample within the sieve & appropriate size of sieve

Apparatus

- Sieve
- Balance

Test procedure:

- To prepare the sample for weighing and sieving, I dehydrated it to an air-dry state. I accomplished this by either drying it naturally at room temperature or by heating it to 100-110°C.
- Once the sample was air-dry, I weighed it and started sieving it using the appropriate sieves, starting from the largest. Before using the sieves, I ensured that they were clean.
- I dehydrated the sample by air-drying it or heating it to 100-110°C before weighing and sieving.
- After weighing the air-dry sample, I started sieving it on the appropriate sieves, starting with the largest.
- Before use, I carefully cleaned each sieve.
- To ensure thorough sieving, I shook each sieve separately over a clean tray for at least two minutes, using various motions such as backward-forward, left-right, circular clockwise and anticlockwise, and intermittent jolting.
- I ensured that the material kept moving over the sieve surface in changing directions.
- I did not use manual force to push the material through the sieve, but I allowed particles to be placed on sieves coarser than 20 mm.
- If there were lumps of fine material present,
- I gently broke them using my fingers against the side of the sieve.
- I used a soft brush to lightly clear the underside of the sieve openings.
- To prevent powder aggregation and blocking of the openings, I used a fine camel hair brush to lightly brush the 150-micron and 75-micron IS sieves.
- I made sure not to use stiff or worn-out brushes and avoided applying pressure to the surface of the sieve to force particles through the mesh.

- After completing the sieving process, I weighed the material remaining on each sieve, as well as any material removed from the mesh..

Table 4.2 Sieve Analysis of Fine Aggregate

SIEVE SIZE	WEIGHT OF FINE AGGREGATE RETAINED				PERCENTAGE RETAINED	CUMULATIVE PERCENTAGE RETAINED	PERCENTAGE PASSING	PERMISSIBLE PERCENTAGE PASSING AS PER IS 383	
	DETERMINATION NO								
	I	II	III	AV G					
10 mm	0				0	0	0	100	90-100
4.75 mm	0.024				0.0024	0.0024	2.4	97.6	75-100
2.36 mm	0.344				0.0344	0.0368	36.8	63.2	55-90
1.18 mm	0.150				0.0150	0.0518	51.8	48.2	33-59
600 mic	0.180				0.0180	0.0698	69.8	30	8-30
300 mic	0.230				0.0230	0.0928	92.8	7.2	0-10
150 mic	0.050				0.0050	0.0978	97.8	2.2	
75 mic	0.022				0.0022	0.1	100	0	
Pan	1kg								
total									

Observation:

Conforming to grading Zone II of table 9 of IS 383

4.2.3 Coarse Aggregate

Coarse aggregates play a crucial role in cementitious compound and are essential in providing structural integrity while minimizing shrinkage. These aggregates can be classified based on their shape and size, such as round, irregular, angular, flaky, and elongated. Additionally, the coarse aggregates can also be categorized based on their size, such as gravels, cobble, and boulders, and can be used in normal resistance to high resistance cementitious compound with sizes ranging from 4mm to 256mm. To achieve the maximum resistance and a workable mix, the coarse aggregates used must be sturdy, impermeable, durable, and capable of forming a suitable mixture. For instance, the coarse aggregate with a size of 20mm used in this project is made of crushed stone with a specific gravity of 2.68.

- **Uncrushed Stone:** Such aggregate is formed by natural disintegration of rocks.
- **Crushed Stone:** It is the outcome of crushing of gravel or hard stone.
- **Partially Crushed Stone:** It forms by blending of the above two aggregate.

4.2.3.1 specific gravity & water absorption of coarse aggregate

The identification of stones can be facilitated by conducting the specific gravity test. Furthermore, the water absorption test can provide valuable information about the resistance of an aggregate. Aggregates with greater water absorption rates are usually more porous and are typically deemed inappropriate, unless they meet acceptable standards for resistance, impact resistance, hardness, and other relevant criteria. These tests are conducted in accordance with the guidelines set forth in IS 2386 part 3 1963.



Fig 4.4 immersing coarse aggregate into the water

Apparatus required

- Balance
- Oven
- Wire basket
- Two soft absorbent cloths
- Tray
- Airtight container
- Water tight container

Test Procedure

- I will begin the specific gravity test by immersing the sample in distilled water at a temperature between 22°C to 32°C in a wire basket, making sure that the water level is at least 5 cm above the basket. Before immersing it, I will wash the sample thoroughly to remove any dust and finer particles.
- After immersing the sample in water, I will remove the entrapped air from the sample by lifting the basket containing it 25 mm above the base of the tank and allowing it to drop 25 times at a rate of about one drop per second. I will ensure that the basket and aggregate remain completely immersed during the operation and for a waiting period of 24 1/2 hours.

- Once the immersion and waiting period is over, I will jolt and weigh the basket and sample in water within a temperature range of 22 to 32°C. If I need to weigh it in a different tank, I will make sure to jolt the basket and sample 25 times in the new tank to ensure accuracy (weight A).
- After draining for a few minutes, I will remove the basket and aggregate from the water and gently empty the aggregate onto a dry cloth. Then, I will return the empty basket to the water, jolt it 25 times, and weigh it in water (weight B).
- Next, I will gently transfer the aggregate from the basket onto a dry cloth and gently surface dry it using the cloth. If the first cloth removes no further moisture, I will transfer the aggregate to a second dry cloth and spread it out, not more than one stone deep. I will leave it exposed to the atmosphere away from direct sunlight or any other source of heat for not less than 10 minutes or until it appears to be completely surface dry.
- I will turn over the aggregate at least once during this period, and if necessary, I will use a gentle current of unheated air to accelerate the drying of difficult aggregates.
- Finally, I will weigh the aggregate (weight B) and place it in a shallow tray, then put it inside an oven with a temperature range of 100 to _____ (fill in the missing value as per requirement).
- Once the time is up, I will take the aggregate out of the oven, allow it to cool in an airtight container, and then weigh it again (weight C).

Calculation:

$$\text{Specific gravity} = \frac{C}{B-A} = \frac{2.520}{2.540-1.62} = 2.739$$

$$\text{Water absorption} = \frac{100(B-C)}{C} = \frac{100(2.540-2.520)}{2.520} = 0.79\%$$

Where:

A = the weight in g of the saturated aggregate in water (A1-As) = 1.62 kg

B = the weight in g of the saturated surface – dry aggregate in air = 2.540 kg

C = the weight in g of oven dried aggregate in air = 2.520 kg

Observations

- The fine aggregate's specific gravity = 2.739
- The fine aggregate's absorption of water = 0.79%

Table 4.3 Physical Attributes of Coarse Aggregate:

S.No	Attributes	Value
1.	Specific Gravity	2.739
2.	Crushing value	14.21%
3.	Impact value	2.5
4.	Density kg/m ³	1560
5.	Water absorption	0.79%

4.2.4 Ground Granulated Blast Furnace Slag(GGBS)

The Ground Granulated Blast Furnace Slag, a substance with cementitious attributes, finds its primary application in cementitious compound and is a residual output from the iron-making blast furnaces. These furnaces function at extreme temperatures of roughly 1,500°C and are distributed with a precisely blend of limestone, coke, and iron ore. The characteristics of GGBS are specified within the factory.



Fig 4.5 GGBS

Table 4.4 Physical Attributes of GGBS:

S.No	Chemical Constituents	% Percentage in GGBS
1.	Calcium oxide CaO	42
2.	Silicon Di oxide SiO ₂	37
3.	Aluminium oxide AlO ₂	9-12
4.	Magnesium oxide MgO	7

4.2.5 Basalt Fibre Reinforced Polymer (BFRP) Rebar

BFRP rebar is a type of reinforced polymer made from basalt fibre that is commonly used as a highly durable and strong reinforcement for cementitious compound. It is often referred to as rock rebar or basalt rock rebar due to its composition. BFRP rebar is also effectiveness in enhancing the overall resistance of cementitious compound structures. Basalt fibre, the key component of BFRP rebar, is much lighter and possesses up to 2.5 times greater tensile resistance than steel. Additionally, it is highly resistant to rust and is able to withstand exposure to salt ions, chemicals, and the naturally high alkalinity found in cementitious compound.



Fig 4.6 BFRP Rebar

Table 4.5 Physical Attributes of BFRP:

S.No	Physical Attributes	Suggested values by supplier
1.	Length (mm)	1000
2.	Yield Resistance (Mpa)	>1000
3.	Density (g/m ³)	2.63
4.	Tensile Resistance (Mpa)	950

4.2.7 Reinforcement Details:

Table 4.6 Reinforcement Details of BFRP Bar

S.NO	SPECIFICATION	DIMENSION
1.	Length Of the Main Rod	950mm
2.	Length of the stirrups	100mmx100mm
3.	Diameter of the main rod	10mm
4.	Diameter of the stirrups	8mm
5.	Number of main rods in the beam	4nos
6.	Beam size	1000mmx230mmx230mm

The table 3.1 describes about the details of reinforcement used in cementitious compound beam. The length of the bar is about 950mm and the stirrup length is about 100mmx100mm diameter of the main rod is about 10mm and the stirrups having diameter about 8mm. the size if the beam is about 1000mm length and width having 230mm and depth having about 230mm where it contains 4 main bars around all corners.

4.3 EXPERIMENTAL INVESTIGATION:

4.3.1 Mix design:

The formulation used to achieve M50 grade cementitious compound adheres to the guidelines outlined in IS: 10262 - 2019. The observationing ratio for the nominal M50 grade is 1:1.54:2.33, while the water-to-cement ratio is 0.35.

4.3.1.1 Mix proportion:

The GGBS is used as portion of replacement in the cement at the range of 0%, 20%, 40% and 60% respectively. Also based on the test mixes the appropriate mix design are also made. The nominal design mix for M50 cementitious compound grade mix proportion is shown in the table.

Table 4.7 mix proportion

Materials	Quantity (kg/m³)
Cement	450
Fine Aggregate	696
Coarse Aggregate	1051
Water	157.5
Chemical Admixture	4.31

4.3.2 Cementitious compound Casting Specimen Process:

As a civil engineer, I understand that casting is the process of creating a solid object from a liquid or semi-liquid material by pouring it into a mold or a form and allowing it to harden. In the context of cementitious compound, I know that casting refers to the process of creating a solid, three-dimensional object or shape from a mixture of cement, water, aggregates, and additives.

To cast cementitious compound elements, I need to follow these steps:

- Formwork preparation: I need to prepare a form or mold based on the required size and shape of the cementitious compound element. The form can be made of various materials, such as wood, steel, or plastic.
- Reinforcement placement: In some cases, I need to place reinforcement such as steel bars or mesh inside the formwork to provide additional resistance to the cementitious compound element.
- Cementitious compound mixing: I prepare the cementitious compound mixture by mixing cement, water, aggregates, and additives in the correct proportions. The mixing can be done manually or by using a cementitious compound mixer.
- Pouring: I pour the cementitious compound mixture into the formwork, taking care to avoid any air pockets or voids.
- Consolidation: I consolidate or compact the cementitious compound mixture to ensure that it is fully distributed throughout the formwork and there are no voids or air pockets. Consolidation can be done using tools such as vibrating screeds, poker vibrators, or rollers.
- Curing: I leave the cementitious compound to undergo a designated duration of treatment and solidification, commonly 28 days, during which the cementitious compound acquires increased robustness and resilience.
- Demolding: Once the cementitious compound has hardened, I remove the formwork, and the cementitious compound element is released.

As a civil engineer, I understand that proper execution of the casting process is essential for the structural integrity and longevity of cementitious compound construction. The casting process is a critical step in the production of cementitious compound elements, as it ensures that the final product is of the desired shape, size, and resistance.

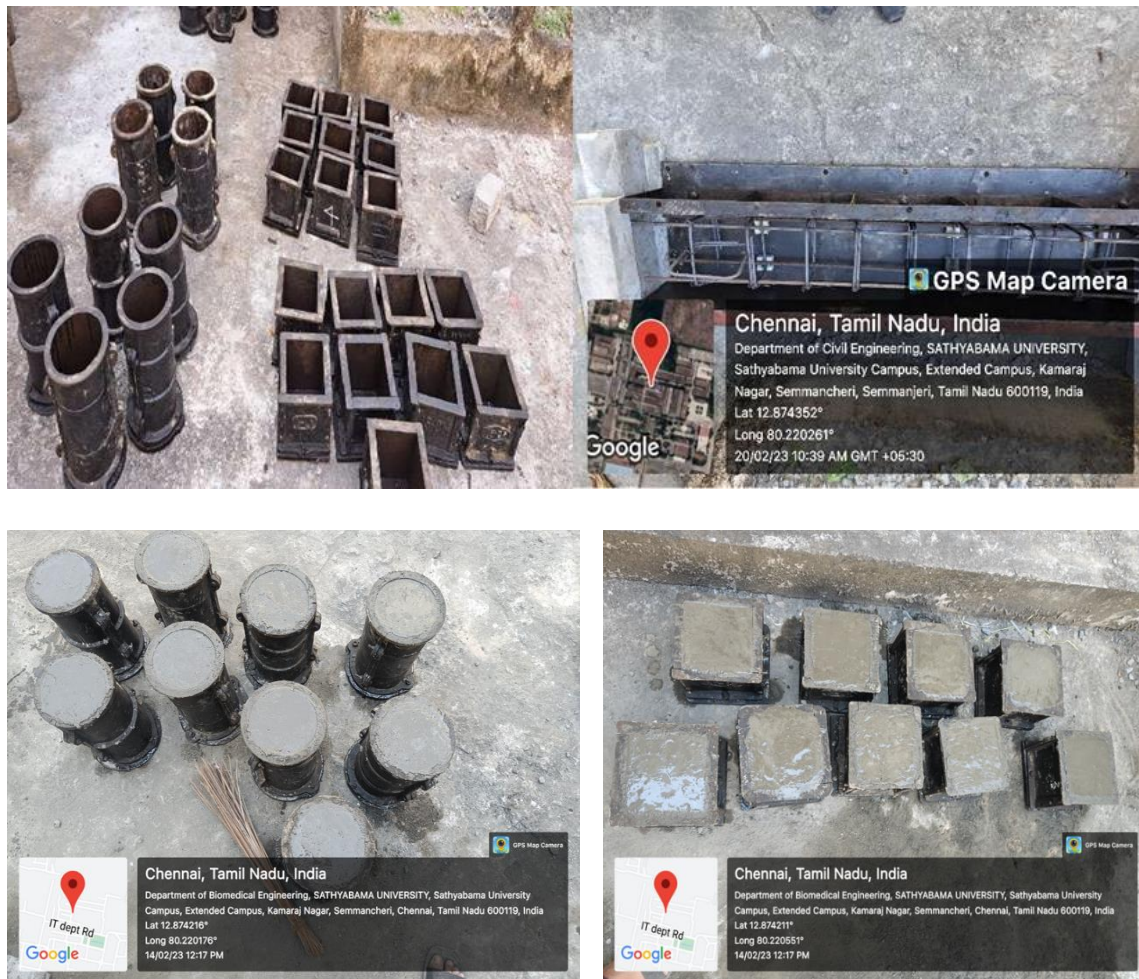


Fig 4.7 cube, cylinder and beam mould with oil applied & casting process

4.3.3 Reinforced Cementitious compound Beams:

Reinforced cementitious compound plays a crucial role in construction and is widely used in various engineering structures such as buildings, bridges, hydroelectric and nuclear power plants, treatment plants, containment structures, and wharves, among others. Its features, including economy, efficiency, resistance, and stiffness, make it highly desirable for various structural applications, creating direct and indirect employment opportunities. To ensure the safety and feasibility of a structure, it is essential to understand the behaviour of its structural elements when subjected to external forces. Various methodologies can be employed to study the response of these elements, such as large-scale experimental studies of reinforced cementitious compound beams. The experimental observations are then compared with theoretical calculation that estimate the internal distributions of tensile and

compressive stresses, as well as beam deflections and deformations. Furthermore, finite element modelling can be used to analyse the behaviour of these elements and compare the experimental observations with those obtained through the finite element method. This provides a complementary approach to the experimental observations.



(a)



(b)



(c)

Fig 4.8 RCC Beam (a) Mould Setup (b) Casting (c) curing

4.3.4 Experimental test and Observations:

The experimental test which consists of both the tests conducted on Fresh cementitious compound and Hardened cementitious compound. The experimental values are calculated and the cementitious compound is cured at the stages of 7, 14 and 28 days respectively. It consists of two types

- Test on Fresh Cementitious compound
- Test on Hardened cementitious compound

4.3.4.1 Test on Fresh Cementitious compound:

4.3.4.1.1 Slump Cone Test:

The slump cone test on cementitious compound is to find out the workability which is a property of fresh cementitious compound. Workability is the property of fresh cementitious compound which means it is easy to place and workable cementitious compound is the cementitious compound which shall be placed and compacted with ease and without any segregation. Workability is capacity working without any extra labor and resistance loss. The cementitious compound resistance depends upon the water percentage. Water percentage and slump are taken from this slump test. It is the vertical height of the fresh cementitious compound compared to its mould height.

The workability is determined by using the slump cone test in fresh cementitious compound. The code book IS: 1199-1959 is required

- Cone shaped slump
- Rod for tamping
- Bottom sheet in metallic

Procedure

- To perform the slump test, I begin by cleaning the mould thoroughly, ensuring that the inner surface is free from moisture and any attached old cementitious compound is cleared. Once the mould is clean, I place it on a smooth and clean surface and compact each layer, tamping 25 times using the tamping rod to distribute equal strokes.
- After each layer, I use the trowel to level and clear any remaining cementitious compound.
- I then carefully remove the mould in a vertical direction from the cementitious compound, allowing the fresh cementitious compound to subside.
- This observations in what is known as a slump, and I measure the height between the top of the slump cone and the top of the deformed cementitious compound, noting the height difference in mm as the slump of the fresh cementitious compound.

- The slump of the fresh cementitious compound provides an indication of its characteristics, and I note the slump value accordingly.
- If the fresh cementitious compound slumps evenly, it is referred to as a slump with true value. If only one part of the fresh cementitious compound falls down, it is called a collapsed slump.
- In a slump with shear, I measure the variation in height between the top of the mould and the average value of the slump as the slump value.
- Finally, I compare the slump values of fresh cementitious compound for 0%, 20%, 40%, and 60% of GGBS replacement, which are shown below.



Fig 4.9 Slump cone Test

Table 4.7 Slump values of 0%, 20%, 40% and 60% replacement of cement with GGBS

S. No	Mix details	Slump (mm)
1.	Mix 1 (conventional cementitious compound)	79
2.	Mix 2 (GGBS is replaced by 20%)	68
3.	Mix 3 (GGBS is replaced by 40%)	56
4.	Mix 4 (GGBS is replaced by 60%)	60

4.3.4.2 Test on Hardened Cementitious compound:

4.3.4.2.1 Compressive Strength Test:

The concept of compressive resistance, which refers to a material or structure's ability to withstand surface loads without cracking or deflecting. When a material is subjected to compression, it tends to shrink in size, whereas in tension, it elongates. The test procedure for determining compressive resistance involves...

Apparatus Required:

- Non-porous enamel tray
- Trowel
- Cube Mould of size 150mm x 150mm x 150mm
- Platform Vibrator
- Compression Testing Machine
- Balance to Measure Weight

Materials Required:

- Cement
- Fine Aggregates
- Coarse Aggregates

Procedure:

- To prepare the cementitious compound, I need to gather the necessary quantities of cement, fine aggregate, and coarse aggregate in a non-porous enamel tray. I will then mix these ingredients with a trowel for at least 1 minute.
- Next, I need to add the required amount of water to the tray and mix all 3 ingredients thoroughly until the mixture is of uniform color.
- I should make sure to mix for no less than 3 minutes and no more than 4 minutes.
- Once the mixture is ready, I will pour it into a cube mould that measures 150mm x 150mm x 150mm. To ensure the cementitious

compound is compacted properly, I will use a trampling rod in a standard specific manner.

- After compaction, I will place the mould in a cabin with a temperature of $24^{\circ}\text{C} + 2^{\circ}\text{C}$ for 24 hours.
- After 24 hours, I will remove the specimen from the mould and submerge it in clean water to cure for 28 days.



Fig 4.10 Compressive Strength test

Table 4.8 compressive resistance values of 0%, 20%, 40% and 60% replacement of GGBS in 7, 14 and 28 days

S. No	Mix Details	7 Days (N/mm ²)	14 Days (N/mm ²)	28 Days (N/mm ²)
1.	Mix 1 (conventional cementitious compound)	32.5	50	57
2.	Mix 2 (cement 80% and GGBS 20%)	31.5	47.6	56.9
3.	Mix 3 (cement 60% and GGBS 40%)	32	50.5	58.5

4.	Mix 4 (cement 40% and GGBS 60%)	30	48	56.3
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Calculation:

Size of the Cube = 150mm x 150mm

Area of the Cube = L x B = 150mm x 150mm

Characteristic compressive resistance = $\frac{\text{Failure Load of cube}}{\text{Area of the cube}}$

Failure load of Cube = 1316 KN

Compressive resistance = $\frac{1316 \times 1000}{150 \times 150} = 58.5 \text{ N/mm}^2$

4.3.4.2.2 Split tensile Strength Test:

The test for splitting tensile resistance involves the application of a compressive load in a diametric direction. This type of loading causes the plane that contains the load to experience tensile stresses while the area surrounding the load experiences compressive stresses. The procedure for split tensile resistance is as follows:

Apparatus Required

- Compression Testing Machine
- Two Packing Strips of Plywood 30 cm long and 12 mm wide

Theory

Cementitious compound is a material that exhibits weakness in tension as it is inherently brittle and does not possess the ability to resist direct tensile forces. When exposed to such forces, the cementitious compound will inevitably develop cracks. As a observation, it is imperative to ascertain the tensile resistance of cementitious compound so as to identify the load capacity at which cementitious compound members may potentially fracture.

Procedure

- To conduct the test, I will need to immerse the specimen in water for 7 days for curing.
- After the curing period, I will remove the specimen from the water and wipe the surface dry using a cloth.
- Then, I will draw diametrical lines on both ends of the specimen to ensure that they are on the same axial plane.
- I will also take note of the specimen's weight and dimensions.
- Next, I will adjust the compression testing machine to the required range and fix a plywood strip onto the lower plate before carefully placing the specimen onto it.
- I will align the specimen so that the marked lines on both ends are vertical and centered over the bottom plate.
- I will then place another plywood strip on top of the specimen and bring the upper plate down to touch the plywood strip.
- I will apply a total load of 990 kg/min to 1485 kg/min and record the breaking load P.



Fig 4.11 split tensile Strength test

Table 4.9 split-tensile values of 0%, 20%, 40% and 60% replacement of GGBS in 7, 14, and 28 days

S. No	Mix Details	7 Days (N/mm ²)	14 Days (N/mm ²)	28 Days (N/mm ²)
1.	Mix 1 (conventional cementitious compound)	2.70	3.5	4.35
2.	Mix 2 (cement 80% and GGBS 20%)	2.7	3.4	4.1
3.	Mix 3 (cement 60% and GGBS 40%)	2.61	3.8	4.48
4.	Mix 4 (cement 40% and GGBS 60%)	2.53	3.5	4.13

Calculation:

Size of Cylinder: Diameter = 150mm, Height = 300mm

Area of cylinder = $\pi \times D \times L$

Characteristic split- tensile resistance = $\frac{2 \times \text{Failure Load of cylinder}}{\text{Area of cylinder}}$

Failure Load = 317 KN

Split tensile resistance = $\frac{2 \times 317 \times 1000}{\pi \times 150 \times 300} = 4.48 \text{ N/mm}^2$.

4.3.4.2.3 young's modulus of cementitious compound:

Young's modulus is a cementitious compound material parameter that quantifies its degree of stiffness when exposed to compressive or tensile stress. It is expressed as the ratio of stress, which represents the amount of force per unit area, to strain, which is the amount of deformation per unit length in the elastic region of the stress-strain curve. The value of Young's modulus can vary due to various factors such as the type and resistance of the cementitious compound, its age and curing conditions, and the testing methodology used to determine it.

Apparatus Required:

- Compressometer assembly with dial gauge
- Test specimen
- Scale
- Compression testing machine

Procedure:

- We prepare four cylindrical specimens with a height of 300 mm and a diameter of 150 mm under standard conditions.
- After curing, we measure the average diameter and height of each specimen. Next, we place the specimen in a testing machine and align it vertically and centrally on the loading plate with the load cell positioned above the specimen.
- We apply a compressive load to the specimen at a rate of 0.2 MPa/s until the load reaches around 40% of the expected maximum load, usually between 30 and 50 MPa.
- During loading, we measure the deformation of the specimen at several load levels such as 20%, 40%, 60%, and 80% of the expected maximum load using a strain gauge or extensometer.
- Using the load and deformation data, we plot the stress-strain curve, which is linear up to the elastic limit of the material.
- We calculate the slope of the linear part of the stress-strain curve by dividing the stress by the strain to determine the Young's modulus of the cementitious compound.
- We repeat the process for the remaining specimens and calculate the average Young's modulus.

Table 4.10 the stress and strain values of M50 grade conventional cementitious compound

Load (KN)	Stress (N/mm2)	Change in length (mm)	Strain	Young's modulus (Mpa)
25	1.414	0.019	5.49×10^{-5}	49967
50	2.829	0.031	12.4×10^{-5}	47854
75	4.244	0.058	4.69×10^{-4}	49245
100	5.658	0.063	3.87×10^{-4}	48144
125	7.073	0.091	4.36×10^{-4}	46548
150	8.488	0.097	5.85×10^{-4}	48126

Table 4.11 the stress and strain values of M50 grade cementitious compound with 20% replacement of GGBS

Load (KN)	Stress (N/mm2)	Change in length (mm)	Strain	Young's modulus (Mpa)
25	1.414	0.019	5.45×10^{-5}	47954
50	2.829	0.031	12.1×10^{-5}	46768
75	4.244	0.058	4.64×10^{-4}	45142
100	5.658	0.062	3.82×10^{-4}	46996
125	7.073	0.091	4.25×10^{-4}	47284
150	8.488	0.094	5.21×10^{-4}	45146

Table 4.12 the stress and strain values of M50 grade cementitious compound with 40% replacement of GGBS

Load (KN)	Stress (N/mm2)	Change in length (mm)	Strain	Young's modulus (Mpa)
25	1.414	0.019	5.2×10^{-5}	45368
50	2.829	0.032	11.9×10^{-5}	47259
75	4.244	0.046	4.34×10^{-4}	46952
100	5.658	0.071	3.45×10^{-4}	48011
125	7.073	0.081	4.12×10^{-4}	49126
150	8.488	0.095	5.4×10^{-4}	44629

Table 4.13 the stress and strain values of 50 grade cementitious compound with 60% replacement of GGBS

Load (KN)	Stress (N/mm2)	Change in length (mm)	Strain	Young's modulus (Mpa)
25	1.414	0.019	5.05×10^{-5}	44689
50	2.829	0.031	12.2×10^{-5}	46862
75	4.244	0.047	4.1×10^{-4}	45974
100	5.658	0.069	3.2×10^{-4}	43259
125	7.073	0.086	4.04×10^{-4}	46824
150	8.488	0.091	5.9×10^{-4}	45168

Observations:

Young's Modulus of Conventional cementitious compound specimen = 49284.5 Mpa

Young's Modulus of Mix - 2 specimen = 47268.83 Mpa

Young's Modulus of Mix- 3 specimen = 48659.16 Mpa

Young's Modulus of Mix – 4 specimen = 46821.33 Mpa

4.3.4.2.4 Flexural Strength Test:

The flexural test assesses the indirect tensile resistance of cementitious compound by measuring the ability of an unreinforced cementitious compound beam or slab to resist failure due to bending. The observations of the test are typically expressed as a modulus of rupture, denoted as (MR) in units of MPa or psi. The procedure for Flexural test is as follow:

Apparatus Required

- RC specimen beam
- frame for loading
- Hydraulic Jack
- Load Cell for the measurement of load
- LVDT (or) dial gauges for the measurements of deflections

Theory

The study aims to analyse the behaviour of the RC beam at different loading stages, starting from the uncracked phase to the ultimate phase leading to collapse.

Procedure

- To conduct the flexural test on the cementitious compound specimen, I should ensure that the test is carried out immediately after removal from the curing condition to avoid surface drying that may reduce the flexural resistance.

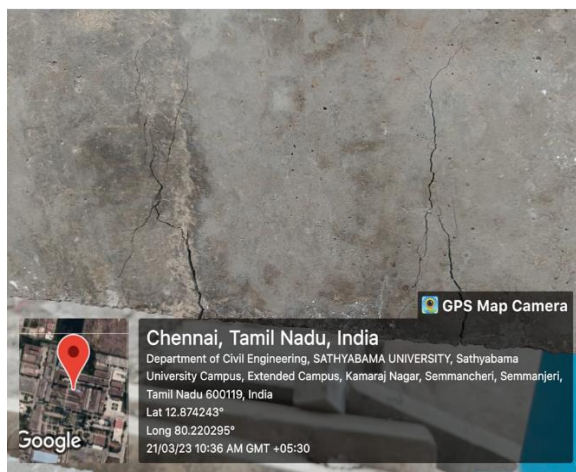
- Next, I should place the specimen on the point of loading, ensuring that the hand finished surface does not come into contact with the loading points.
- This ensures acceptable contact between the specimen and the loading points. I will then center the loading system relative to the applied force.
- After that, I should place the block in contact with the specimen surface at the loading points, and loads are applied between 2 to 6 percent of the computed ultimate load.
- I should check for gaps greater than 0.10mm, which can be eliminated using leather shims (6.4mm thick and 25 to 50mm long) that extend the full width of the specimen.
- If the gap is in excess of 0.38mm, capping or grinding should be considered to remove the gap.
- I should load the specimen continuously and without shock until it fails at a constant rate (Indian standard specified loading rate of 400 Kg/min for 150mm specimen and 180kg/min for 100mm specimen, stress rise rate 0.06+/-0.04N/mm².s according to British standard).
- Finally, I will measure the cross-section of the tested specimen at each end and at the center to calculate the average depth and height.
- The flexural test observations are expressed as a modulus of rupture denoted as (MR) in MPa or psi, which indirectly evaluates the tensile resistance of cementitious compound.



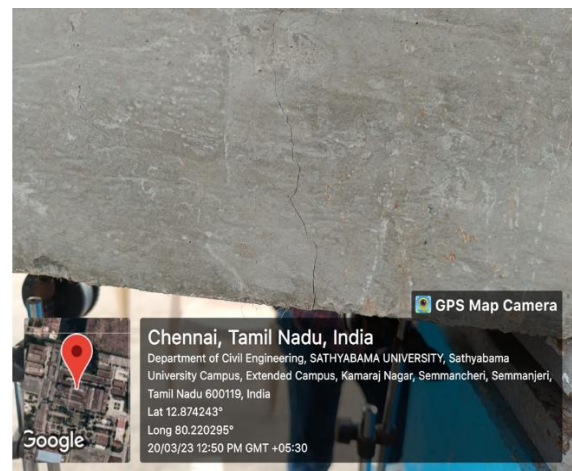
(a) Mix 1 beam



(b) Mix 2 beam



(c) Mix 3 beam



(d) Mix 4 beam

Fig 4.12 Beam crack pattern

Table 4.14 Experimental Deflection for four beam specimens

S. No	Load (KN)	Deflection (mm)			
		Mix 1 - CB	Mix 2	Mix 3	Mix 4
1.	10	0.35	0.43	0.27	0.59
2.	20	0.76	0.8	0.59	0.75
3.	30	0.93	0.97	0.9	0.95
4.	40	1.25	1.36	1.22	1.28
5.	50	1.5	1.68	1.71	1.53

6.	60	2.12	2.35	2.38	1.76
7.	70	2.55	2.56	2.65	2.32
8.	80	3.2	2.85	2.93	2.73
9.	90	3.65	3.25	3.05	3.32
10.	100	4.15	3.86	3.78	4.35

4.3.5 Microscopic Images Investigation:

4.3.2.3 Field Emission – Scanning Electronic Microscope Topography (FE-SEM):

The field emission scanning electron microscope is an advanced imaging technique that has a wide range of applications in various fields, such as biology, materials science, nanotechnology, and more. FESEM operates by using an electron beam that is directed towards a sample, which produces detailed topographical and morphological information about the sample's surface. FESEM has several advantages over conventional scanning electron microscopes (SEM), including higher resolution, better contrast, and rised surface sensitivity. Additionally, FESEM allows imaging of non-conductive samples without requiring a conductive coating, making it a valuable tool for many applications.

In the laboratory, I carried out an FESEM test on my cementitious compound cylinder specimen after 28 days of curing with 0% and 40% GGBS replacement for cement. I obtained a few images at 50 micrometres and 260 micrometres for sample 1 and sample 2, respectively.

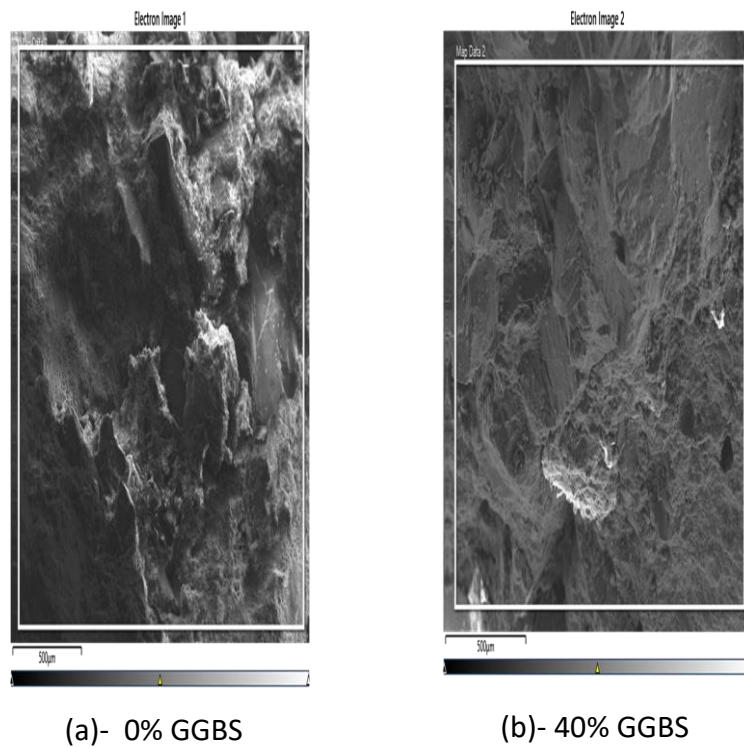


Fig 4.13 FE-SEM images

The images presented here are obtained from the cylinder specimens subjected to 28 days of curing, with 0% and 40% replacement of GGBS. Sample 1's images were captured at 50 micrometers, and sample 2's images were taken at 250 micrometers. Figure 4.12 shows FE-SEM images of the conventional cementitious compound sample and the sample with 40% replacement, Mix-3.

CHAPTER 5

ANALYTICAL INVESTIGATION

5.1 GENERAL:

Analysis using finite element method is a type of computer-based analysis that employs software to simulate digital models of structures. This analysis method is used in various fields in engineering to evaluate the resistance, toughness, elasticity, & other related factors of different materials and structures. The detailed view of FEA is as follows.

5.2 FINITE ELEMENT ANALYSIS:

Finite element analysis (FEA) is a computational technique used to predict and comprehend the behaviour of structures under various physical situations. FEA is employed by engineers for identifying design errors in their models. The finite element method, which divides an object's structure in the form of smaller components or elements and connects these elements at nodes, is utilized in FEA. The algebraic equations produced by FEM can be used by designers, engineers, and programmers to conduct finite element analysis. Partial differential equations (PDEs) are certainly employed to elaborate physical phenomena such as structural or fluid behaviour and heat transfer. With the advent of finite element analysis, computers can now able to sort both linear and nonlinear PDEs. FEA can help minimize the number of physical prototype created and experiment conducted while optimizing all components during the design phase. In the 1970s, finite element analysis software such as Abaqus, Adina, and Ansys were developed. Nowadays, virtual testing and design optimization are commonly incorporated into the product improvement cycle to enhance product quality and reduce time for market.

Types of FEA tests

Different types of test utilized during analysis of finite element method, such as:

- Finite element analysis involves a variety of analyses conducted on digital models of structures. One such analysis is structural static analysis, which employs scaled models to verify that the full-scale structure can perform well.

- Another type of analysis is thermal engineering analysis, which examines how temperature changes affect the structure's design. Modal analysis, on the other hand, is utilized to examine an object's vibrations and its response to external vibrations. This type of FEA allows designers to make adjustments for vibrations during the design stage to ensure a robust final product.
- Finally, engineering seismic calculations evaluate the product's performance when subjected to various ground vibrations and frequencies, guaranteeing a stable foundation for the final structure.

5.3 ABAQUS:

Abaqus is a software utilized for finite element analysis in mechanical engineering, designed to create digital models of structures, electronics, and machine components to study their attributes, including resistance, elasticity, toughness, temperature distribution, fluid flow, and electromagnetic efficiency. It helps engineers analyze the product's functionality under different circumstances without requiring them to build test products or perform crash tests. The software allows engineers to model and test individual components that make up larger structures, with users defining the dimensions of the object and adding physical attributes like weight, pressure, & temperature to simulate movement, fatigue, fractures, fluid flow, temperature distribution, and electromagnetic effects over time. Abaqus also offers software for data management, backup, academic research, and teaching.

- One of the software's benefits is that it can import CAD geometries of all kinds (3D and 2D) from various CAD software to conduct simulations. It also includes CAD developing software such as Design Modeler and Space Claim to simplify the workflow. Abaqus can execute advanced engineering simulations precisely and realistically, utilizing various contact algorithms, time-dependent simulations, and nonlinear material models. It can also integrate various physics into a single platform, such as thermal analysis with structural and fluid flow analysis with thermal and structural. Abaqus can optimize different features, such as geometrical design and boundary conditions, and analyze product behaviour under various criteria.
- However, one of the software's downsides is that the simulation is only as good as the input and the process's representation. It necessitates time and

skill to master the simulation environment and the simulated components. The simulation output may also provide perplexing and seemingly contradictory observations, and explaining the observations may present challenges regarding the validity of inputs and processing assumptions. Despite its capabilities, simulation is not a substitute for reality.

5.4 PROPERTY MODULE:

One crucial step in the finite element modeling process is to define the attributes of the material and section being used. For instance, in the case of a composite beam made of cementitious compound and basalt fibre bars, with a yield stress of 415 MPa, defining the attributes of the section involves specifying the section's thickness and all the relevant material attributes necessary for the analysis.

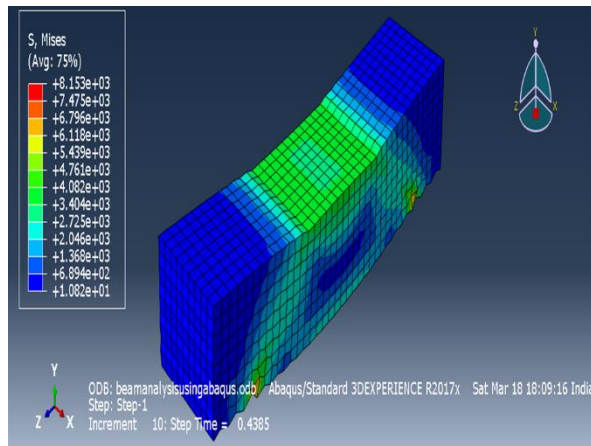
Table 5.1 Attributes of materials used in the model

ATTRIBUTES	PERCENTAGE OF GGBS REPLACEMENT			
	0%	20%	40%	60%
Young's modulus	49.27 Gpa	48.36 Gpa	48.65 Gpa	46.5Gpa
Poisson's Ratio	0.28	0.23	0.29	0.24

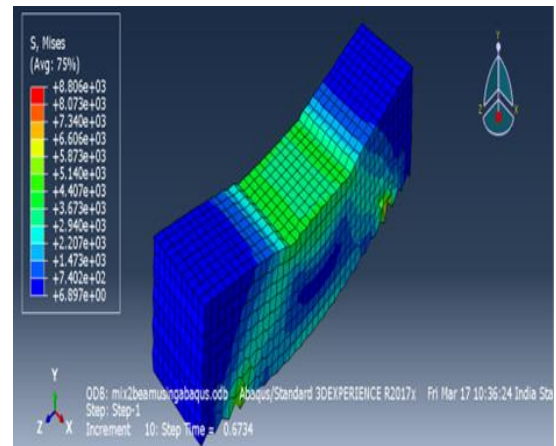
5.5 ANALYTICAL OBSERVATIONS:

The model of analytical and their observations of the beam is tabulated and the images of the observations are also shown:

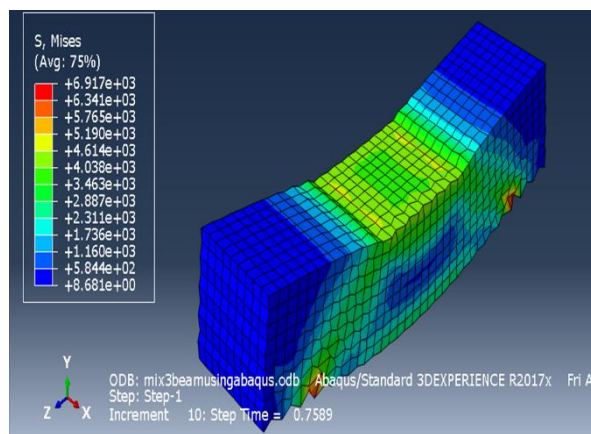
The observations indicate that the mix 3 beam outperformed the others in terms of load carrying capacity and deflection. GGBS-replaced beams with 20%, 40%, and 60% replacement rates were compared to traditional beams. The BFRP bar showed increasing resistance and decreased deflection at higher loads with 40% GGBS replacement in contrast to conventional cementitious compound. However, the resistance gradually decreased and deflection rised at lower loads with a higher replacement of 60% GGBS. The deflection of the beam occurred in a particular direction under four-point loading, with Abaqus analysis showing downward deflection and values indicating the load at which high deflection occurs.



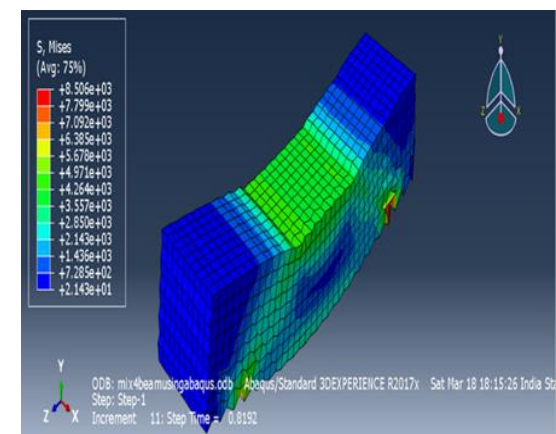
(a) Mix-1 (0%)



(b) Mix-2 (20%)



(c) Mix-3 (40%)



(d) Mix-4 (60%)

Fig 5.1 Analytical observations of the beam model

Table 5.2 Analytical observations of load & deflection of beam

S. No	Load	Deflection			
		Mix -1- CB	Mix- 2	Mix- 3	Mix- 4
1	10	0.2991	0.4407	0.3028	0.5741
2	20	0.7364	0.7961	0.478	0.7932
3	30	0.8715	0.968	0.7368	0.9455
4	40	1.0727	1.4798	1.1149	1.2948

5	50	1.6237	1.7928	1.6558	1.5362
6	60	2.4123	2.2831	2.3937	1.7924
7	70	2.695	2.6914	2.6584	2.3641
8	80	3.1035	2.9563	3.0781	2.8571
9	90	3.6774	3.2942	3.2711	3.5595
10	100	4.2523	3.9501	3.6948	4.2621

Models of four beams are created with varying percentage were created in ABAQUS and the material attributes are obtained from experimental investigations are applied to the models. The beam's load and deflection are shown in the table and the figure.

CHAPTER 6

RESULT AND DISCUSSION

6.1 GENERAL:

This chapter shows that the detailed view about the observations and it also explains more about it and their graph of rise or decrease of cementitious compound specimen's resistance etc.

6.2 TEST ON HARDENED CEMENTITIOUS COMPOUND:

6.2.1 Compressive Strength:

The compressive resistance is performed following the IS 516-1999 standards on a cementitious compound sample measuring 150mm x 150mm x 150mm. The samples are immersed in clean water and removed after 7, 14, and 28 days to test their resistance. They are then placed in a dry area to ensure that all water is drained out before testing, observationing in more accurate observations. The specimen is placed in a compression testing machine and loaded gradually until it fails. The observations of the test are graphically displayed to represent the compressive resistance of the sample.

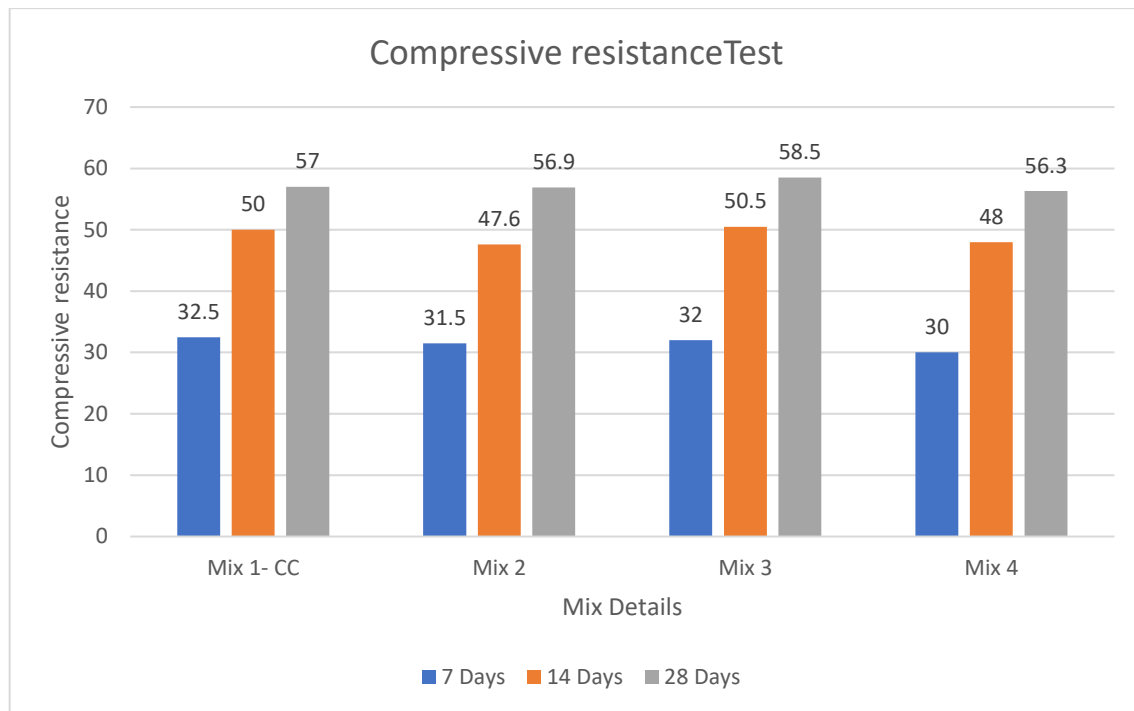


Fig 6.1 Graphical Representation of compressive strength test

A graph is used to illustrate the compressive resistance of cementitious compound cube specimens for four different mixes, with values taken at 28 days. Mix 1, which is a conventional cementitious compound specimen, has a compressive resistance value of 57 N/mm². Mix 2, with a compressive resistance value of 56.9 N/mm², is another conventional cementitious compound specimen. The third mix, with a compressive resistance value of 58.5 N/mm², contains a replacement of 40% GGBS instead of cement. Mix 4, with a compressive resistance value of 56.3 N/mm², is another conventional cementitious compound specimen. The compressive resistance test was conducted in a compression testing machine.

At 28 days, the test observations indicate that the Mix 3 specimen, which has 40% replacement of cement with GGBS, has a higher resistance than the conventional cementitious compound. The 20% replacement of GGBS also observations in an improvement in resistance compared to the conventional cementitious compound specimens. However, at replacement rates greater than 40%, specifically at 60% of GGBS, the specimens show a reduction in resistance when compared to the resistance obtained at 40% replacement. The time required to reach higher resistance levels was not measured in this test. Therefore, Mix 3 is considered to

have achieved the desired resistance level and is stronger than the conventional specimen.

6.2.2 Split tensile strength:

The split tensile resistance test is conducted in compliance with the IS 516-1999 standards on cylindrical cementitious compound specimens that measure 150mm in diameter and have a length of 300mm. The cylindrical specimens are placed diagonally between the compression testing machine's loading surfaces, and a load is gradually applied until the cylinder fails, observationing in diagonal cracks. The graph depicting the split tensile resistance is presented below:

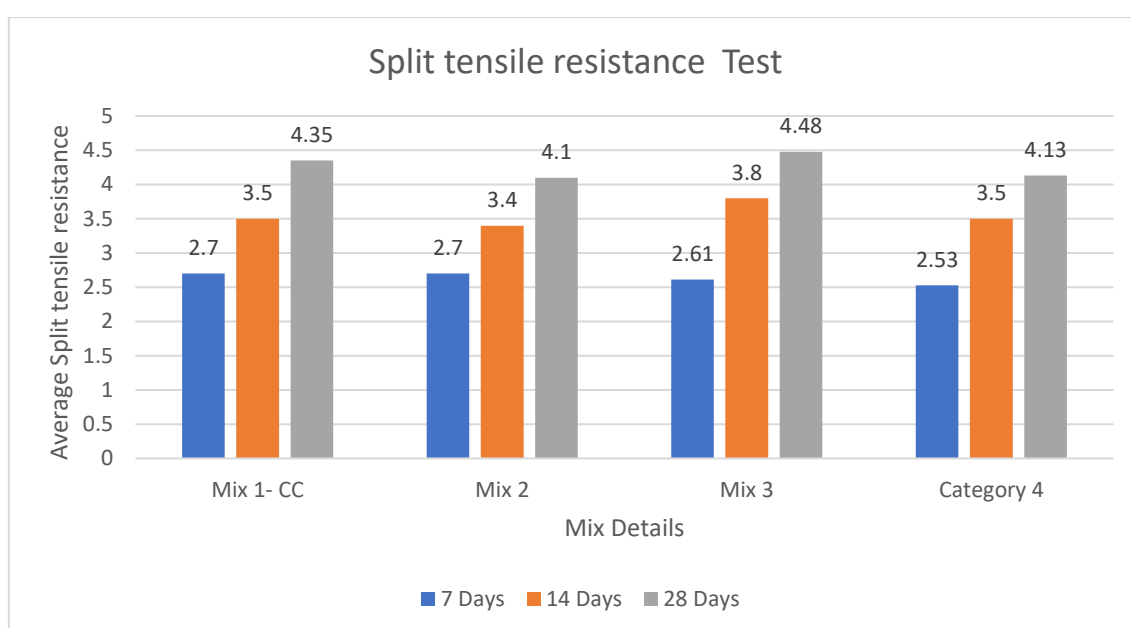


Fig 6.2 Graphical representation of split tensile strength

The graph represents the split tensile resistance of four different cementitious compound mixes that contain different proportions of cement and GGBS at different curing ages, including 7 days, 14 days, and 28 days. The split tensile resistance of all cementitious compound mixes rises as the curing age rises, and the highest compressive resistance values are observed after 28 days of curing, which is a typical trend in cementitious compound.

Mix 1, which is conventional cementitious compound, has the highest resistance values at all three curing ages, indicating that it is the strongest mix. However, Mix 2 (cement 80% and GGBS 20%), Mix 3 (cement 60% and GGBS 40%), and Mix 4 (cement 40% and GGBS 60%) also show good resistance values, suggesting that

GGBS can be used as a portion of replacement for cement to produce cementitious compound with comparable resistance to conventional cementitious compound.

Additionally, Mix 3 (cement 60% and GGBS 40%) has the highest resistance value at 28 days of curing among the GGBS-containing mixes, indicating that a higher proportion of GGBS can enhance the resistance of cementitious compound. The average split tensile resistance values are based on the 28-day resistance of the specimens. Each specimen has a gradual rise in split tensile resistance, and the mix containing 20% GGBS and the mix with 40% GGBS replacement exhibit an rise in resistance.

However, a decrease in split tensile resistance is observed with GGBS replacement above 40%, and the mix with 60% GGBS replacement shows a decrease in every characteristic, including split tensile resistance. In conclusion, the use of GGBS as a portion of replacement for Portland cement can observation in cementitious compound with good resistance values, which can lead to cost savings, reduced environmental impact, and enhanced durability of cementitious compound structures

6.2.3 Flexural Test:

The flexural test is conducted in compliance with the standards outlined in IS 516-1999. Beams contains length 1000mm, breadth 230mm, & depth 230mm are placed at two points of a hydraulic jack. The top two points are subjected to load distribution and four-point loading is executed. This observations in formation of cracks at the surface of the beam. The graph below represents the observations of the flexural test:

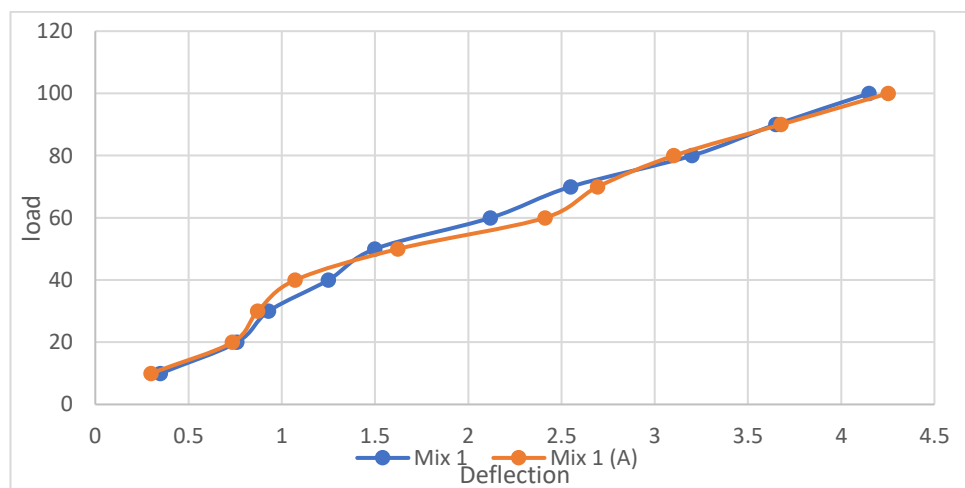


Fig 6.3 Experimental and analytical graph of Mix 1 beam

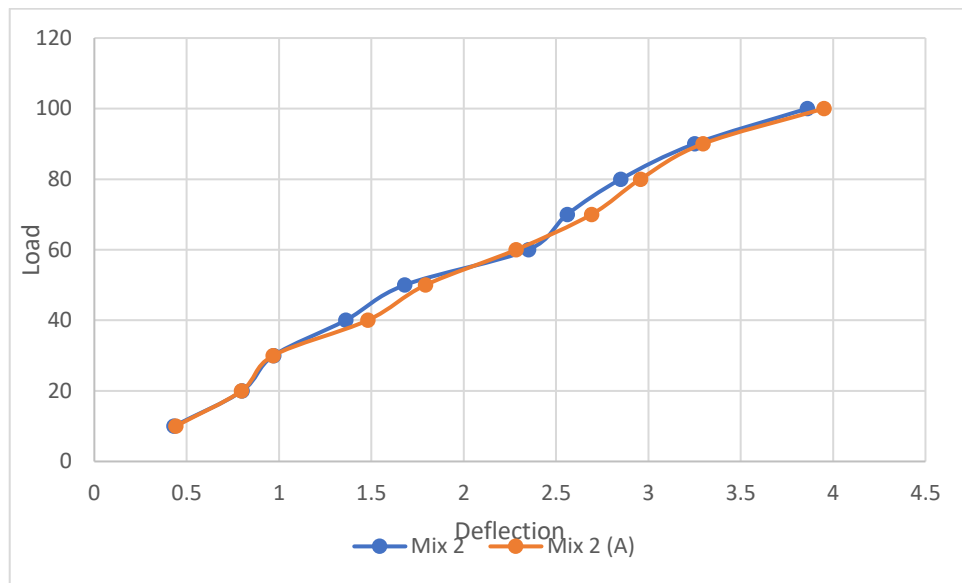


Fig 6.4 Experimental and analytical graph of Mix 2 beam

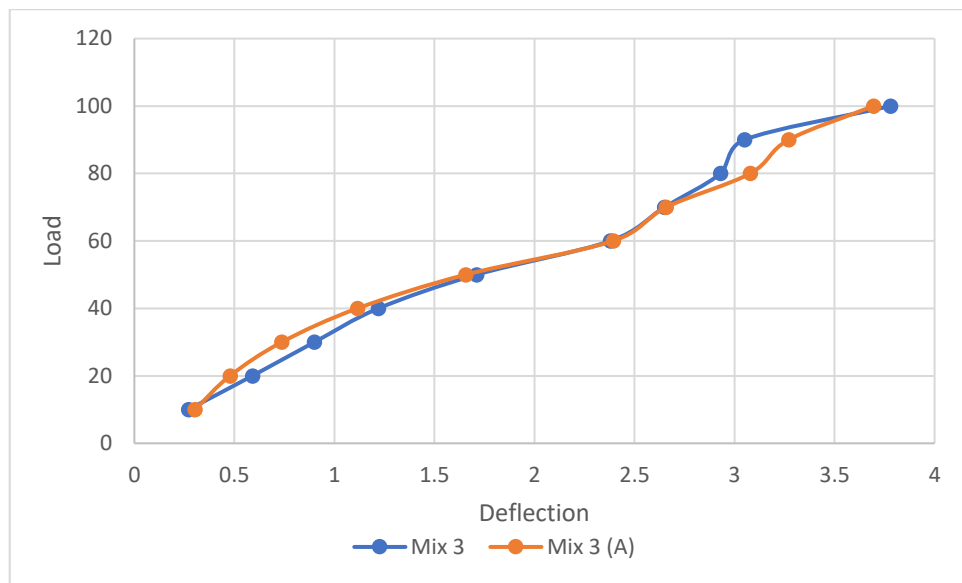


Fig 6.5 Experimental and analytical graph of Mix 3 beam

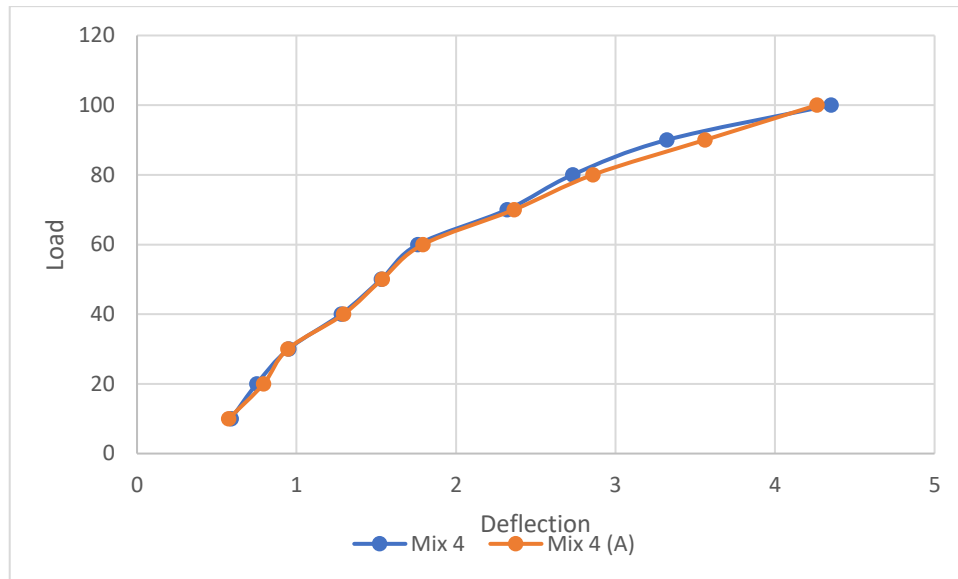


Fig 6.6 Experimental and analytical graph of Mix 4 beam

The presented graph depicts the deflection values of four different cementitious compound mixes, namely Mix-1 - CB, Mix -2, Mix- 3, and Mix- 4, under varying load values ranging from 10 KN to 100 KN. The deflection values are a measure of the deformation undergone by the cementitious compound specimens under the applied loads.

It can be observed from the graph that the deflection of all cementitious compound mixes rises with an rise in the applied load. However, the rate of rise in deflection differs for different mixes, indicating variations in their structural behaviour.

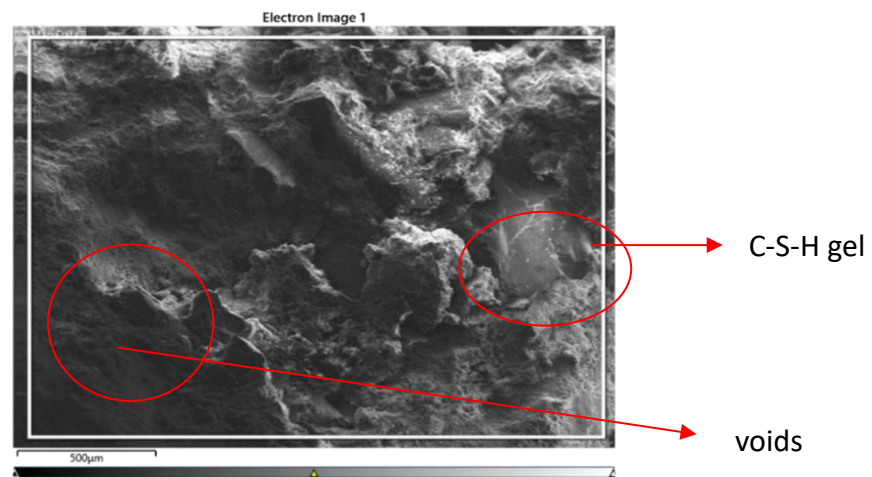
Mix 3 - Beam shows the lowest deflection values at all load values, implying that it is the most rigid mix. Mixes 1, 2, and 4 exhibit higher deflection values than Mix 3 - Beam, indicating their relative stiffness. Among the mixes, Mix 4 shows the highest deflection values, indicating that it is the least stiff, while Mix 3 exhibits good stiffness by showing less deflection, hence it is a better alternative. This reveals that the replacement of 40% GGBS shows relatively good stiffness than the others.

It is worth noting that all mixes have deflection values that fall within acceptable limits, indicating that they meet the design requirements for the specific application. However, the deflection values can substantially affect the structural behaviour and performance of cementitious compound structures. Therefore, the choice of mix should be based on a comprehensive assessment of various parameters, including flexural resistance, compressive resistance, durability, and cost.

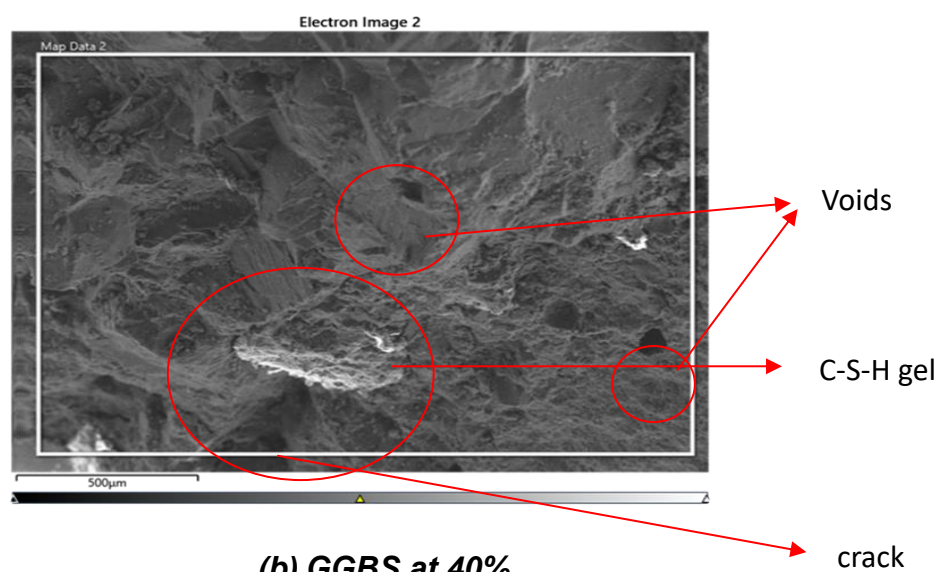
In summary, the graph underscores that different cementitious compound mixes can exhibit variations in flexural resistance and structural behaviour, and the selection of a mix should be based on a comprehensive evaluation of multiple factors..

6.2.4 SEM Analysis:

SEM is an analytical technique that enables the investigation of the composition and surface morphology of materials. It involves the use of a focused electron beam to scan the surface of the sample, which observations in interactions between the atoms of the material and the electrons, leading to the generation of signals that provide comprehensive insights into its attributes.



(a) GGBS at 0%



(b) GGBS at 40%

Fig 6.7 FE- SEM images

SEM analysis is a valuable tool for studying the surface morphology and composition of materials. It can be used to compare the microstructure of conventional M50 grade cementitious compound with that of M50 grade cementitious compound with 40% GGBS replacement. SEM analysis gives insight inside the changes in the microstructure of the cementitious compound due to GGBS replacement. To carry out SEM analysis, a sample of the cementitious compound is taken and scanned using a beam of electrons. This creates a high-resolution image of the surface of the sample, which can be analyzed to identify changes in the microstructure of the cementitious compound.

When studying M50 grade cementitious compound with 40% GGBS replacement using SEM analysis, changes in the morphology and distribution of the cementitious phases may be observed. GGBS reacts with calcium hydroxide to create additional cementitious compounds such as C-S-H and C-A-H, which may observation in a denser and more tightly packed C-S-H phase in GGBS cementitious compound. SEM analysis may also show a more uniform distribution of cementitious phases in the GGBS cementitious compound, improving its durability and resistance. In summary, SEM analysis is a powerful tool for understanding the microstructure and attributes of M50 grade cementitious compound with 40% GGBS replacement.

CHAPTER 7

SUMMARY AND CONCLUSION

7.1 SUMMARY

- The study reviewed various journals and literature on the addition of Basalt fibre reinforced bars, the portion of replacement of GGBS, and identified related problems.
- Based on the literature survey, the project objectives, scope, and methodology were formulated.
- The chosen materials for the project are Ground Granulated Blast Furnace Slag (GGBS) for partial cement replacement and Basalt Fibre Reinforced Polymer (BFRP) rebars for steel rebar replacement in cementitious compound preparation.
- Mechanical attributes such as compressive resistance, split tensile resistance, and flexural resistance of the cementitious compound will be tested in this study.
- The experimental observation will be compared with the analytical observation derived from ABAQUS software, and the conclusions will be drawn by comparing both observations.

7.2 CONCLUSION:

In this study from the above discussions of hardened attributes, microstructural attributes and flexural behaviour of the cementitious compound the GGBS replaced cementitious compound is examined.

- To ensure suitability of fine and coarse aggregates for M50 grade cementitious compound as per Indian Standard (IS) specification, water absorption and sieve analysis tests were performed. The former measures the water retention capacity of aggregates while the latter determines the particle size distribution. The observations showed that both fine and coarse aggregates were of appropriate size and had acceptable water absorption

characteristics, indicating their suitability for M50 grade cementitious compound.

- By partially replacing cement with 40% GGBS, compressive and split tensile resistance of M50 grade cementitious compound were significantly risen as compared to conventional M50 grade cementitious compound. GGBS reacts with calcium hydroxide in cementitious compound, leading to the formation of additional C-S-H gel which is a key contributor to its resistance. This observations in a denser mix with fewer voids, making it more resistant to tensile and compressive stresses. Additionally, it reduces the formation of cracks in the cementitious compound, observing in a smoother surface finish and improved durability.
- Basalt rods provide greater flexibility in M50 grade cementitious compound as compared to steel. This flexibility is beneficial when used in combination with GGBS as it can withstand tension and bending forces in the cementitious compound, leading to a more durable and long-lasting structure.
- C-S-H gel in cementitious compound provides significant bearing resistance under compressive loads, which is important for the construction of strong and durable structures capable of withstanding heavy weights and pressures.
- Flexural resistance is the ability of cementitious compound to bend or flex without breaking. By using GGBS as a portion of replacement for cementitious compound at 40%, flexural resistance of M50 grade cementitious compound was improved. This can be attributed to the denser and more compact nature of the mix which reduces the formation of voids and improves interlocking of particles.
- The design mix was determined to find the optimal combination of materials to achieve desired cementitious compound attributes. The observations showed that replacing 40% of cement with GGBS and adding basalt fibre rods reduced deflection compared to other mixes, making it the most effective combination in reducing bending or sagging of cementitious compound.
- Additionally, using GGBS as a portion of replacement for cement in M50 grade cementitious compound reduces carbon dioxide emissions. As cement production is a significant contribute for carbon dioxide emission, using

GGBS reduces the amount of cement required in the mix. This makes the cementitious compound more environmentally friendly.

Overall, replacing cement with 40% GGBS and using basalt fibre rods in M50 grade cementitious compound will improve its flexural resistance and reduce deflection. Additionally, the use of GGBS will help reduce carbon dioxide emissions, making it a more sustainable option.

REFERENCES

1. Ahmad Altalmas, Ahmed El Refai and Farid Abed, "Bond degradation of basalt fibre-reinforced polymer (BFRP) bars exposed to accelerated aging conditions", Journal of Construction and Building Materials, Vol. 12, 2015, pp. 162 - 171.
2. Andreea Serbescu, Maurizio Guadagnini, and Kypros Pilakoutas." Mechanical Characterization of Basalt FRP Rebars and Long-Term Resistance Predictive Model. Journal of Composite Construction, Vol.13, 2014 0401403, pp.1 to 13.
3. Chaohua Jiang, Ke Fan, Fei Wu and Da Chen "Experimental study on the mechanical attributes and microstructure of chopped basalt fibre reinforced cementitious compound", journal of material and design. Vol 8, 2014, pp.187 to 193.
4. Dong, Wang and Guan, "Material attributes of basalt fibre reinforced cementitious compound made with recycled earthquake waste", journal of Construction and Building Materials", 2016, pp.1 to 11.
5. Douglas Tomlinson and Amir Fam "Performance of Cementitious compound Beams Reinforced with Basalt FRP for Flexure and Shear", Journal of composite structures, 2014, 04014036, pp.1 to 10.
6. Eric Hughes, Adeyemi Adesina, Bruno Paini, Sreekanta Das, and Niel Van Engelen,,"Resistanceening of Cementitious compound Beams with Basalt Fibre Reinforced Polymer", Vol 10, 2020,pp.449 to 456.
7. Fareed Elgabbas , Ehab A. Ahmed and Brahim Benmokrane, "Flexural Behaviour of Cementitious compound Beams Reinforced with Ribbed Basalt-FRP Bars under Static Loads" Journal of Composite and Construction, 2016, pp.1 to 12.
8. Fareed Elgabbas, Ehab Ahmed and Brahim Benmokrane, "Physical and mechanical characteristics of new basalt-FRP bars for reinforcing cementitious compound structures", Journal of Construction and Building Materials, 2015, pp.623 to 635.

9. Giri Prasad Goud, Marimuthu Kannimuthu, Srinivasa Reddy and Saikrishna, "Corrosion resistance studies on the cementitious compound made with basalt fibres and basalt fibre reinforced rebars" *Journal of construction*, Vol 11, 2021, pp.1 to 6.
10. Jason Duic, Sara Kenno and Sreekanta Das, "Performance of cementitious compound beams reinforced with basalt fibre composite rebar", *Construction and Building Materials*, 2018, pp. 470 to 481.
11. John Branston, Sreekanta Das, Sara Y. Kenno and Craig Taylor, "Mechanical behaviour of basalt fibre reinforced cementitious compound", *Journal of Construction and Building Materials*, 2016, pp.878 to 886.
12. Jongsung Sim, Cheolwoo Park and Do Young Moon, "Characteristics of basalt fibre as a resistanceening material for cementitious compound structures", *Journal of composite structure*, 2005, pp. 504 to 512.
13. Julio F. Davalos, Yi Chen and Indrajit Ray. "Effect of FRP bar degradation on interface bond with high resistance cementitious compound", *Cement & Cementitious compound Composites*, 2008, pp.722 to 730.
14. Lina Xu, Daohan Song, Ning Liu and Wei Tian," Study on Mechanical Attributes of Basalt Fibre-Reinforced Cementitious compound with High Content of Stone Powder at High Temperatures". *Advances in Materials Science and Engg.*,2022, pp.1 to 15.
15. Md Hasham, Srinivasa Reddy, Seshagiri Rao and S Shrihari, "Flexural behaviour of basalt fibred cementitious compound slabs made with basalt fibre reinforced polymer rebars", *Journal of construction*,.2021, pp.1 to 7.
16. Mehran Khan , Mingli Cao , S.H. Chu and Majid Ali," Attributes of hybrid steel-basalt fibre reinforced cementitious compound exposed to different surrounding conditions", *Journal of Construction and Building Materials*,2022, pp. 322 to 337.
17. Naraindas Bheel, "Basalt fbre-reinforced cementitious compound:review of fresh and mechanical attributes". *Building Pathology and Rehabilitation*, 2021, pp. 6 to 12.

18. Qiaoyun Wua, Shiye Xiao and Kentaro Iwashita, "Experimental study on the interfacial shear stress of RC beams resistanceeened with prestressed BFRP rod", *Observations in Physics* , 2018, pp. 427 to 433.
19. R.K. Majhi, Nayak, Mukharjee, "Improvement of sustainable cementitious compound using recycled coarse aggregate and ground granulated blast furnace slag", *Journal of Construction and Building Materials*, 2018, pp. 417 to 430.
20. Rami A. Hawileh , Jamal A. Abdalla, Fakherdine Fardmanesh, Poya Shahsana, Abdolreza Khalili, "Performance of reinforced cementitious compound beams cast with different percentages of GGBS replacement to cement" , Vol. 12, 2017, pp. 511-517.
21. Saikrishna, Srinivasa Reddy, Seshagiri Rao and S Shrihari. "Moment - curvature behaviour of basalt fibred cementitious compound beams made with basalt fibre reinforced polymer bars", *Journal of Building materials*, 2021, pp. 1 to 7.
22. Yihong Guo, Xinyu Hu and Jianfu Lv," Experimental study on the resistance of basalt fibre-reinforced cementitious compound to chloride penetration". *Journal of Construction and Building Materials*, 2019, pp. 142 to 155.
23. Yiqing Dai; Zhenyi Wang; Junxiu Lv; and Xingyu Gu, " Numeric Analysis of Basalt Fibre Reinforced Cementitious compound Pavement", Vol. 8, 2016, pp. 323 to 332.
24. Zhihua Li, Sichao Wan, Chengfei Ma and Xuan Guo," Flexural behaviour of cementitious compound-basalt FRC beams with steel bars under concentrated load", *Structures*, 2022, pp. 237 to 252.
25. Zhongyu Lu , Lizhu Su , Guijun Xian , Baihang Lu and Jianhe Xie, "Durability study of cementitious compound-covered basalt fibre-reinforced polymer (BFRP) bars in marine environment", *Journal of composite structure*, 2019, pp. 263 to 279.